DRUMLINS IN THE HIMALAYAS: GEOGRAPHY, GENESIS, CLASSIFICATION AND EVOLUTIONARY HISTORY

Dissertation submitted to Jawaharlal Nehru University in partial fulfillment of the requirement for the award of the degree of

MASTER OF PHILOSOPHY

SOURAV SAHA

CENTRE FOR THE STUDY OF REGIONAL DEVELOPMENT
SCHOOL OF SOCIAL SCIENCES
JAWAHARLAL NEHRU UNIVERSITY
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INDIA
2013

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20 May, 2013

DECLARATION

I, MR. SOUROV SAHA, hereby declare that the dissertation entitled **"DRUMLINS IN THE HIMALAYAS: GEOGRAPHY, GENESIS, CLASSIFICATION AND EVOLUTIONARY HISTORY"** submitted by me for the award of the degree of **MASTER OF PHILOSOPHY** is my bonafide work and that it has not been submitted so far in part or in full, for any degree or diploma of this university or any other university.

SOURAV SAHA

CERTIFICATE

It is hereby recommended that the dissertation may be placed before the examiners for evaluation.

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Dedicated to

My Parents and Eternal Mother

Chapter—1

INTRODUCTION TO DRUMLIN

"All the progress is born of inquiry. Doubt is often better than over confidence, for it leads to inquiry and inquiry leads to invention."

...Hudson Maxim[1]

1.1. Statement of problem:

Drumlins are one of the most fascinating and easily recognizable glacial landform on the earth. They are the most enigmatic subglacial landform (Benn and Evans, 1998; Shaw, 2002; Menzies and Rose, 1987), which have long fascinated glacial geomorphologists and glaciologists alike, perhaps, more than any other glacial landforms over a century (Smalley, 1981). However, the major question which still remains is that the landform, in the peak of the hunt list for the glacial geomorphologist, has no satisfactory general explanation till now, as far as the origin or genesis of this landform is concerned (Spagnolo et al., 2010; Menzies, 1979) and therefore still remain understand imperfectly (Menzies and Rose, 1987). According to Stokes et al. (2011) the very essence of the drumlin problem lies to the fact that how ice flow creates a pattern of upstanding mounds (streamlined forms) in their flow when they themselves are a kind of obstacle. A certain '*something critical*' is necessary for drumlin formation (Arronow, 1959 in Menzies, 1979). Menzies (1979) and Menzies and Rose (1987) have also pointed out this half satisfactory known '*trigger*' mechanism for drumlin initiation and defined it as '*drumlin origin puzzle*'. This puzzle is largely attributed because of the lack of direct evidences of subglacial

[1] Powell, 1998.

processes and drumlinization (Shaw, 2002). It is also in a view unrealistic to use modern evidences to the formation of large scale landforms like drumlins because modern subglacial environments are still largely inaccessible and provide either point view (Mahaney et al., 1991; Mahaney and Andres, 1991; Helland and Holmes, 1997; Rose and Hart, 2008) or only marginal condition of recently vacated ice sheets (Boulton, 1976). The time period, as well, is so limited to explain extensively the long term subglacial behaviour and processes (Benn and Evans, 1996; Knight, 2010) which may have a lifetime of 10-1000 years or more (Hart, 1995). Recently only a very few drumlins are seen emerging from present day ice masses (Menzies,1979) which also do not contribute to understand the puzzle with sufficient confidence.

Drumlins are streamlined landforms, found '*en echelon*' in a field or Swarm[2] (Rose and Letzer, 1977; Kerr and Eyles, 2007; Knight, 1999; Clark et al., 2009), and produced beneath actively flowing ice, generally long axes parallel to former ice flow directions (Kerr and Eyles, 2007), and that they possess forms which offer minimum obstruction to ice movement (Menzies, 1979; Knight, 1997; Stanford and Mickelson, 1985). According to Meehand et al. (1996) drumlins reflect least deformed and most resistant parts of the subglacial deforming layer. According to knight (1997) they are the '*positive relief*' features and one of the key indicators of subglacial processes. Drumlins are generally oval shaped elongated hills with length-to-length ratio less than 25:1 and height generally greater than 3 m. (Coglan and Mickelson, 1993)[3]. They possess steep stoss face in the up-ice direction and gentle lee face in the down-ice direction (Menzies, 1979).

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[2] A swarm or drumlin field is a typical field contains 10 to 1000 of drumlins (Kerr and Eyles, 2007; Knight, 1999; Clark et al., 2009).

[3] Flutes, on the other hand, are parallel ridges end grooves with length-to-width ratios typically greater than 25:1 and a height less than3m. Larger composite forms are defined as mega drumlins, generally longer than 3000m. and composed of several crests or superimposed drumlins (Coglan and Mickelson, 1993).

Drumlins are, generally, believed to have formed under warm or temperate glacier base (Knight, 2006; Schomaker et al., 2006; Hattestrand et al., 2004; Smalley and Unwin, 1968) along with related subglacial landforms like flutes, rogenmoraines etc. (Schomacker et al., 2006; Benn and Evans, 1998; Brodzicowiski and Van Loon, 1991). Basal melting conditions, therefore, likely to be a prerequisite condition for drumlin formation (Hattestrand, 2004). However, the drumlin's internal composition is widely variable (Smalley and Unwin, 1968) and often cited as a major obstacle towards a satisfactory unifying explanation of their genesis (Menzies, 1979; Stokes et al., 2011). This factor often leads to widely contradictory conclusions of drumlin genesis, being the product of erosion, or deposition, or deformation, or a hybrid of these processes (Menzies, 1979). Although Menzies (1979), Menzies et al., (2007), and Hart (1997) are of the view of combined and even multiphase complex processes of erosion, deposition, and deformation for drumlin formation. Knight (1997) on the other hand advocated drumlins as the result of net-subglacial erosion, and in the view of Hart (1997), drumlins are the remnant of subglacial erosional forms. Hence disagreement exists regarding the dominant processes of drumlin formation. Some interpretation, however, even includes complex internal sedimentological structures baring from stratified drift materials to folded structures, laminated structures, augen and boudinage structures (Smalley and Unwin, 1968; Menzies, 1979), sorted glaciofluvial sediments (Knight, 2006; Shaw, 2002) etc. which strongly pointed towards a more hybrid theory of drumlin formation rather than a single dominant process. Evidences of rockcored—'*crag*' type drumlins with plastering in lee side have also been reported Menzies (1979) and others. Completely depositional—'accretionary' types (net depositional) of drumlins have been mentioned by Shaw (2002), Smalley (1981) and co-workers as well. All these interpretations point towards complex and variable nature of internal composition of drumlins and processes of their formation. These are discussed briefly in the section 1.3.

However, the debate between drumlin internal sedimentology verses outline form and their relative importance have long been discussed. Drumlin geometry (shape and size) generally reflect the relative importance of these complex depositional, deformational, and erosional processes in a drumlin field (Smalley, 1981) and is often regarded as the end product of these interacting processes (Menzies, 1979). Menzies (1979), on the other hand, provide emphasis on the dynamic balance between the pressure of overlying ice mass and shearing forces and internal materials in determining the final shape of drumlins. However, since the identification of drumlins is based solely on the superficial streamlined forms rather than internal composition and structures, according to Hill (1973) morphology must be more important. 'Form analogy' is also receiving greater emphasis by Shaw (2002) and co-workers and has been used not only to decipher the palaeo-ice flow directions but also to former subglacial mega-flood path conduits. But as the modern knowledge of subglacial processes and drumlin formation increases with time both geomorphology and geology of drumlins are given equal weitages (Benn and Evans, 1998) (see section 1.6). Recent studies, however, have also pointed out the importance of the glaciological factors as the even more important conditions for drumlin formation and their form determination (Knight, 2010; Menzies, 1979). All these evidences pointed to the fact that drumlins are more ubiquitous than previously thought and does not required any unique explanation[4] of their formation (Knight, 2010; Menzies, 1979). According to Menzies (1979) any theory of drumlin formation must be holistic and take the subglacial system as a whole and must predict all possible permutations of size, shape, internal sedimentology, surfacial material and location. More elaborate description is given the section 1.3.1.

A wide range of literature also discussed about '*drumlinization*' as a major process-mechanism of many of the drumlin formation in the former ice-sheet covered areas.

[4] Benn and Evans (1998) have mocked while interpreting the '*uniqueness*' of drumlin theories by stating that "*there are as many theories of drumlin formation as there are drumlins*" (p-431).

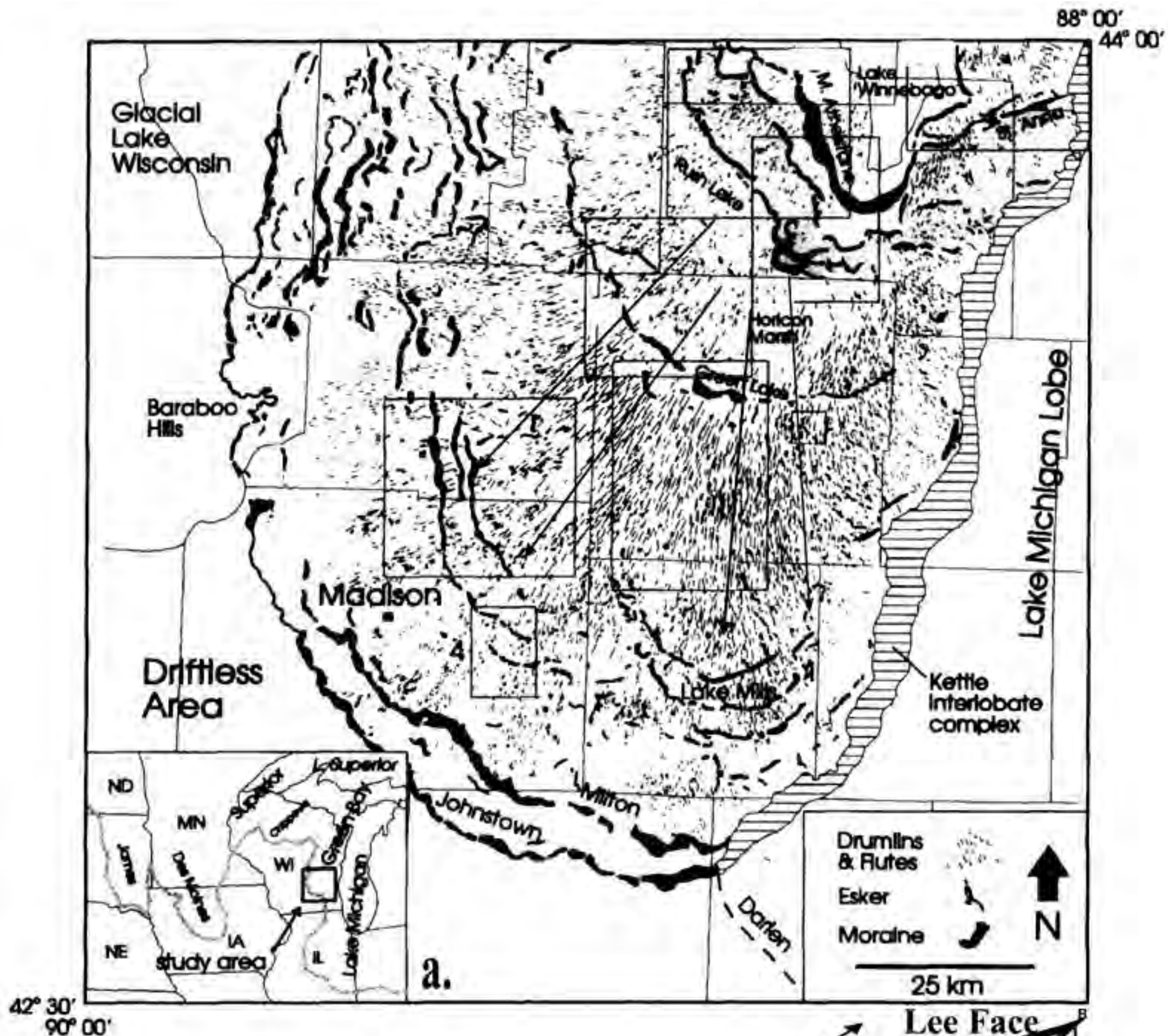
Drumlinization is the process in which predrumlin deposits undergo modification and produce drumlin like landforms due to ice-mass advance in subglacial condition (Hart, 1997; Newman et al., 1989; Kerr and Eyles, 2007). Drumlinization, therefore, is a time transgressive over space (Knight, 1997). Often the term '*drumlinoid*' is also used by researchers, which are actually applied to elongated needle shaped drumlin like streamlined landforms (Fig. 3.b). Such drumlinoid forms are recorded by Zelcs (1997) in Baltic Countries.

However, these drumlin and drumlinoid forms along with other subglacial landforms (flutes, rogen or ribbed moraines etc.) are considered now as the product of subglacial continuum (Benn and Evans, 1998; Brodzicowiski and Van Loon, 1991) and changes in the subglacial conditions and ice-mass characters are mainly responsible for these form variations within a field (Menzies, 1979). So understanding the subglacial environment is of primary signifance in any drumlin forming theory (Menzies, 1979), especially in the light of pore water pressure fluctuation and deformational history (Meehan et al., 1997). In past 150 years, subglacial and drumlin related studies have undergone large paradigm shift (see section 1.5). Huge upsurge of modern research has taken place especially after 1980's (Menzies et al., 2007; Clark et al., 2009; Knight, 2010) and according to Spagnolo et al. (2010) there are in total nearly around 1400 papers solely contributed to drumlin studies only. However, with time more and more emphasis is paid on the requirement of interdisciplinary (sedimentology, glaciology, geophysics, hydrology, GIS and Remote sensing techniques etc) nature of drumlin study (Knight, 2010; Menzies, 1979).

Most of the present day drumlins are largely thought to be the product of Quaternary glaciations and mostly the respective immediate glaciation histories of the areas of former ice-mass (Menzies, 1979). However, there are now quite a large evidences in literature of drumlins being related to past ice-sheet marginal conditions and end-moraines and possibly associated with ice retardation and thinning (Menzies, 1979; Trenhaile, 1975; Wright, Jr., 1957). Often large concentration of drumlins are also reported form low land areas where ice-mass might have radiated out and creating fan like pattern of drumlin distribution (Trenhaile, 1975; Hill, 1973; Hart, 1997; Knight, 2006) (Fig. 1.a). However, no relation yet can be identified between substrate geology and topographic settings and drumlin distribution (Benn and Evens, 1998; Clark et al., 2009). A brief discussion is given in section 1.3. Over all this important '*landscape*' scale (Knight, 2010) feature has long influenced human activities and landscape development in glaciated environment and is required to give due importance of every aspects because drumlins and subglacial dynamics hold the key to unrevealed the mystery of palaeo-glacial amd palaeo-environmental conditions. This problem certainly has tremendous future implications.

In the Himalayas till now scattered evidences of drumlins are given in the literature based on morphology or 'form analogy' (Owen et al., 1997, 2001; Raina and Srivastava, 2008; Nainwal et al., 2008). Details, both geological and geomorphological, evidences of the landforms is rare, which fuel the debate around the so existence of the landform in the Himalayan glaciated areas, especially in the light of whether valley glacier is capable of creating and presenting such blister like basket of egg landforms. Chronology of Quaternary glaciations of the Lahul Himalayas has already been given (Owen et al., 1997, 2001) base on their form and distribution and longitudinal axes orientations, around Chandra Tal area of Lahul and Spiti, Himachal Pradesh. Hence it is required to open-up the curtain of uncertainty behind the drumlins in the Himalayan conditions. The evidences of the very existence of these landform and the necessary theoretical reconstructions for their genesis and evolution and why they are recognized from limited areas of the Himalayas only etc., are required to be answered in detail by applying both geomorphological and geological techniques based on field evidences and logical explanations. Present work is a preliminary attempt to light on this aspect of drumlins in the Himalayas.

Evidences and theoretical explanation, thus, are provided keeping in view the very objectives of the study.



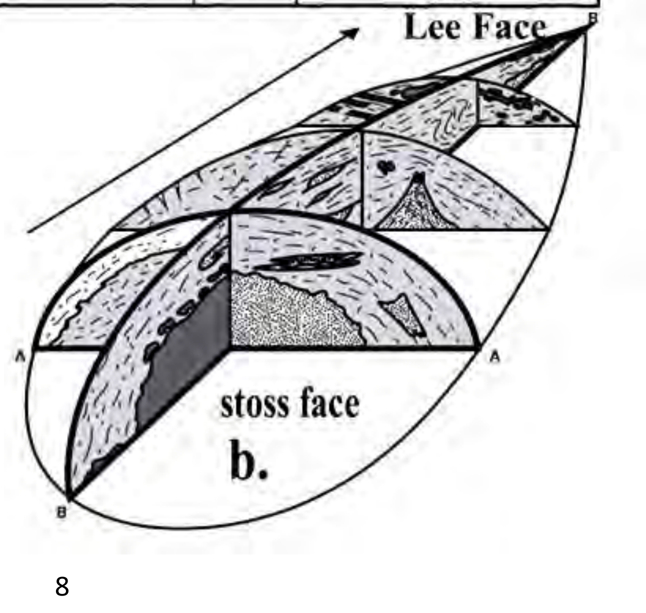


Fig.1. Geographical distribution of drumlins in the Green Bay Lobe area, US, along with major end moraines. **a.** Map shows the radiating out distributional pattern of drumlins en echelon in the field (adapted from Colgan and Mickelson, 1997). **b.** The three dimensional outline of a drumlin, with steep stoss up-ice and gentle lee down-ice faces; arrow indicates the general ice-flow direction (adapted from Menzies and Rose, 1987).

1.2. Definition:

Agreement exists among researchers behind the general definition of drumlins but it ceases at the point where their general formative mechanism is taken into consideration. However, Menzies (1979), Benn and Evans (1998) defined drumlins as,

"*Drumlins are typically smooth, oval shaped hills or hillocks of glacial drift resembling in morphology an inverted spoon or an egg half-buried along its long-axis. Generally the steep, blunter end point in the up-ice direction and the gentler sloping, pointed end faces in the down-ice direction, these two ends being respectively known as the stoss and lee sides*" (p- 315)

So drumlins are smooth rounded to elongated streamlined hills (Fig. 1b.) (Trenhaile, 1975; Clark et al., 2009; Knight, 2010; Benn and Evans, 1998). Classical drumlins are '*tear drop*' shaped (Meehan et al., 1997; Schomaker et al., 2006). They have steep up-ice (stoss) face and gentle down-ice (lee) face (Clarke et al., 2009; Meehan et al., 1997; Schomaker et al., 2006; Stokes et al., 2011) and found en echelon in a vast field (Benn and Evans, 1998) numbering hundreds to thousand drumlins (Spagnolo et al., 2010) (Fig. 1a.). The major specialty of drumlins is that their long axis generally aligned parallel to the direction of regional ice movement (Fig. 1a.) (Zelcs et al., 1997; Stokes et al., 2011; Clark et al., 2009; Menzies, 1979; Menzies and Rose, 1987; Shaw, 2002; Piotrowski and Vahldiek, 1991; Benn and Evans, 1998). This makes '*drumlin*' as a key indicator of palaeo ice-flow directions and subglacial dynamism (Menzies, 1979). However, H.M. Close in 1867 in Ireland was the first to recognize and named the landform as '*drumlin*'. '*Drumlin*' actually is an English word deviated from the Irish Gaelic word '*droimnin*'[5], meaning '*small elongate hill*' (Knight, 2010, p-91).

[5] According to Menzies (1979) and Benn and Evans (1998) the name is deviated from the Gaelic 'druim' meaning 'a hill' instead of 'droimnin' as stated by Knight (2010). However, such discrepancies in wording are rather insignificant and have no such importance in describing drumlin forms.

1.3. Characteristics of Drumlins:

The above definition of drumlins (section 1.1.) has already provided a glimpse of their general characteristics. However, a very good account of drumlin characteristics can be found in Smalley and Unwin (1998), Menzies (1979) and recently in Stokes et al. (2011). In the present paper they are briefly discussed as follows under two major classifications, viz. 1) Morphological Characteristics of Drumlins, 2) Sedimentological Characteristics of Drumlins.

1.3.1. Morphological Characteristics of Drumlins:

The identification of drumlins is mainly based on the superficial tear-drop shaped streamlined morphology of the landform (Hill, 1973) rather than their internal sedimentology which varies widely within a single drumlin field and across as well. The later is discussed briefly in section 1.3.2. Form or morphology, therefore, comes at the first place for the recognition of drumlins. Classical drumlins, however, as stated in section 1.2, are tear-drop shaped asymmetrical form (Fig. 1.b) with steep up-ice face (stoss) and gentle down-ice (lee) face (Clark et al., 2009; Meehan et al., 1997; Schomacker et al., 2006; Stokes et al., 2009; Menzies, 1979). But this age old widely recognized 'classical shape' of drumlins, as referenced in many of the previous literature, is rather rare than a communality (Spagnolo et al., 2010), often a wide range of morphological forms are stated in the literature, especially after the use of remote sensing tools which allow to take larger area and greater precision into account (Spagnolo et al., 2010; Benn and Evans, 1998; Knight and McCabe, 1997; Hanvey, 1988; Kerr and Eyles, 2007; Wright, Jr., 1957; Clark et al., 2009; Knight, 1997; Meehan et al., 1997). Any changes in the equilibrium conditions of the ice velocity and/or pressure, drift supply and availability, texture, and porewater conditions are mainly responsible for such changes in the outline forms of drumlins (Menzies, 1979). However, composite over-printed forms, often recognized as '*superimposed*' drumlins, on the other hand, largely owe their morphology to different phases of glaciation or ice-sheet advancement [6] (Coglan and Mickelson, 1997; Rose and Letzer, 1977; Knight and McCabe, 1997; Knight, 1997; Benn and Evans, 1998) along with the changes in above mentioned equilibrium conditions. Overall the changes in the morphology and morphometry, across and within a single swarm, hold the first place for characterizing drumlins and are discussed here.

According to Benn and Evans (1998) the morphology and morphometry of drumlin fields include drumlin spacing, density, distribution, and their shape and size variation within and between fields. These are briefly discussed as follows.

1.3.1.1. Drumlin Spacing:

Drumlin spacing can be defined as the calculated perpendicular distance between drumlins (Reed et al., 1962; Menzies, 1979; Benn and Evans, 1998). Changes in this morphometric characteristic generally denote periodicity in distribution in a swarm (Menzies, 1979) and widely different glacial conditions across different fields (Benn and Evans, 1998). The spacing measurement is usually under taken from drumlin centre (or high point) to centre, not edge to edge (Menzies, 1979) and generally normal to multimodal distributions, with large variations across different fields of drumlins, are recorded (Benn and Evans, 1998; Menzies, 1979). They are also often found smaller in size and more closely spaced near ice margins where glacial driving stress decreases (Knight, 2010). These kinds of morphometric analysis of

[6] Drumlins within a swarm are more of discontinuous rather synchronous and they are formed incrementally rather by single phase of formation (Benn and Evans, 1998).

drumlins field often exclude associated structures like roches moutonee and/or bedrock protrusions etc. Menzies (1979) criticized that such exclusion is often unnecessary in spacing analysis and may lead to understatement of their characteristic and importance.

1.3.1.2. Drumlin Density:

Drumlin density is generally calculated as the number of drumlins per unit area[7] (Benn and Evans, 1998; Smalley and Unwin, 1968; Menzies, 1979). However, Trenhaile (1975) has used a circular template with an area of four square mile (10.36 km^2) and place it at the centre (ridge high) of each drumlin summit and calculated the number within the circle and calculated the density. He found greater density of drumlins at the centre of the drumlin field. Although density study in different literature indicates variability between different fields (Menzies, 1979) few general similarities are very important to provide emphasis. Drumlin density is found highest near the margins of former ice-sheet lobes and decreases in the up-ice direction (Smalley and Unwin, 1968; Menzies, 1979). Vernon (1966 cf. Menzies, 1979) used this character to link to low ice pressure regime at the margins. Contrary to this, Hill (1973), like Trenhaile (1975) have found rise in density in the inner margin to a high density at the centre followed by decline towards the margins in the County Down area, Ireland. However, such variations in the density of drumlins between different fields are attributed by Menzies (1979) to the availability of drift, drift thickness, drift particle size distribution, melt water activity and volume, ice pressure and velocity differential and other subglacial environmental parameters. Few studies have recorded higher drumlin density over local bedrock highs than lows (Zelces et al., 1997) whereas others,

[7] According to Menzies (1979) density of drumlins varies from 19.3 km^2 (England) to as low as 1.8 km^2 (Nova Scotia) and the value may vary largely even in a single field.

contrary to this, have found greater density in lowland areas[8] suggesting either dying or slow moving ice as prerequisite to drumlin formation(Smalley and Unwin, 1968; Benn and Evans, 1998).

Drumlin density measurement also possesses several inherent critiques. As pointed out by Menzies (1979), density measurement only takes a set of points, neither areal or volumetric character nor topographical influence are given due consideration. Widespread variability and contradiction also question the viability of the technique for further use. However, apart from these inadequacies, drumlin density studies provide several useful insight of past ice-sheet conditions and subglacial dynamism.

1.3.1.3. Drumlin Distribution:

Distributional pattern of drumlins within and across different fields is much more variable than the density variability and this variability is partly caused by the use of different techniques and scaling factor. Smalley and Unwin (1968) have applied '*random placement model*' and '*nearest-neighbour analysis*'[9]. They have found uniformly spaced to random distribution of drumlins within a field. According to them a critical stress condition is required to account for such distribution. Very high stress in the up-ice direction and very low in the down-ice direction are rather incapable of account for drumlin formation (Smalley and Unwin, 1968; Menzies, 1979). Trenhaile (1975) have also found random distribution. Benn and Evans (1998) have mentioned although regular pattern is discernible but more likely pattern is random.

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[8] Lowland areas like Great Lake basin, USA and Canada, Ireland, Scotland, and Scandinavia (Smalley and Unwin, 1968).

[9] Smalley and Unwin (1968) have used nearest-neighbour' statistical tests for degree of distributional measurements of drumlins in the natural field. It is expressed as, $R=D_{obs}/0.5\ (A/N)^{-1/2}$ …..1.. where, D_{obs} is the linear distance between any point in a specific area, A is the nearest neighbor using point, N is the number of points within the area.

Jauhiainen, (1975 cf. Menzies, 1979), however, have found cluster to random pattern. So, while random pattern is readily recognizable from different literature, non-random pattern is not uncommon (Benn and Evans, 1998). Hill (1973) have also used '*Trend Surface Model*' and found non-random distribution at three scales opposite to the random distribution. He emphasized the role of scale as an important factor in any statistical analysis of natural features. He also criticized the use of the techniques like, *near-neighbour analysis* (Smalley and Unwin, 1968), *negative binomial, poisson and Decey's more regular than random distribution probability models* (Trenhaile, 1975) for analyzing the pattern of drumlin distribution. According to him drumlins are found clustered at a liner scale of one kilometer and probably the result of variations in stress conditions and debris load at the base of the ice-sheet. Menzies (1979) have also mentioned a degree of non-randomness especially in the oblique and right angle zones to the general ice-flow direction. Contrastingly, Trenhaile's (1975) usage of trend surface analysis[10] and near-neighbour technique yield rather random radiating out fan like distribution pattern of drumlins. According to Menzies (1979) it is better to mention that drumlin distribution is random to non-random in relation to themselves only and since several differing, superimposed patterns, each related to different phases of formation, are all taken together, they may give wrong impression. Hence, the degree of comparison across different studies and drumlin fields is largely inadequate and equally difficult, leaving only the broad conclusion that the general distributional pattern can vary from clustered to random.

[10] 'Trend-Surface' analysis is a technique whereby increasing complex polynomial surfaces are fitted to an actual or theoretical surface (Trenhaile, 1975).

1.3.1.4. Drumlin Size and Shape:

These geometric parameters have long been used in characterizing drumlins (Menzies, 1979; Hill, 1971; Finch and Walsh, 1973; Clark et al., 2009; Spagnolo et al., 2010; Trenhaile, 1979; Benn and Evans, 1998; Hattestrand et al., 2004; Kerr and Eyles, 2007). And there is found considerable diversity in size and shape within a field (Hill, 1971). Length of long axes of drumlins is, generally, the first to be recorded in size analysis. Their lengths and directions are very important in deciphering former general ice flow direction (Menzies, 1979). According to Menzies (1979) lengths of drumlins generally vary from several meters to several kilometers[11]. Very small classical drumlins called mini-drumlins of less than 100m. in length have been studied by Finch and Walsh (1973) in the low lands of County Clare drumlin field. The maximum width of the intermediate axes is also noted together with length and Clarke et al. (2009) have established a relationship between drumlin width and length (r^2= 0.48) and that is , W = 7 L ^{½} when measured in meters (when, L = length and W = width). Hattestrand et al. (2004) reported average drumlin height of 5m. in the central and northern Sweden. These morphometric parameters are widely varied across and within a single drumlin field (Menzies, 1979) and rather site specific; not favourable for comparison.

However, for comparison purpose the first dimensionless non-volumetric approach, which is extensively used, is the simple Elongation ratio (E). That is E = L/W ……….2., where L is length and W is width (Menzies, 1979; Benn and Evans, 1998; Trenhaile, 1975; Knight, 2011; Kerr and Eyles, 2007; Hattestrand et al., 2004). According to Menzies (1979) drumlins E vary from 2:1 to as great as 60:1, average being 2:1 and 3:1. Rose (cf. Benn and Evans, 1998)

[11] According to Menzies (1979) length of drumlins range from less than 1 m. (in Tweed Basin, Scotland) to 1km. or more.

has recorded E upto 7:1 for drumlins[12]. Kerr and Eyles (2007) have identified three major forms of drumlins based on E in Upper New York State, USA. They are spindle forms with E between 6:1 and 18:1, broader forms with E between 3:1 and 6:1 and ovoid forms with E between 1:1 and 3:1. Hattestrand et al. (2004) recorded E in central and northern Sweden ranges between 3.37:1 and 6.24:1 with maximum reaches 10 to 11:1; according to Benn and Evans (1998) with increasing E drumlins grade into mega flutings. Variations in drumlins E depends up on the velocity of ice-moment (Trenhaile, 1975). Correlation with other size parameters does not prove to be fruitful (Menzies, 1979). Although, Menzies (1979) mentioned constant width-to-height ratios, he has found height-to-length ratios are poorly correlated. Trenhaile (1975) also have mentioned no overall relationship between drumlin E and size (area and volume) nor between E and drumlin height and between E and density. But he has recorded nearly constant decline in drumlin E near the margins and attributed that declining ice thickness rather than ice retardation may be responsible for such pattern and smaller drumlins at the marginal zones. He has also mentioned more symmetric or rounded forms of drumlins near the margins and larger elongation in up-ice section.

Other techniques which are often applied and compared with drumlin E are Chorley's (1959 cf. Menzies, 1979; Trenhaile, 1975; and Benn and Evans, 1998) *Lemniscate loop* (r) i.e. $r = a^2 \cos k$ …………3. , where r is the form of loop, a is the length of long axis, k is the dimensionless constant and A is the area. k is determined using following equation i.e. $k = a^2/4A$ ……….4. According to Trenhaile (9175) larger k means more the length than overall area, than width and hence, more E. He has found the average k value of 3. Spagnolo et al. (2010),

[12] According to Rose (cf. Benn and Evans, 1998) drumlins are larger forms (>100m. long axis) with E up to about 7:1; flutings are <100m. with E ranges between 2:1 and 60:1 or more; drumlinoid (mega drumlins) are larger than 1000m. long. However, according to Rose such classification is rather arbitrary and commonly differs from study to study and region to region.

however, criticized Chorley's 'r'. According to them r is nothing but the proxy for the E only[13]. Another alternative to r is *Rose curve* (R) (Reed et al., 1962 cf. Menzies, 1979 and Benn and Evans, 1998). It is, R = a cos k ………..….5. Menzies (1979) has given more weitage to R than Chorley's r because it fits much better to drumlin shape.

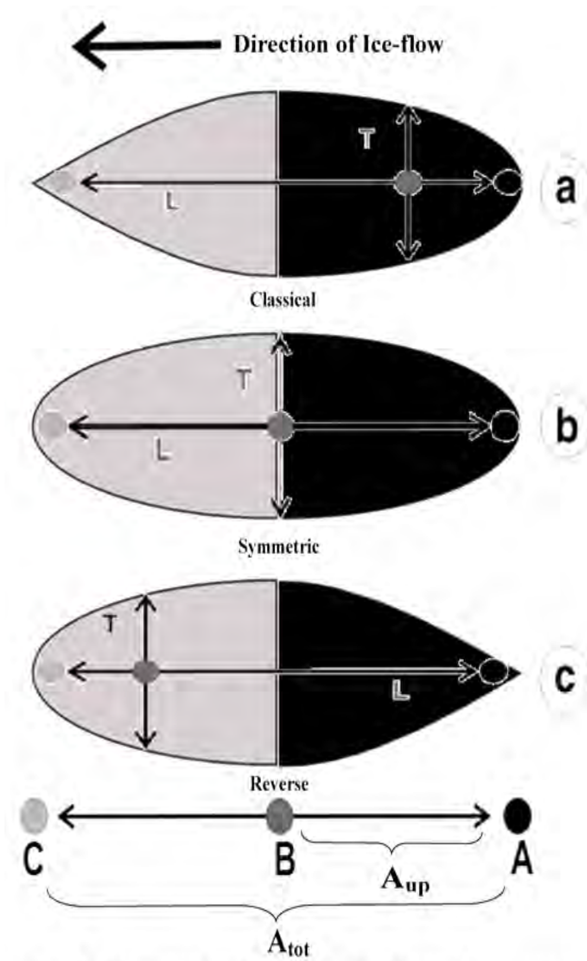


Fig.2 Three predominant drumlin planer shapes are **a.** Classical, **b.** Symmetric, **c.** Reverse, after Spagnolo et al. (2010). The planer shapes are calculated using AS_{pl} and volumes as AS_{pl}-A method. For AS_{pl}, first the longest line (longitudinal axis, L i.e. C-A) is measured, followed by perpendicular longest line (transverse axis, T) and the point B intersection of both the L & T lines are recorded. AS_{pl} is calculated as $\frac{AB}{AC}$. For classical shapes AS_{pl} is 0.2, for symmetric shapes AS_{pl} is 0.5, and for reverse shapes AS_{pl} is 0.8. AS_{pl}-A is also calculated as, $\frac{Aup}{Atot}$. Modified from Spagnolo et al., 2010.

For drumlin's volumetric analysis Trenhaile (1975) has used the following (modified) equation, i.e. e = 2/3 π abc ………..6. Where, e is the volume of a half-ellipsoid, a is the length, b is the width and c is the height.

The above morphometric techniques still possess some of the key inherent short comings (Menzies, 1979). Recently Spagnolo et al. (2010) have used a modified approach to measure the planer shapes of 44,500 drumlins of North America and parts of Europe, to reduce some of the weakness of planer shapes. They have used the following two equations:

AS_{pl} = AB/AC ……….7. where, AB is the

[13] Chorley's Lemniscate loop (r) is nothing but just the proxy for the elongation (E) of a drumlin, according to Spagnolo et al. (2910), because k is the ratio between length and area of a drumlin and since area is generally a function of length times the width so k is the approximation of elongation and thus does not form any special relationship.

stoss side longitudinal length and AC is the longitudinal length of drumlin (Fig.2a.).

$AS_{pl}\text{-}A = A_{up}/\ A_{tot}$ ……….8. where A_{up} is the area of the upstream half of a drumlin and A_{tot} is the total area (Fig. 2a.).

On the basis of equation 7 they have identified three major shapes, viz. a) Classical (<0.33) (Fig. 2a), b) Symmetric (0.33-0.66) (Fig. 2.b), and c) Reversed (>0.66) (Fig. 2.c) and when coupled with equation 8, they have come to the conclusion that drumlin symmetry is more common than asymmetry (classical shape).

However, the above approach helps is identifying various outline shapes of drumlins within a field. These are variously termed, identified and classified by various workers. A few of them are discussed as follows.

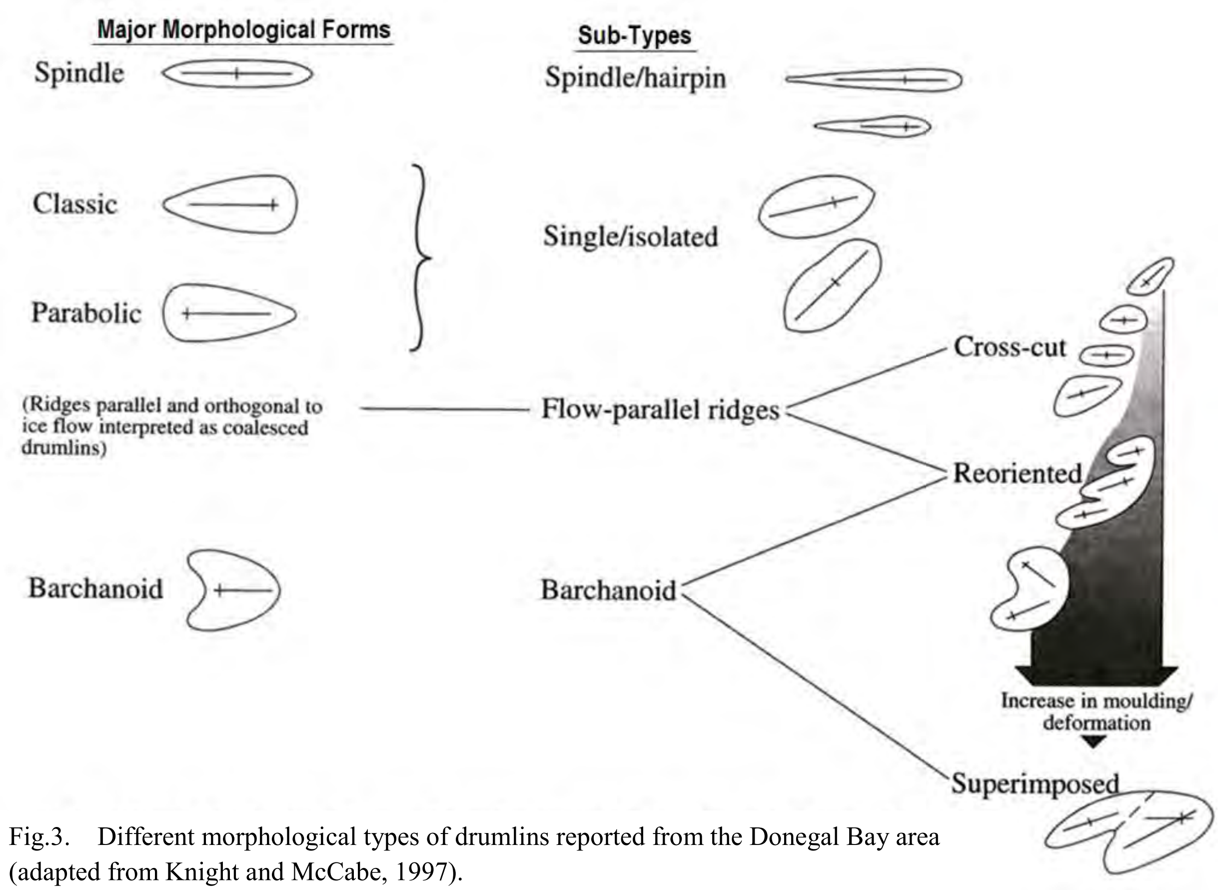


Fig.3. Different morphological types of drumlins reported from the Donegal Bay area (adapted from Knight and McCabe, 1997).

Knight (1997) has identified five morphological typess of drumlins on the basis of outline morphology and topographic settings. They are a) classical, b) shield type, c) barchanoid, d) fused, and e) superimposed. Of these the first three types are of simple types and rests are of composite in character. Clark et al. (2009) have pointed four morphological types in Britain and Ireland. They are a) classical type, b) spindle-like form, c) two-tailed barchaniod form, and d) circular hill (with E = 1:1). Elongate to oval shaped drumlins from Wadena field, USA, have reported by Wright, Jr. (1957). Four major types, viz. a) spindle, b) classical, c) parabolic, and d) barchanoid are reported by Hanvey (1988). Knight and McCabe (1997) further modified Hanvey's morphological types in Donegal embayment area, Ireland with more subclassification Fig. 3. can be taken as the modified form of Hanvey's original classification.

Based on the quantitative (morphometric) measurements, Knight (2011) classified several types of drumlin forms viz. a) classical, b) elliptical, c) lenticular, d) spindle, e) oval, f) half-lemniscate loop and other elongated forms, Finch and Walsh (1973) have recorded rock drumlins, crag and tail drumlins, classical drumlins and kame-like drumlins on the basis of both morphology and internal sedimentology in the County Clare drumlin field. Three fold form classification has been given by Benn and Evans (1998). They are a) spindle form, b) parabolic form, c) transverse asymmetrical drumlins or superimposed drumlins. Spagnolo et al. (2010) have also reported several planar shapes like, lenticular, elliptical to sub-circular, oval, half torpedo, half egg, inverted bowl or spoon, baguette, tear drop, cigar or spindle, foil shaped etc. Shaw (2002) has mentioned three major forms of drumlins, viz. a) parabolic, b) spindle, and c) transverse asymmetrical in and around Livingstone lake field. Zelcs et al. (1997) have identified ellipsoidal, tear-drop shaped, and needle like (drumlinoids) drumlin forms. Menzies (1979) in his reviewed paper on drumlins also discussed about few of the common morphological types of

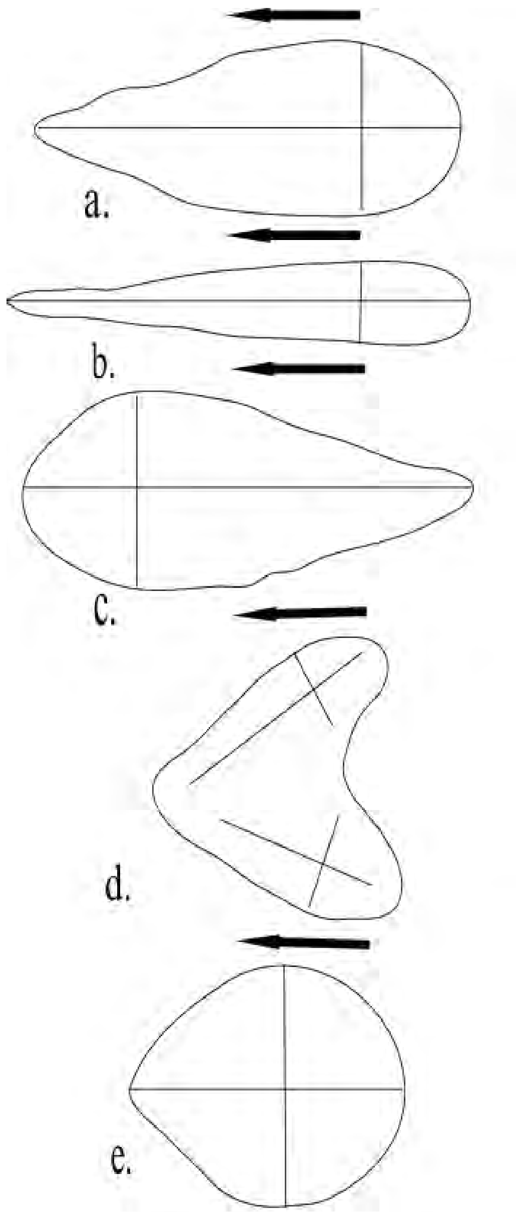


Fig. 4 General morphological types of drumlins commonly encountered in the field. They are **a.** Classical/Tear-Drop shape, **b.** Spindle/Hair pin/ Cigar/Needle shape, **c.** Parabolic/Inverse/Reverse/ Torpedo shape, **d.** Barchanoid/ Superimposed/Transverse-asymmetrical shape, and **e.** Circular/Dome shape. Arrow indicates the general ice-flow direction.

drumlins, which include tear-drops, half-eggs, torpedoes, cigars, air craft wings and even a racing car, domal (ovoid) shapes etc.

A variety of morphological types are outlined above. Among these few common morphological types can be identified and discussed as follows.

a) Classical or Tear-drop Shape:

Most ideal type of form consists of steep stoss-end and gentle lee-end (Fig. 4a).

b) Spindle or Hair-pin or Cigar or Needle like Shape:

These are more elongated forms and often termed as Drumlinoids (Fig. 4b).

c) Parabolic or Inverse or Reverse or Torpedo Shape:

They are reverse in morphology to the classical shape i.e. gentler stoss-end and steeper lee-end (Fig. 4c).

d) Barchanoid or Superimposed or Transverse Asymmetrical Shape:

These are often the products of polyphase glacial advances and complex in form. They generally contain smaller drumlins at their crests (Fig. 4d).

e) Circular or Domal Shape:

These are more of rounded in shape with elongation ratio 1:1 (Fig. 4e).

Some of the forms are also identified in the present study area and are discussed briefly in Chapter 5. *However, the form characteristics of drumlins can be summarized with few points in view, that finding correlation between different morphometric attributes does not yield fruitful relationships. In most of the cases drumlins of different phases are taken together without much cautious. Often results are also subject to individual preferences, definition, and choice of methods. Recently remote sensing techniques help studying larger sample size more precisely within sufficient control, but until and unless morphometric studies are not correlated with, as Menzies (1979) pointed out, the internal composition, bedrock lithology and topography, drift thickness, etc., they will merely contribute to the already populated data bank on drumlin morphometry without improving further understanding of drumlin origin and subglacial dynamism. However, several major points can be identified from the aforesaid discussion. They are a) drumlin classical forms are only one of many possible forms and are not so common as like symmetric forms, b) drumlin density is likely to high in the centre and/or in the marginal part of the drumlin field with marginal drumlins are, generally, smaller in size with low elongation, c) high needle like elongated drumlins are common in up-ice section, possibly due to higher stress and ice-velocity condition, d) drumlin spacing is low near the margins indicating preferences of drumlin formation near the margins of ice-masses, e) distribution of drumlins vary between cluster to random and is site-specific; depends upon the geology, terrain condition and past glaciations.*

1.3.2. Sedimentological Characteristics of Drumlins:

Internal composition and structures of drumlins are more variable than their form characteristics (Menzies et al., 1997; Knight, 1999; Kerr and Eyles, 2007), making the way for a unifying theory of drumlin formation a difficult proposition (Stokes et al., 2011). Their '*composition*', for example, incorporates range of lithologies, clast and grain shapes, sizes, fabric, roundness, grain surface textures etc. and '*structures*', for example, includes stratified sediments to homogeneous till, evidences of deformation, deposition and erosion, shearing and shear strain responses etc. (Menzies et al., 1997) (see Chapter 3). Broadly, therefore, the sedimentary characteristics of drumlins can be discussed under two major headings, viz. 1) Compositional Characteristics, and 2) Structural Characteristics.

1.3.2.1. Compositional Characteristics:

A large number of literature suggests that drumlins are mainly consists of locally derived bedrock materials which might involve minimum sediment transport history (Hattestrand et al., 2004; Menzies, 1997; Menzies at al., 1997; Hill, 1971; Stokes et al., 2011). However, for larger drumlins, according to Stokes et al. (2011), the influence of locally derived materials may diminish upward. Drumlins are often reported from easily erodible fine grained lithology. Menzies (1979) has also reported predominance of shale substrate in northwest New York drumlin field, US, although, Hill (1971) has found no such obvious link between substrate lithology and drumlin formation. Patterson and Hooke (1996 cf. Benn and Evans, 1998), however, have reported that drumlins are found on substrate with composition of 34% of unconsolidated sediments, 18% of till, and 16% of stratified sediments, remaining 66% are rock substrate in which shale and slate (1/3), crystalline rock (1/3), carbonates (1/4) and sandstone, conglomerate, and basalts dominate. So, although the relationship between substrate lithological influences on drumlin formation is unclear, agreement exists on the processes of derivation of local subglacial materials (Knight, 2010). Major processes includes, as outlined by Evans et al. (2006), melt out from ice-base, quarrying and abrasion of hard rock surfaces and the excavation/liberation of rafts or soft clasts from weak or unlithified substrate through the processes of comminution (including quarrying, crushing, and pulverizing) and ploughing. Particle chemical and textural analysis has also been reported by Rattas and Kalm (2001) in the east-central Estonia.

Grain size, sorting, and matrix composition are other most important influencing factors. According to Evans et al., (2006) amount of clasts, their density, sand-silt-clay ratio etc. all play key role in determining the characteristics of till-matrix and consequent pore water pressure and resultant character of deformation. According to him sandy matrix dilates more rapidly than clay rich till and is, thus, commonly reported in most cases. According to Benn and Evans (1998), porosity increases with increasing grain size and sorting. Rattas and Kalm (2001) have reported unsorted bimodal distribution of fine sandy to fine silty till-matrix from the Estonian drumlin field. Polymodal sand matrix is also reported elsewhere (Cook et al., 2011; Knight, and McCabe, 1997). Coglan and Mickelson (1997) have also recorded predominant sandy till from the Green Bay lobe drumlin field. The till consists of approximately 65% of sand, 25% of silt, and 10% of clay with interbedded sand and gravel. Schomacker at al. (2006) have, similarly, reported sandy matrix supported diamicton from the northeastern margin of the Vatnajokull ice cap, East Iceland. Calcareous sandy till has been observed by Wright, Jr. (1957), in Wadena drumlin field, USA. Menzies (1979) is also of the view that till drumlins mostly contains sandy materials with low clay content. However, Zelcs et al. (1997) have found coarse grained to fine grained pastic sediments within drumlins. They have reported deformed gravelly, sandy and finer materials of glacigenic origin and locally derived materials from the Baltic countries. Hence, sand dominated matrix is found to be the common characteristics of drumlin's internal composition, although some deviation is expected.

Clasts shape and roundness equally play a major role. More angular faceted and fractured clasts are reported by Cook et al. (2011). According to Stokes et al. (2011) clast shapes within drumlin bed are highly variable as well. While, according to them, subangular and faceted clasts are predominant, angular and rounded clasts are also reported from elsewhere. Meehan et al. (1997) have also reported predominance of striated subangular to subrounded clasts from the Kings Court drumlin field, Ireland.

Drumlin composition also depends on the type of core or nucleus around which drift materials deposit and ultimately lead to drumlin formation. Menzies (1979) in his review mentioned the core of rock, sand, boulders and/or laminated clays. Internal composition of these cores vary widely from stratified sand to unstratified till to entirely solid bedrock with every possible overlapping and permutation in between (Menzies, 1979; Finch and Waksh, 1973; Rattas and Kalm, 2001).

Bedrock cored drumlins and thin carapace (veener) covering the drumlins have long been reported by number of researchers from different drumlin fields (Zelcs et al., 1997; Menzies, 1979; Hart, 1997; Kerr and Eyles, 2007; Meehan et al., 1997; Knight, 1997). And their formation is described analogous to '*Crag and Tail*' formation; often the term '*Crag*' drumlins are also applied in different literature (Menzies, 1979; Stokes et al., 2011; Shaw, 1980; Hattestrand et al., 2004) (Fig 5). According to Vernon (1966 cf. Menzies, 1979) bedrock knobs act as resistant (obstacle) at the ice-bed interface leading to high pressure of ice and retardation of flow in the stoss end of the bedrock knob. Increasing ice pressure leads to increase in melting and porewater pressure at the proximal end (stoss). This causes deposition of drift in the low pressure dominated lee side or distal part of the obstacle and relatively increase in flow. Saturated slurry-like materials deposit in the distal part and with gradual deposition and erosion, the final form of drumlins takes place, because as the critical thickness[14] is already achieved the pressure melting is likely to cease and erosion starts. This simple mechanism is criticized by Smalley and Unwin (1968) and proposed their '*dilatancy theory*' (see section 1.5. for more detail). However, it is to be clear that a marked change can possibly be observed in geotechnical characteristics of subglacial sediments due to resistance imposed by bedrock knob, and further complex homogeneous till (Smalley and Umwin, 1968; Menzies, 1979) to any kind of deformation tills are likely to be observed within such drumlins. Entirely bedrock dominated drumlins, which appear to be similar to other types of till drumlins of intermediate scale (1-10 km.), are also reported from many areas (Stokes et al., 2011; Knight, 2006). Kerr and Eyles (2007) have confirmed the rocky drumlins with thin mud carapace submerge in the lake Ontario, USA, from modern bathymetric study.

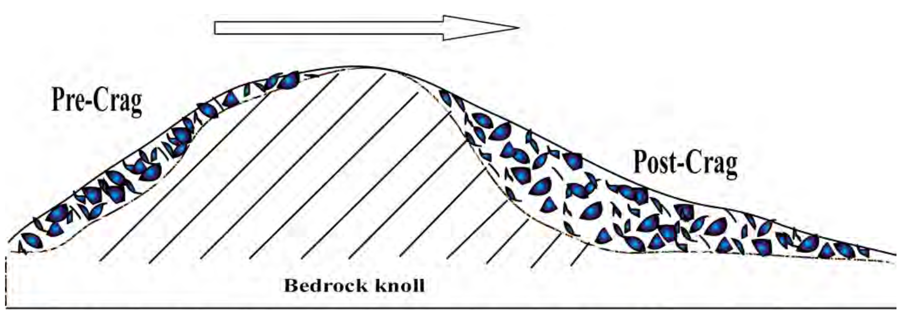


Fig.5 'Crag Drumlin' with bedrock knoll as obstacle, and formation similar to Crag and Tail. Although Lee side cavity filling takes place, but Tail is not developed, rather the term 'Pre-crag' and 'Post-crag' is used in literature for Stoss and Lee sides deposits respectively. Arrow indicates ice-flow direction.

[14] According to Menzies (1979), since at a critical thickness, possibly, both ice velocity and pressure both ice velocity and pressure change in direct relation to each other, the effect of changes might cancel themselves out resulting in bedrock slope being a passive factor exerting no further influence.

However, till dominated drumlins have also been reported to be composed of verity of deposits barring from glacio-marine to mass deposits, shallow-water boulder pavement (ice-shelf environment) to glacioterrestrial deposits (subglacial. glaciolacustrine, ice-contact deltaic etc.), and in some cases the deposits may experience later stage of drumlinization and final form creation, often consists of thin carapace of sand and/or diamict at the surface (Knight and McCabe, 1997; Kerr and Eyles, 2007). Menzies (1979) reported such till dominated drumlins from New York State, US, consisting of sand and gravel beds interfingered with till, sand, and silt lenses, lines of boulders, pseudo faulting and folding, and bedded till. He also reported lenses of lenticular outline and separated by thin partings of sand and silt, similar to fluvial crossbedding structures. Lenses of sand have also beem reported by number of workers from different drumlin beds (Hart, 1995; Benn and Evans, 1998). These are likely to be the product of pre-drumlin forming glacial and glaciofluvial processes which later have shaped by overriding ice-mass (drumlinization). According to Menzies (1979) basal ice layer must be rich in debris (≥50%) in order to account for such depositional origin of drumlins. Knight (1997) defined diamict dominated drumlins as those in which subglacial diamict and other sediments constitute >80% of the observed sediment sequence. However, Menzies (1979) also pointed out the effect of reincorporation of older glacigenic and non-glacigenic materials and/or older drumlin forming subglacial materials during the later phase of drumlin formation and/or drumlinization as a major source of deposited materials. Zelcs et al. (1997) have corroborated the above finding with their works. They have found drumlins in Baltic Countries are mainly composed of reincorporated deformed gravelly, sandy or finer materials of glacioaquatic origin and locally derived till. Hart (1997) reported commonness of inhomogeneous tills from drumlin beds and assumed that they may act as competent core, a necessary condition for the formation of till dominated drumlins. Menzies et al. (2007) at the Port Byron drumlin field, New York State, have identified steeply dipping deltaic structures within drumlin bed. It consists of cemented sands and gravels of proglacial origin with thin till carapace, indicating drumlinization during recent ice sheet advance (Laurentide ice sheet advance) on preexisting deposits and thin veneer formation at the surface during the late retreating phase. They have also reported sand stringers, different sizes of clasts ranging from pebble to boulder size, horizontal planner bedding as well as steeply dipping bedding, fine to medium sand with gradual contact with the subjacent unit (upward and normal gradation) or sharp erosional contacts etc. Even Meehan et al. (1997) have reported seven types of facies within a single till dominated drumlin from Kings Court swarm, Ireland. Evidences of preweathered surfaces within diamict-dominated drumlins have also been reported by Newman et al. (1989) from the Boston Harbour field, US. Similarly, Knight (1999) also mentioned variety of sediment composition from the Irish drumlin field barring from rain-out (meltout) diamict to massive gravelly deposits and laminated mud facies. All these evidences point the wide variety of composition within till or diamict-dominated drumlins. Stokes et al. (2011), however, has tried to simplify this widely variable drumlin composition into five basic categories. These are i) mainly bedrock type, ii) part bedrock/part till type, iii) mainly till type, iv) part till/part sorted sediment types, and v) mainly sorted sediment type. More detail studies in future are required to critically evaluate the significance of thin framework and only then the quest for achieving a unifying theory can be successfully fulfilled.

Clast longitudinal (or long) axes or a-axes macro and micro fabric is another major component of drumlin sedimentological composition. Clast fabric essentially reveals direction of ice movement, that is direction of principle stresses imparted by the ice to the till, and mode of deposition etc. (Menzies, 1979). However, different researchers have recorded different orientations and degree (weak or strong) of fabric. Clast fabric generally found parallel to drumlin's long axes (Stokes et al., 2011; Menzies, 1979; Stanford and Mickelson, 1985; Meehan at al., 1997; Wright, Jr., 1957; Knight and McCabe, 1997), and transverse to long axes (Menzies, 1979; Stanford and Mickelson, 1985; Meehan at al., 1997; Wright, Jr., 1957; Hill, 1971; Boulton, 1976) and in some cases oblique to long axes (Zelcs et al., 1997; Stanford and Mickelson, 1985; Wright, Jr., 1957). While parallel fabric pattern indicates the principle ice flow direction (direction of principal stress) within drumlin, oblique fabric orientation may be the result of deformation (Zelcs et al., 1997; Menzies et al., 2007). Parallel fabric may also be due to the extending flow regime whereas compressive flow regime is assumed to have produced transverse (perpendicular) fabric (Piotrowski and Vahldiek, 1991). Parallel fabric, according to Carr and Rose (2003), is attributed to '*Jeffery rotation*' and transverse fabric to '*Taylor rotation*'. Benn and Evans (1996) interpreted the evolution of transverse mode of fabric under high cumulative strains in deformation tills and according to their interpretation elongate particles expand least energy in transverse position and roll like logs. Wright,Jr. (1957) attributed longitudinal orientations as a product of clast sliding (dragging) under subglacial conditions and transverse orientation as a product of clast rotation. Subglacial dragging and parallel longitudinal orientation of clasts has also been corroborated by Hill (1971). However, strength of clast fabric actually depends on variety of factors, such as drift thickness, height of drumlin and probable deflection of ice, stress level, pore water pressure and dilation, deformational processes etc. Hart (1995), Stokes et al. (2011), Hill (1971), Benn and Evans (1998) have attributed that the deformation processes are responsible for weak fabric strength. He also found strong fabric near the surface. Schomaker et al. (2006) has also interpretated strong fabric of surface till. According to Stokes et al. (2011), the higher shear stress at the surface is possibly responsible for strong fabric. Hill (1971) and Stokes et al. (2011) also reported gradually diverging till fabric upward from base may be due to higher ice deflation upward with increasing drumlin height and/or thick deforming layer. They have also interpreted diverging fabric at the stoss end and converging fabric at the lee end (herring bone pattern) of crag type of drumlins. Menzies et al. (2007), Zelcs et al. (1997), however, have reported expected strong fabric in a thin deforming layer. Higher shearing also may destroy the primary depositional fabric and leading to weaker (dispersed) fabric instead (Doweswell and Sharp, 1986). Clast micro fabric study has also demonstrated similar pattern as clast macro fabrics (Piotrowski and Vahldiek, 1991; Menzies et al., 1997). However, plunging of clasts varies according to the dominant processes; although Hill (1971), Stokes et al. (2011) advocated the up glacier plunge as more preferable. Hence, although clast fabric pattern is one of the key indicators of principle ice-flow directions and also indicates key (unknown) processes of clast deposition, Menzies (1979) warned against putting too much emphasis on fabric results only. More elaborative discussion on clast fabric pattern is discussed in section 6.2.2.4 in Chapter-6.

1.3.2.2. Structural Characteristics:

Identical to widely variable drumlin composition, internal structures also reveals large variations. The reason being different geology, terrain condition, ice mass characteristics, temperature condition, porewater pressure and dilation, rheological properties of subglacial materials, weathering history, and depositional-deformational-erosional history along with typical site specific drumlinization processes (Hill, 1997). However, in the present section such structural characteristics are discussed through different, widely recognized, subglacial diamicton (till) types as discussed in most of the literature.

Subglacial diamicts (till) are variously classified into several known groups which include deformation till, galcitectonite, lodgement and comminution till, meltout and sublimation till (Evans et al, 2006; Benn and Evans, 1996, 1998). These are briefly discussed in chapter 3.

Deformation tills are extensively homogenized, usually diamictic materials, formed by glacially induced shear of subsole materials (Evans et al, 2006; Benn and Evans, 1996). Such till generally produces two commonly recognized structures within drumlins. Menzies et al (1997) categorized them as a) *ductile deformation structures*: which incorporates mainly recognizable structures of folding, boudins, shadows, rotations and squeeze, galaxy structures around large clast and diffusion forms among others; and b) *brittle deformation structures*: which includes faults, shear lines, planes and zones, slickenside structures etc. both of these deformational structures are often found very close to each other, shows over printing and polyphase events (Menzies et al. 1997). Deformational till, therefore, appears either as massive or shows visible deformed structures (Menzies et al., 1997) and generally produced hybrid final till-matrix (Dowdeswell and Sharp, 1986), not necessarily related to primary structures and composition (Stokes et al., 2011).

Deformation, however, thought to take place under temperate (warm base) glacier (Hicock, 1990; Hart, 1995; Menzies et al., 1997; Menzies, 1979; Benn and Evans, 1998). Further, while one school of workers talked about the role of constructional deformation[15] as the major cause for drumlin formation (Boulton, 1976; Benn and Evans, 1998), another school support net erosion and excavational deformation[16] as the major process mechanism for drumlin streamlined formation (Hart, 1997). The evidences and logical conclusions regarding type of deformation, although, are rather site specific and depends upon the interpretation of individual researchers. The present research will try to corroborate which mechanism has taken place in the Himalayas and critically evaluate in chapter-6. However, several commonly reported structures from both the schools can be reported as follows.

[15] Deformation which involves deposition i.e. net accretion is known constructional deformation (Benn and Evans, 1998)

[16] Excavational deformation are those where later deforming bed of sediment or diamict cut the previously deposited material to form drumlin (Hart, 1997).

Various folded structures at macro and micro level are reported in literature (Zelcs et al., 1997). These include recumbent fold (Hart, 1995, 1997; Menzies, 1979), isoclinal fold, overturned fold (Benn and Evans, 1998), recumbent isoclinals fold, upright isoclinals to open fold (Stanford and Mickelson, 1985), sheath fold (Hart, 1995, 1997; Boulton, 1976), drag fold (Menzies et al., 2007; Shaw, 1980) etc. Boudinage structures are reported by Hart (1995) from ductile deforming belt. Evans et al. (2006), Menzies et al. (1997), Hart (1995, 2007) have recorded, on the other hand, galaxy type clast rotational structures generally at micro level from such deforming tills. Hart (1995) also attributed strain evidences as the diagnostic to ductile deformation. Menzies et al. (1997) have corroborated this fact with the evidence of strain partitioning within drumlin belt; possibly the result of discrete motion of ductile units. Hart (1995), even have given a simple equation to calculate the longitudinal strain from the visible structure within drumlin bed. This is, e = (deformed length - original length/ original length) x 100……9, where e is the longitudinal strain. Similarly, brittle deformation structures are also extensively reported in literatures. These structures include thrusting (Hart, 1995; Meehan et al., 1997), well developed fissilty (Stokes et al., 2011; Meehan et al., 1997), shear planes (Stokes et al, 2011; Zelcs et al., 1997), fissure and jointing (Menzies, 1979) etc. largely due to higher shear stress and/or porewater dissipation or frozen bed condition in the basal ice, or localized limited clay/silt contents leading to easy desiccation or very high clast content (Menzies, 1979; Menzies et al., 1997, Coglan and Mickelson, 1997). Boulder pavement or lodgement till which also indicate increase in the effective normal pressure (see section 6.2) at the ice-bed interface and a kind of diagnostic to deformation have also reported from many literature (Menzies, 1979; Benn and Evans, 1996; Hart, 1997; Newman et al., 1989; Meehan et al., 1997; Knight, 1997; Knight and McCabe, 1997). Shaw (2002) attributed lag boulder as the evidence of his meltwater cavity filling hypothesis (see section 1.5.) of drumlin formation and other subglacial landforms. Meltout till evidences are also limited if not uncommon from drumlin beds (Meehan et al., 1997). However, glacitectonic origin of drumlins is also noted uncommon. Therefore, deformational origin of drumlins is reported to be a common phenomena and a integral part of geological record (Zelcs et al., 1997). Menzies at al. (2007) have also expressed similar view point and attributed deformation as the likely process of drumlin formation. Hence, '*structure-to-process*' evidences can prove to be a great tool for the genesis of drumlins in any region. Apart from these hybrid deformational-depositional-erosional structures of drumlin beds, simple deposional and erosional structures are also common and reported in the literature. Like, '*Onion-skin*' type (Fig. 6a) (Menzies at al., 1997) and '*Layer-cake*' Stratigraphy type (Fig. 6b) internal undeformed drumlin structures are also reported elsewhere (Stokes et al., 2011). The former is purely accretionary (layer by layer) in genesis whereas the later is purely a erosional product.

However, in summery few general points regarding compositional and structural characteristics of drumlins can be pointed out. Drumlins generally contain largely locally derived bedrock materials. Their proportion can vary but generally diagnostic to their subglacial origin. There is no relation between drumlin formation and substrate lithology but their presence is commonly encountered in soft bed lithologies. Grain size also vary and generally depends on substrate lithology, distance of transport, ice-mass characteristics, and on abrasion-attrition-comminution mechanism. However, general preference of sandy till-matrix is mostly found in literature. Clast shapes also vary between more angular to subrounded. Both rock cored and entirely till dominated drumlins are extensively variable in composition, except entirely bedrock drumlins. Although, homogeneous massive composition is common, widely varying predeposited stratigraphy which later might experience drumlinization, is also very common and results in complex composition within drumlin bed; a major impediment to a *unifying theory of drumlin formation. Clast macro and micro fabric composition generally shows preference to parallel (Jeffrey rotation) and transverse (Taylor rotation) longitudinal axes orientation, although oblique fabric pattern is also not uncommon. Strength of fabric also depends upon the subglacial processes. Lodgement processes tend to have strong fabric pattern whereas moderate to weak fabric pattern is generally diagnostic to deformational processes. Since deformation is likely to be most dominant processes under subglacial conditions[17], both ductile and brittle deformation structures are extensively reported. Other structures like, lodgement, meltout, glacitectonics and purely accretionary (onion-skin type), and erosional structures (layer-cake) are also mentioned elsewhere.*

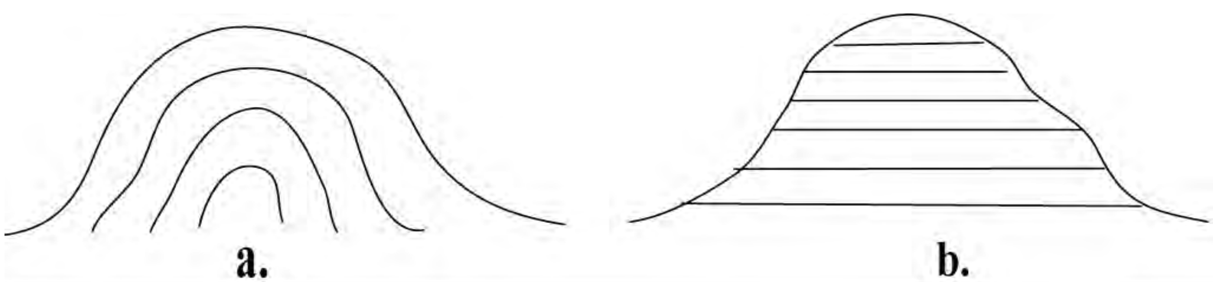


Fig.6 a. Onionskin Drumlin—entirely accretionary origin of drumlin

b. Layer-cake Drumlin—erosional origin of drumlin.

1.4. Association of Drumlins with Other Subglacial Landforms:

With the present understanding of subglacial processes, drumlin is no longer regarded as single rather as an intermediate landform in a broader spectrum of subglacial landforms, especially in the former ice-sheet covered areas. This acceptance of bedform continuum helps in extending the horizon of knowledge of subglacial processes in large and drumlins in particular. With little ambiguity among researchers, it is now generally believed that there exists '*a*

[17] Deformation in underlying till is responsible for 80-90% of the all forward movement of the glaciers (Benn and Evans, 1996).

continuum of bedforms' between roches moutonee[18], rock-cored drumlins, till-drumlins, till-fluted moraines[19] and transverse moraines[20] (Menzies, 1979; Hart, 1997; Brodzicowiski and Van loon, 1991; Knight, 2006, 2010; Coglan and Mickelson, 1997). Clark et al. (2009) also support this hypothesis and also added mega-scale glacial lineations in the intermediate position. Although, this hypothesis vary across different fields, in response to the relative position of these landforms, but largely drumlins may be regarded as an intermediate stage in a spectrum of subglacial landforms barring from flutings to rogen moraines (Menzies and Rose, 1987). Benn and Evans (1998) too put rogen moraines and flutes as the end-member of the bedform continuum. An evolutionary time series, therefore, can be constructed using this hypothetical pattern which also has received support from field verifications. Apart from roches moutonee and whale-backs, drumlins

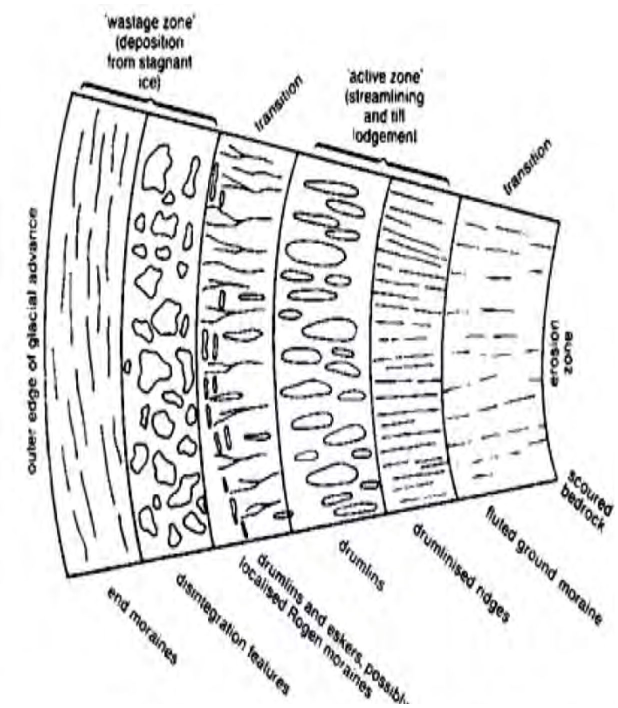


Fig.7 The 'Bedform Continuum' hypothesis explains the systematic distribution and very close association of drumlins and other streamlined forms (such as, flutes, rogen moraines, eskers, and moraines etc.), which are expected to develop beneath Mid-latitude Pleistocene ice-sheet or ice-cap periphery, at the time or just after the maximum glaciation, in relation to ice-thickness and rate of ice movement (stress gradient), and sediment supply and their rheological characteristics. Adapted from Brodzikowiski and Van Loon (1991).

[18] Polished, elongated, streamlined rocky outcrop in glaciated terrain with gentle stoss-end and very steep lee-end, generally formed due to subglacial abrasion and plucking, is called roches moutonee (Raina and Srivastava, 2008).

[19] Flutes are *".....long parallel-side ridge width indicates accurately the direction of ice-movement, and which occurs when deformable subglacial materials are intruded into tunnels which open-up on the lee-sides of single, rigid obstructions on the glacier bed*" (Boulton, 1976, p-309). Flutes are believed to be formed by *rhythimic formative* processes and according to Boulton (1976) flute and drumlins may have same formative mechanism. This is one of the major points based on which later Boulton propounded his '*pervasive deformation'* origin theory of drumlins and other subglacial forms (Benn and Evans, 1998).

[20] The moraines which are transverse to the corresponding ice-flow direction and are showing gradual transition to drumlin are variously termed as rogen moraines (Knight, 1999, 2006; Zelcs et al., 1997; Benn and Evans, 1998) or ribbed moraines (Shaw, 2002). According to Knight (1999) rogen moraines may be prior to drumlinization phases and thus support both Boulton's deformational origin of drumlins and Shaw's melt water hypothesis in entirely different ways.

are also thought to have closely associated with lee-side cavity fill, tunnel channels, and eskers (Knight, 2010; Shaw, 2001; Benn and Evans, 1998). However, since these bedforms are positioned in relation to ice-divides and ice-streams at various times during active glaciation, Benn and Evans (1998) has put greater emphasis on this hypothesis because they are not just related to substrate morphology, local stress variations and sediment supply but also to ice-flow and sediment deformation histories (Fig. 7). Greater weitage, however, is also placed on the genetic relationship between drumlins and end moraines. Already, former ice-flow direction and ice-marginal positions are tried to infer from these data (knight, 1995, 1997; Piotrowski and Vahldiek, 1991). Although this approach has some inherent discrepancies but the influence that drumlin has on modifying ice-sheet characteristics are widely recognized. Recently, Knight (1999) himself criticized this assumption and mentioned about the greater need of more rigorous field verification to prove or disprove this relationship. Clark et al. (2009) have also criticized the continuum hypothesis in the following ground that the scale for drumlin and mega scale lineation etc. is largely distinct from that of flutes. Hence, putting all of them in a single frame may be tricky. However, to prove or disprove the continuum hypothesis is not the purpose of this dissertation. Hence, their relationship is not discussed further. A far better understanding may be obtained when they will be discussed in the next section in the light of changing paradigm and thinking of subglacial processes and mechanism of drumlin formation.

1.5. Changing Paradigm and Thinking: Theoretical development in Drumlin Study:

Drumlin study, unlike many of the subfields in glaciology, has experienced dramatic changes (paradigm shift) over a time period of 150 years since its first appearance. H.M.Close in 1867, in Ireland was the first man to recognize and named the landform (Knight, 2010). Since then it has greatly fascinated geomorphologists and glaciologists, alike, more than any other glacial landforms (Smalley, 1981). According to Knight (2010) drumlins were not amongst the first glacigenic landforms to be recognized and studied. In fact, the pioneering works of Venetz de Carpentier and Agassiz in European Alps were more concentrating on the identification of erratic, striae and moraines (Powel, 1998). However, late but not least drumlin study found its grip since a key paper of H.M.Close in geomorphology in 1867, where '*drumlin*'—the name is given to a '*detrital ridge*' composed of glacial till (Knight, 2010). Subsequently the initial works of Martin (1901), and Fairchild (1907) came into light and since then it becomes a matter of intense interest, scrutiny and discussion to the glaciologists, first in Ireland and Britain and then gradually elsewhere (Menzies at al., 2007). Spatial geomorphological mapping and their systematic observation started very early since the start of 20th century but greater advancement started since 1950's (Knight, 2010; Menzies and Rose, 1987).

According to Hill (1971) two prominent schools of theories dominated during early half of the 20th century. These were, a) formation by erosional processes of preexisting glacial deposits or rock outcrops, and b) formation by depositional processes i.e. drift deposition from ice. The first school used the evidences of bedrock drumlins while concentric shells like banding structures were used by second school of thought. Initiating processes, however, attributed possibly to the presence of preexisting obstacles (such as rock outcrops, hummocks of older till, stratified deposits and large boulders) to the flow at the base of the ice-mass. However, before 60's the study of the drumlins were majority based on outline geometry and their initiating mechanism was largely ignored in the ground of assumed preexisting obstacles. A major path breaking research in this field came from Smalley (1966) and Smalley and Unwin (1968) with their geotechnical approach—the '*Dilatancy Theory* '. In the words of Menzies and Rose (1987) it was a '*dramatic turn*'; they cautious against use of the term 'paradigm shift' in this case but undoubtedly it were not less than that.

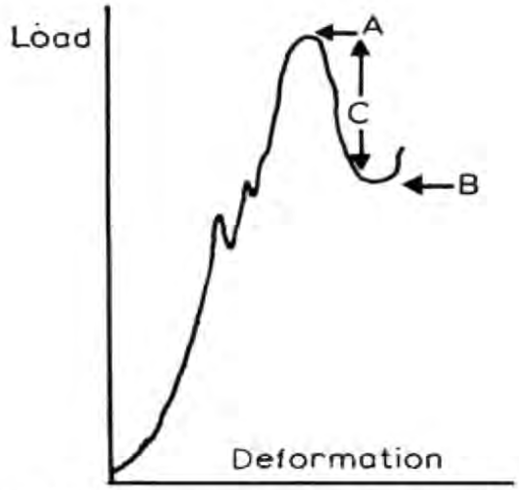


Fig.8 The 'Load-Deformation Curve' indicates the critical stress level i.e. C. According to the 'Dilatancy Theory' a thin layer of boulder clay, otherwise static and packed in nature, and undergo expansion (dilatancy) when subject to high pressure by the overlying ice-mass (A). When the critical stress level (C) is reached and maintained, deformation occurs and with higher stress (B), the collapse of the materials may take place. Adapted from Smalley (1966).

For the first time the logical inclusion of soil engineering properties and techniques (geotechnical approach) in the field of geology was done, which not only provided some sort of scientific solution to the initiating mechanism of drumlin formation but also opened a very newer window to view subglacial dynamics in the light of rheological response of till to possible stress provided by over lying ice-mass. However, according to the 'dilatancy theory' there exists a thin mobile layer of boulder clay materials (lubricant because of thixotropic[21] properties of clay and higher density of angular granular till) at the ice-bed interface which may undergo dilation when subject to a critical pressure, '**c**' [22](Fig.8) due to ice-stress (Smalley, 1966). During this critical stress level, the otherwise static and tightly packed dilatants materials may undergo expansion i.e. increase in volume of materials due to rearrangement and adjustment of particles from edge-to-edge contact to point-to-point contact under applied pressure, and subsequent deformation (Menzies, 1979). When the critical stress level (c) drops below a certain level (b), the dilating materials collapse into static

[21]It is actually a property of clay which denotes with increase in stress, viscosity reduces (Smalley, 1966).

[22] The laboratory experimental provides the graph for dilatant materials, here only the experimental graph of glacial till is shown (see Smalley and Unwin, 1968 for more detail).

form (Smalley and Unwin, 1968). According to Smalley (1966) in natural environment when flow in a separating layer possibly is interrupted either due to decrease in critical stress level (c) or the till reaches its critical boulder-content density, dilation stops and transform into stable obstruct. Rest of the materials then, rigorously but infrequently, flow around this obstruction and gradually giving a streamlined form. Shaping of drumlin form, however, depends largely on the rheological complexity of the dilating material. Thus, the theory logically explained the initiating mechanism of drumlin formation. Further, according to Smalley and Unwin (1968), in the upglacier zone the basal ice stress is more and deformational erosion (constructional deformation) prevails and localized packing is rather absent (giving fewer but more of elongated drumlin forms) (Fig. 9a). On the contrary in the peripheral zone, towards ice-sheet margins, the stress levels drop the critical level and may be too low to allow the formation drumlins (more favourable for end moraine formation). Here drumlins are low in volume but higher in density (Fig. 9b). But in the central zone the critical level i.e. the optimum level exists and allows localized packing and drumlin formation. Here drumlins are found to be larger in volume and lower in density (Fig.9c).

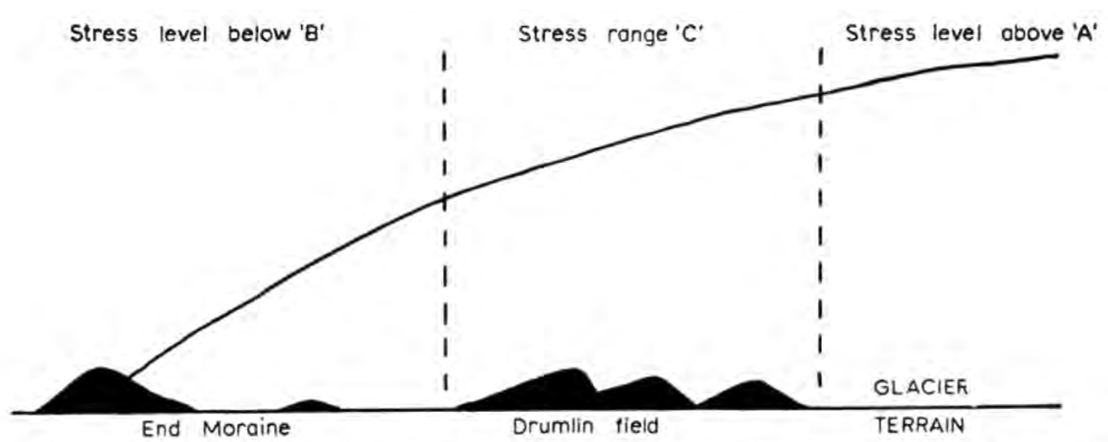


Fig.9 Hypothetical cross-section at the edge of the ice-sheet with critical stress regions indicated. Adapted from Smalley (1966). The figure indicates that very high stress regime (A) exists in up-glacier, hence no drumlin formation, whereas at the end stress levels fall (B), hence end moraine formation takes place, leaving the middle part to have optimum stress level (C) and drumlin formation.

The two decades between 1950 and 1970, experienced a new interest in drumlin shape, distribution, and related formative mechanism analysis due to the introduction of quantitative techniques, numerical modeling and remotely sensed data. More interest in drumlin sedimentology, on the other hand, came since 1980 onwards (Knight, 2010). The immediate response of this revived interest in drumlin sedimentology was due to the postulation of Boulton's path breaking '*Pervasive Deformational Model*' of drumlin formation. Already Boulton in 1976 have postulated complex deformation as the major process under subglacial conditions when studying the flutes in Spitsbergen of Iceland, Norway, and the Alps. However, the model explains that within a subglacial deforming layer there are zones having relatively stronger and stiffer till materials than the average. When the average will deform (or remain static) slowly due dilation, in contrast, the intervening stiffer areas will remain static and undergo higher strain rate (Fig. 10a). According to Boulton (1986 cf. Benn and Evans, 1998) the gravelly deposits (coarser materials) are often permeable and acted as stiffer core than the relatively finer impermeable materials surrounding them (Fig. 10b). Hence, the impermeable materials are ripe for pervasive deformation, forming far travelled sheaths of highly attenuated galcitectonite or deformation till around the stiffer core and eventually responsible for drumlin formation (Fig. 10c). Such kind of pervasive deformation, however, has been noted in North Saskatchewan drumlin field from where the brilliant idea came. Boulton (1987) also mentioned the derooted cores as the characteristics of highly deformed stratigraphy whereas the stratified cores are attributed to have undergone none or very little deformation. According to him, they are likely to act as the hypothesized stiffer core than the surroundings.

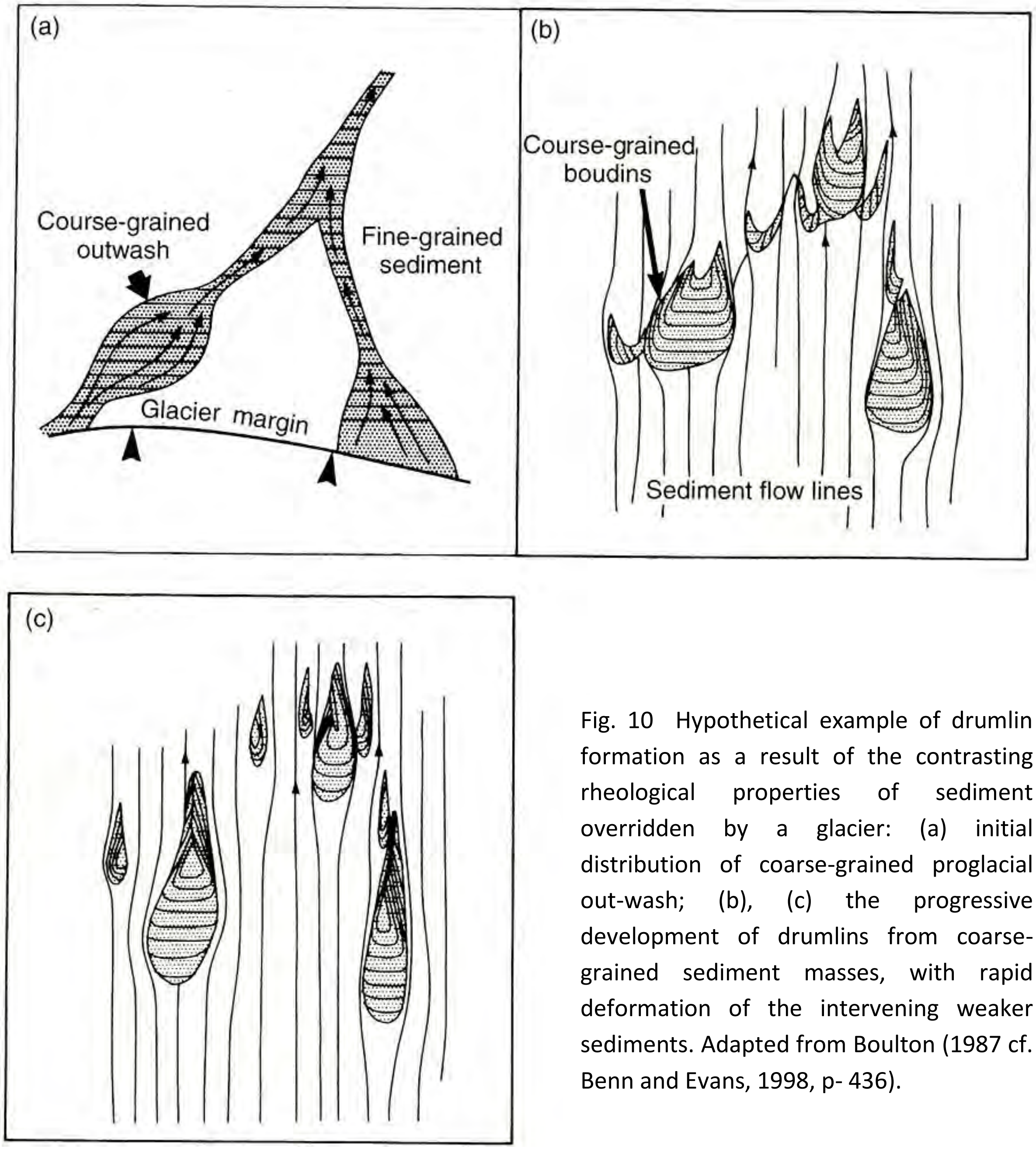


Fig. 10 Hypothetical example of drumlin formation as a result of the contrasting rheological properties of sediment overridden by a glacier: (a) initial distribution of coarse-grained proglacial out-wash; (b), (c) the progressive development of drumlins from coarse-grained sediment masses, with rapid deformation of the intervening weaker sediments. Adapted from Boulton (1987 cf. Benn and Evans, 1998, p- 436).

Although, Hart (1997) support that the depositional form of drumlin is similar to flute formation, but criticized that pervasive deformation does not able to explain all the widely variable depositional forms of drumlins; already excluding entirely bedrock drumlins. However, Boulton's deformational theory receives most modern supports and recognition than any other model of drumlin formation till now and if not satisfactory, but not less than that as well.

According to Boulton (1976), "*...drumlins are morphologically defined landforms, and since a number of processes may produce similar or identical morphologies* (Principal of equifinality)*, there need not be a single origin for all drumlins*" (p-226 in Stanford and Mickelson, 1985). By the early 1980's, it became largely appreciated that the glacier beds are not passive and rigid substrate but rather active part of a ice-bed couple system where unlithified subglacial materials deformed in response to applied glacier stress and thereby contribute to glacier motion (Evans et al., 2006). This theory thus considered by Evans et al. (2006) as the major paradigm shift in drumlin thinking and approach. Even Smalley and Unwin (1968) stated that *"... the Boulton model is closer to reality and that as the stress level rises above the critical and till deformation begins, then drumlins from, but as the level of deformation drops in a down-stream direction, the conditions fail to be fulfilled and drumlin formation becomes sparser*" (p-505).

Another major theory which invokes enormous debate in drumlin study is the '*Outburst Flood Hypothesis*' of Shaw (1983, 2002) and Shaw and Freshchauf (1973 cf. Menzies, 1979). This theory essentially talked about the megaflood origin of drumlins, but also incorporates the origin of fluted moraines, rogen moraines, hummocky terrain and transverse ridges (Shaw, 2002). This theory is based on the close form analogy between inverted erosional marks at the base of turbidities and sedimentary deposits and that of drumlin streamlined forms (Fig. 11). According to Shaw (2002) '*megaflood*' means violent turbulent floods of enormous magnitude, beyond any historical flood event. Such flood events according to him were likely to be more common during the past glaciations and these floods during their waxing stage might cut giant scours upwards into basal ice as like the erosional scours formed due to turbidities. At the waning stage of megaflood event, however, infilling of saturated sediments might take place at these cavities as sorted and/or stratified sediments, apparently undisturbed (at macro scale) and whose bedding conforms to the surface shape of the landform. Hence the theory successfully explains the accretionary origin of drumlins. The outburst flood model also invokes '*a halicoidal motion*' (Shaw and Freschauf, 1973 cf. Menzies, 1979) or later named as '*Secondary Flow*' (Shaw, 2002) of ice for explaining the formation of flutes and similar rock-cored drumlins, when ice flows at specific velocities over the irregular bed. Not only that, Shaw (2002) also provided a number of erosional evidences to account for even the origin of entirely bedrock drumlins e.g. presence of '*S*' form erosional marks, horseshoe vortices and hairpin scour structures etc. evidences of subrounded to subangular clasts, clay beds, parallel to surface clast fabric, close proximity to tunnel channels etc. are also applied in order to further strengthen the hypothesis.

However, the megaflood hypothesis of the origin of drumlins (and other subglacial streamlined landforms) has received more criticism than acceptance but should not be overlooked easily. Equifinality is common in natural environment, but comparing form analogy between two entirely different features with scale difference of very high magnitude (i.e. turbidity scour marks and drumlins) based on only form, is believed to be a wishful thinking rather than a scientific theory. According to Benn and Evans (1998) this model is more like a body of cleaver ideas rather than a testable scientific theory, because there is no way to prove or disapprove it. Boulton (1987) also criticized the theory. According to him the well drained stratified cores are not diagnostic to cavity infilling, rather they are likely to act as stiffer cores and bypass deformation.

Although the above theories partly explain the formation of drumlins in certain environments, no satisfactorily explained theory or model of drumlin origin is given till now (Stokes et al., 2011; Menzies, 1979). *The search still continues*. Clark et al. (2009) have recently tried to postulate the '*Physical Model*' of drumlin formation but yet to receive support from other studies. Hence the above three theories presently dominate the thinking in drumlin related study in one way or the other. Different workers have discussed different sets of theoretical explanations and approaches. Few of them can be discussed here, for example, Menzies (1979) reviewed 5 sets of early theoretical explanations of drumlin formation. They are, a) the accretionary theory, b) the till squeeze theory, c) the dilatancy theory, d) the frost heave theory, and e) the glacial kinematic fluting theory. Hart (1997) and Clark et al. (2009) categorized the modern theories of drumlin formation into two sets, viz. a) deformational theory (Smalley and Unwin, 1968; Boulton, 1976, 1987), and b) the fluvial theory (Shaw 1983, 2002). Beside these theories, Hill (1973) considered two way approach of studying drumlins. They are a) morphometric analysis, and b) investigation of internal sedimentology. Knight (1997), on the other hand, mentioned three way approaches, viz.

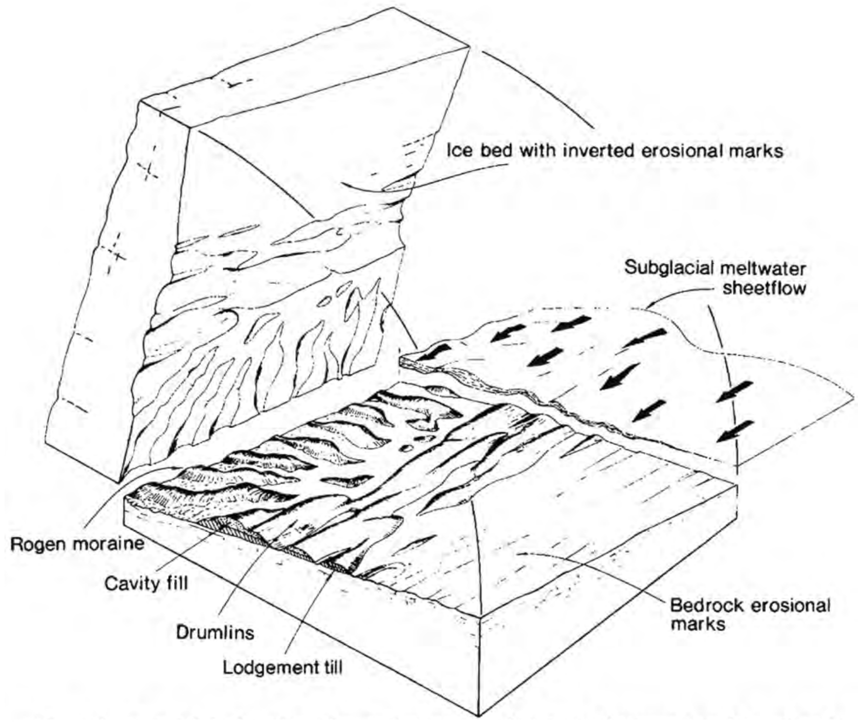


Fig.11 A model showing the components of the 'Meltwater' (or Megaflood) hypothesis. The bedforms result from interaction between the ice-bed, the ground surface, and the broad meltwater flow. Areas of erosion (sculpturing) are illustrated. Adapted from Shaw (2002).

a) theoretical, b) sedimentological, c) morphometric. Recently he also incorporates glacier dynamics (Knight, 2010). Individually these approaches have their own weaknesses and merits. Hence in the present dissertation a hybrid of all the three approaches i.e. a) mapping and morphometry, b) sedimentary and c) theory reconstruction, especially in the Himalayan condition are undertaken. However, studying drumlins has a lot of importance and in the present study area they are one of the best keys for unlocking the palaeoglaciation history of the region. They are briefly discussed in the following section.

1.6. Relevance of Drumlin Study:

Relevance to study drumlins has long been recognized and appreciated with increasing knowledge and changing paradigm and thinking. Their characteristics reflect the nature and general dynamics of ice flow (Trenhaile, 1975). They are readily recognizable landforms at the landscape scale, but equally difficult is the interpretation of their evolution. However, graeter agreement exists regarding their importance to both glaciology and palaeoglaciology (Stokes et al., 2011). Both geomorphology and geology of drumlins have their individual implications to indicate some of the very important behaviours of past ice-sheet/ice-mass. For example, in the words of Hattestrand et al. (2004), the spatial evolution of the ice-sheet is typically reconstructed from analysis of the glacial geomorphological record and the timing of different glacial events is constructed by geochronology and stratigraphical records (i.e. geology). According to Knight (1999) drumlin alignment and outline morphology of subglacial bedforms and by the nature of their internal sediments along with their internal stratigraphy, overprinting structures, crosscutting and superimposed bedforms etc. reveals the relation to the single or multiple phases of ice-oscillations, ice-cap location changes in the past and subglacial thermal and hydraulic regimes and these, in turn, determine the preservational capacity of subglacial landforms. Cook et al. (2011) has also emphasized the internal sedimentology of drumlins as a record of palaeo-ice mass behaviour. The study of drumlins and associated subglacial streamlined landforms are, further, important because modern evidences of substrate glaciological conditions are rare and equally difficult to direct observations. Their knowledge is thus critical to the understanding of the dynamics of present day ice-mass (Stokes et al., 2011). Its future implication in the light of '*climate variability*' further adds to the tally of their importance.

In terms of glacial geomorphology, drumlin's longitudinal axis has been recognized to have oriented in the direction of general ice flow (Rattas and Kalm, 2001; Stokes et al., 2011; Knight, 1997, 1999, 2006). Therefore, they have been largely applied along with other directional indicators, like striae, stoss and lee of lodged boulders etc. to infer the general flow direction of palaeo-ice mass (Hattestrand et al., 2004; Knight, 2004). Glacier '*inversion modeling*', presently also uses the data of drumlin's long axes orientations, their spatial distribution, overprinting and crosscutting relation to associated bedforms etc. in order to predict the extent and dynamics of palaeo-ice sheets (Stokes et al., 2011; Knight, 2010). Researchers are also of the view that drumlin long axis and longitudinal drumlin field may, possibly, be the diagnostic to fast-ice stream activities (Benn and Evans, 1998; Schomakers et al., 2006; Stokes et al., 2011). Based on drumlin morphological attributes (e.g. geometry, density, spacing and distribution; see the section 1.3.1.) and their association with other glacial landforms (e.g. end-moraines, eskers, flutes, rogen moraines etc. ; see the foot notes in section 1.4.), past ice-surface profile and bed conditions have also reconstructed at temporal scale by many workers (Coglan and Mickelson, 1997). Overprinted and superimposed drumlin bedform patterns have also been confidently applied in many areas. On the basis of this, single or multiple phases of drumlin formation and/or drumlinization are reported which further helps in reconstructing the glacial chronology of the area (Knight, 1997, 1999, 2010; Hattestrand et al., 2004; Stokes et al., 2011; Rose and Letzer, 1977; Owen et al., 1997, 2001).

Apart from wide geomorphological relevance, geological relevance of drumlin beds (internal sedimentary composition and structures) is massive in deciphering past ice-sheet behaviour and dynamics which morphology alone cannot account for. Detail study of internal drumlin sedimentary can reflect evidences of past ice-mass balance destabilizing, episodic fast ice flow and ice marginal oscillations (Knight and McCabe, 1997). They can also be correlated with millennial time scale climatic changes (Knight, 1997) through detail geological analysis, Knight (1997) and Knight and McCabe (1997) have postulated two different ice-flow conditions experienced during Devensian glaciation in the Donegal Bay area, northwest Ireland. Hart (1995) has given refined chronology of Dinas Dinlle drumlin swarm, northwest Wales, on the basis of detail study of drumlin internal composition. Similar chronology of glaciations in the past is given by Knight (1999) from Irish ice-sheet area as well, during Laurentide ice-sheet event. He also tried to correlate the ice-sheet dynamics with changing ice-ocean-atmosphere system in this area. Systematic mineralogical study within drumlin bed also enables Newman et al. (1989) to refined the glaciation history of drumlin formation in the Boston harbor drumlin field, New England. Menzies et al. (2007) in the Port Byron drumlin field, and Zelcs et al. (1997) in the Burtniks drumlin field, Baltic nations, have recorded different phases of ice sheet readvance in their respective areas, followed by drumlinization and subsequent retreat with, lastly, thin till carapace deposition at the surface. All these interpretations, therefore, are made possible through the detail study of the geology of drumlins. Hence, both geomorphology and geology of drumlins are equally and largely relevant in the context of providing insight of many unknown possible glaciological and climatic dynamics and their interactions, and reconstructing the glacial chronology of the area as well.

1.7. Limitation of Drumlin Study:

There is no ambiguity regarding the importance of studying drumlins in the former glaciated areas but drumlin studies in general, since early days, have some inherent limitations. The major limitations are: the lack of direct evidences of subglacial processes and drumlin formation, and the sample data for characterizing drumlins in the field is too low to extrapolate for the whole population. Another major backlog, as pointed out by Benn and Evans (1996), is the time scale of the present studies which is very limited compared to the geologic time scale of this landform development. Hence modern studies only show a glimpse of the vast geologic time period, which is often having a period of 10-1000 years (Hart, 1995). Therefore, the geologic records of former glacier beds are a very important source of the data, and their interpretation must be based on proper objectives and rigorous scientific understanding. But even they possess a great many limitations. In the words of Piotrowiski and Vahldiek (1991), "… an accurate interpretation of glacially derived landforms often possesses difficulties because of the great complexity of glacial sedimentary processes, deposits facies and their geometric expression" (P-231). Stokes et al. (2011) have reported that 40 percent of the studies are based on the data from less than five drumlins and 44 percent don't specify even sample size. Nearly in most cases suitable longitudinal and transverse exposures are also rare and so as the two dimensional internal composition of drumlin's bed materials. One dimensional records are mostly provided and the author did not found any paper interpreting three dimensional exposures. Also there is a huge lack of data from interdrumlin areas either due to lack of exposures or the inability of the site to reveal any productive insight except the nature of predrumlin condition. According to Stokes et al. (2011) complex and inhomogeneously composed drumlins are rather more preferred then the homogeneous drumlins. Similarly, apparently massive till (homogeneous) composition within drumlin beds is often simply taken as the diagnostic of deformation, whereas by standard, micro level study must be conducted to prove it before come to any conclusion (Evans et al., 2006). Major limitations can also be experienced in fabric studies. In many cases too much stress is paid on limited number of fabric analysis and often they are in isolation. According to Dowdeswell and Sharp (1986), a multi criteria approach must be adopted which should includes clast wear patterns and range of lithofacies analysis all together to have sufficient confident.

Morphometric analyses of drumlins study equally have many unavoidable limitations. According to Stokes et al. (2011) although such analyses takes quite a sufficient number of samples within a drumlin filed but correlation between morphometry and composition of drumlins over time and space is lacking substantially. Hill (1973) already pointed out many of these limitations regarding morphometric techniques. These are: as drumlin distributional analysis and spacing includes selected area for analysis rather than the whole broad regions, at least before the extensive use of satellite remote sensing data, many of such results are half truth, b) drumlins of different ages (superimposed drumlins, Barchanoid drumlins etc.) are all taken together or exclusion of bedrock drumlins have done deliberately etc., which may deviate the results away from actuality, and c) scale factor is also ignored in morphometric analysis in many cases, if not all etc. Hence, there are some major limitations attached to drumlin related studies. However, progress in last two decades in our technologies and understanding enable us to eliminate many of the above limitations. Such as, high resolution satellite imageries, Differential Global Positioning System (DGPS), Light Detection and Ranging (LIDAR) and subsurface geophysical methods such as Ground Penetrating Radar (GPR) etc. now possess great power to map the landforms even in three dimensional mode with very high accuracy (millimeter scale) and numerically analyzed their internal and external properties—thus enabling us with greater precision and control than ever have before. Many of the aforesaid limitations may no longer be so in near future and better understanding is likely to be achieved at both macro and micro level.

1.8. Distribution of Drumlins in the World:

Drumlins are abundantly found in the former ice-sheet covered areas (Menzies, 1979), dating mostly from the last glaciation. According to Clark et al. (2009) 70 percent of Canada, 50 percent of Ireland, 40 percent of Scandinavia, and 15 percent of Britain’s glaciated area is covered by drumlins and associated substrate streamlined landforms, indicating their predominance in these areas (Fig. 12). Although they are rare in the Himalayas and present study is a first detail approach to the genesis of this landform, further study may confirm their proportion of coverage to the total glaciated area and this fact will certainly have a lot of relevance in terms of ice-mass conditions in the past in this area and their subsequent characteristics changes with changes in climate and tectonism—a region to global climatic implication.

However, drumlins are extensively studied for more than a century in Ireland and Britain –one of the first reported areas. The major drumlin field, reported from these areas, include Clew Bay area, County Mayo (Knight, 2010), Renvyle, Connemara field (Hart, 1997), Kings Court field in Northern Ireland (Meehan et al., 1997), Omagh basin field in north central Ireland (Knight, 1997, 1999, 2006), Kanrawer area in western Ireland (Stokes et al., 2011), County Down and South Antrim (Hill, 1971, 1973; Stokes et al., 2011), Donegal Bay and Mullinasole drumlin swarm in northwestern and northen Ireland respectively (Knight and McCabe, 1997), County Clare, County Galway in western Ireland (Knight, 2010), Clogher valley field in north central Ireland (knight, 2006), Glasgow (Menzies, 1979), Vale of Eden, Gargrave in west Yorkshire, Wigtown in southwest Scotland, Carlisely in north Cumbria (Rose and Letzer, 1977), South Anglesey and Arvon in northwest Wales (Hart, 1995), Lleiniog in north Wales (Hart, 1995; Stokes et al., 2011), Loch Portain, Langlass, Claddach-Baleshare area in North Uist, Sligachan drumlin field in Skye, UK, northwest Wales (Hart, 1997), Tweed basin in Scotland

(Menzies, 1979), etc. Besides, Menzies also reported accretionary characteristics from west central Scotland. Clark et al. (2009) mentioned about the drumlins of Britain and Ireland at larger scale. Hart (1995) and Stokes et al., (2011) reported drumlins from northwest Wales. Smalley and Unwin (1968) interpretated drumlin fields of northern half of Ireland as largely the product of Weichsel glaciation. Knight (2010) also conducted spatial mapping of drumlin fields in Britain and Ireland along with drumlin swarms in Scandinavia, Central Europe and North America.

Apart from these detail studied areas, drumlin fields of other regions of Europe are studied either lacks in detail or their lack of reporting in popular English journals; most of them being in their native languages e.g. in German or in Russian etc. However, a few drumlin fields are reported from Iceland, such as Vestari-Hagafellsjokull and Langajokull drumlin fields (Hart, 1995; Stokes et al., 2011), Mulajokull (Stokes et al., 2011), Vatnajokull ice-cap marginal field (Schomaker et al., 2006) etc. Other extensive area of drumlin is Scandinavia. The major fields include west Pitzbergen (Menzies, 1979), Asnen area of Sweden and southwestern Finland (Stokes et al., 2011), northern and central Sweden (Hattestrand et al., 2004; Menzies, 1979), southeast Norway (Menzies, 1979) etc. Besides, other reported drumlin fields of Europe are Saadjarve swarm in east central Estonia[23] (Rattas and Kaim, 2001), Burtneiks drumlin field in Latvia (Zelcs and Draimanis, 1997), Schonhorst and Schleswig-Holstein in Denmark (Piotrowski and Vahldiek, 1991), Valais in Switzerland (Shaw, 1980), Bodanruck in southern Germany and Rhine area drumlin field (Stokes et al., 2011), and in Poland (Menzies, 1979).

Next to Ireland and Britain, drumlins are extensively studied in and around the Great lake region, especially around New York state and Ontario (Menzies, 1979; Hart, 1997; Menzies and

[23] The major thrust area in this belt generally includes northern Latvia, and southern Estonia, and parts of Lithuania (Zelcs and Draimanis, 1997).

Rose, 1987; Stokes et al., 2011). The major drumlin fields are Wadena field in Minnesota (Wright, Jr., 1957; Menzies, 1979), Green Bay region, eastern and southern Wisconsin (Coglan and Mickelson, 1997; Stanford and Mickelson, 1985), Waukesha field (Stanford and Mickelson, 1985), Peterborough in north of lake Ontario (Stokes at al., 2011), Guelph and Galt field in Hamilton, south Ontario (Trenhaile, 1975), Woodstock in Ontario (Stokes at al., 2011; Piotrowski and Vahldiek, 1991), Oswego field and Chauntauqua County in New York etc. (Menzies, 1979), Chimney Bluff State park area in New York (Menzies 2007). According to Kerr and Eyles (2007) the Upper New York State, USA, consists of the largest drumlin field (12,000km^2) on the North America continent. Nearly 10,000 drumlins are reported between Lake Ontario in the north and the Finger lakes, mostly are the product of late Wisconsin glaciation. Menzies (1979) also reported around 10,000 drumlins from the New York State, 300 from the New England, 5000 from the Wisconsin and 2300 from the Nova Scotia, North America. Other important drumlin fields from this continent includes, North Dakota (Menzies, 1979, Finch and Walsh, 1973), Livingstone lake drumlin field in Athabasca, Canada (Shaw, 1980, 2002), Boston Harbour field in New England (Newman et al., 1989), Bow valley in Albarta, Boston basin field in Massachusetts (Menzies and Rose, 1987; Stokes et al., 2011), Puget Sound field in Washington, Southern and Central Nova Scotia (Stokes et al., 2011).

However, apart from these widely studied areas, drumlin swarms are also reported from elsewhere. Recently drumlins are reported from the Antarctic continental shelf (Clarke et al., 2009) and recently vacated ice-sheet and palaeo-ice stream (bedrocky drumlins) areas (Stokes et al., 2011). Menzies (1979) reported drumlins from New Zealand. Owen et al. (1997, 2001) reported from the Himalayas, India etc. There are probably more drumlin fields which are distributed elsewhere and hence the possibilities of more inclusion remain wide open.

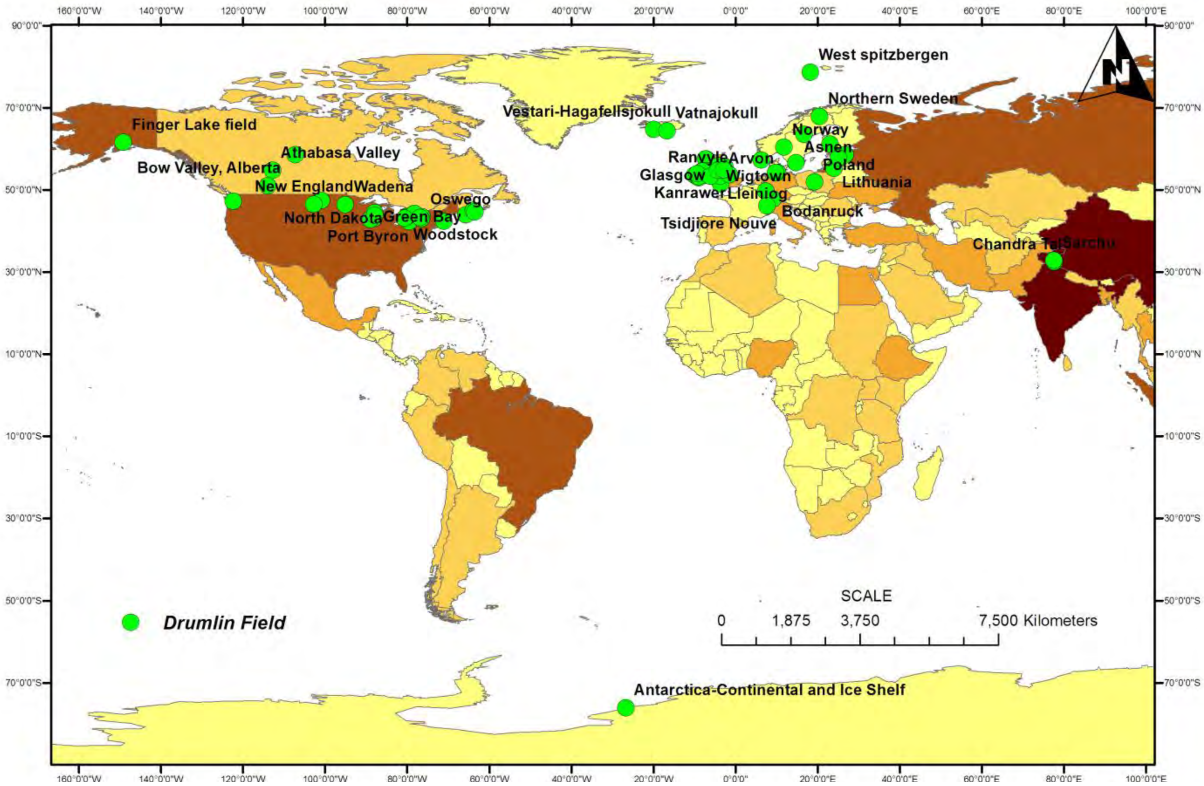


Fig.12 Map showing the geographical distribution of drumlin fields (swarms) in the World.

1.9. Rationally behind the Selection of the Study Area:

The present region of study is the most interesting region in terms of its preservation of some impressive glacial landforms like drumlins and is also a transitional zone of the two important regional climatic systems; the Indian summer monsoon coming from the Indian ocean and the winter westerlies coming from the Caspian, Mediterranean, Black seas. The interplay of these two climatic systems, since the initiation of this young mountain belt, may determine the environmental conditions and largely responsible for the different phases of glacial advances in this high mountain realm. Since climatically this region holds a very interesting location, any reconstruction of palaeoenvironmental conditions will be very effective interms of its wide ranging response not only in the basin itself but adjacent regions as well. The literatures tell that older Quaternary extensive valley glaciation was the regular feature of the north of the Great Himalayan range and glaciation in the younger times were more of restricted and discontinuous type, whereas south of the range experienced extensive glaciation even during the late glacial interstadial period. This sharp contrast in the environments in this present semi-arid region thus provides the basic curiosity in the mind of Quaternary glaciologists, and also attract the attention on the interplay of the above two regional climatic systems in this transitional region. Reconstruction of such environmental condition definitely has immense importance interms of understanding the climate change response in this region and also acts as an effective input to the present global climatic models.

Besides, the Impressive moraines and drumlins are also well preserved in this part of the Himalayas and Trans Himalaya allowing the reconstruction of the palaeoenvironmental history of the region. Already workers have given glacial chronology of the Lahul Himalaya (enclosed by the monsoon influenced Pir Panjal range in the south and the westerly influenced Greater Himalaya in the north) on the basis of the drumlins, but their analysis is restricted to only outline form analogy. The detail analysis of the morphology as well as the internal composition of this landform thus is a major research gap. Since drumlin field is only reported from this area, this is chosen for the preliminary study of the drumlins. Beside the wide valley configuration of the Chandra valley and Yunan valley possibly allowed thick glacier ice to spread (radiating out) during extensive glaciation and certainly provided a conducive condition for the formation of impressive drumlins, which is very rare in other parts of the Himalayas and Trans Himalaya. The region thus is the natural choice for conducting the present study. Hence, together these factors stimulate and encourage the author under the careful supervision of M.C. Sharma to choose the Lahul Himalaya and Zanskar region for the detail study of drumlins, which are also believed to be the representative of the Himalayas in general.

1.10. Research Questions:

From the aforesaid analysis of drumlins and its characteristics, several relevant research gaps may be identified. Many of these gaps (questions) are discussed, in one way or other, in some of the reviewed research papers e.g. Menzies (1979), and Stokes et al. (2011), but the scheme under which they have discussed, are rather idealistic approach and far more general than site specific complexities which are encountered in most of research papers. However, many of these questions, if not all, are tried before to provide answers but have failed partially. Hence satisfactorily answers are yet to provide, which could lead to a step ahead towards a more unifying theory of drumlin formation. Till now no detail study is undertaken regarding the genesis and evolution of drumlins in the Himalayas (discussed in section 1.8.). Thus, the following questions are believed to be the major research gaps in the present context. Any study of the drumlins in the Himalayas, therefore, must give special attention to the following research questions.

i) Where and why drumlins are located in some glaciated areas and not in others?

ii) Why the outline morphology of drumlins varies even within a single field and what is the implication of these morphological variations to the Quaternary glaciation history of the region?

iii) What relation exists between drumlins and other subglacial streamlined forms (e.g. roches moutonee, flutes, ribbed moraines etc.)? Do they have similar relationship between varieties of environments?

iv) Why drumlins are regarded as the diagnostic to ice-mass marginal landform? Do they hold same characteristics across different environments?

v) What are the internal composition and structures of drumlins in the study area and do they differ from other subglacial environments?

vi) What processes causes clustering of drumlin-streamlined forms? –Whether they are the product of single process of erosion, deformation, and deposition or a hybrid of these processes.

vii) Why different processes can able to produce similar streamlined landforms (principle of equifinality)? What could be the diagnostic signatures to subglacial processes of landform evolution?

viii) Why subglacial processes vary widely between and even within a single drumlin field (s)? Do they pose very close relationship with ice-mass thickness, velocity, basal debris content, basal ice temperature, subglacial pore water conditions, substrate lithology, ice-surface profile etc.?

ix) Why postulation of a single unifying theory of drumlin formation is a difficult aspect? Is the '*process-specific*' approach more appropriate than '*site-specific*'?

1.11. Objectives of the Study:

The present dissertation intends to fill up some of the research gaps mentioned in section 1.9. The major objectives of the study are outlined as follows.

It aims: a) to identify and map the geographical distribution of drumlins in the study area and their long-axes orientations.

b) to classify different morphological types of drumlins and their geographical distributional pattern interms of Quaternary glaciological characteristics in the main valley.

c) to reconstruct the subglacial dynamics and genesis of the drumlins in the study area during the late Quaternary glaciation on the basis of their internal composition.

d) to build a hypothetical model of drumlin evolution in the study area.

1.12. Data Base:

The following data sources are, so far, used in the present dissertation. These can be broadly classified into two groups and are listed as follows.

1.12.1. Primary Data: One set of primary data is collected directly in the field whereas another set is later analyzed in the laboratory under specified conditions. These are, therefore, listed under two headings.

1.12.1.1. Data Collected in the Field:

Following data base have been recorded during the two field surveys (see section 4.4 in chapter 4) in the study area.

i) Geomorphological maps, surveyed using Compass and Clinometer, Laser Ranger Finder (LRF), and Hand Held Global Positioning System (GPS).

ii) Clast macro fabric and shape analysis, including fabric of lodged surface boulders.

iii) Field sedimentary logs.

iv) Field photographs.

v) GPS readings for morphological cross sections and length and height measurement.

vi) Field notes and descriptions.

1.12.1.2. Data Analyzed in the Laboratory:

These are later processed following the standard methods (see section 4.4 in chapter 4) in the laboratory conditions.

i) Sediment samples are analyzed for grain size measurement using standard dry sieving method.

ii) Surface textural analysis of Quartz sand grains (size fraction 200-500µm.) with the help of Scanning Electron Microscope (SEM).

1.12.2. Secondary Data: this data set is collected from different literature, Government Agencies and Websites.

i) Topographical sheet at 1:50,000 scales, published by Survey of India (SOI). The study area covers mainly the following two topographical sheets viz. 52 D/12, and 52 H/5; excluding very small parts of adjacent topographical sheets.

ii) Geological and rock distribution maps, precipitation distribution map, soil map, relative relief map, average slope map, stream frequency, drainage density and drainage textures maps, and many of the maps, and diagrams are taken from different sources of literature.

iii) Google Earth satellite imageries are used for modifying and correcting field maps.

iv) Both Indian Remote Sensing (IRS) series Cartosat 1 data is used for characterizing a number of terrain conditions e.g. Digital Elevation Model (DEM) creation, relative relief mapping, contouring, hill shading, aspect and slope generation etc.

v) LISS III data (taken in 29th October, 2006) of Indian Remote Sensing (IRS) series is also used for generating land use and land cover mapping and identification of some of the geomorphological features.

vi) Meteorological data is collected from Keylong, Indian Meteorological Department (IMD), Himachal Pradesh.

Since, the major thrust of the present study is put on the primary data, recorded and generated in the field and later in the laboratory, secondary data are of limited use and mainly used for characterizing the study area.

1.13. Achievements and Scheme of Chapterisation:

In the present study the chapters are organized in such a way that first the back ground knowledge of the landform i.e. drumlin and their relevance of study is discussed followed by the over view of the study area in the context of the present study and general characteristics and approaches to study the composition of such impressive glacial landforms. After conceptualizing the essential characteristics of drumlins, the study area, and glacigenic sediments in general, the morphological and compositional (or sedimentological) study of the drumlins in the present study area are under taken. Together they are utilized to reconstruct the evolution of drumlins in the study area and the palaeoclimatic condition in the region during their formation. Thus the essential scope of the study that is (i) the geographical distribution of drumlins, (ii) the morphological classification of the drumlins, (iii) the genesis and evolution of the drumlins are sequentially covered in the present study.

Hence the Chapter—1 is discussing the essential morphological and sedimentological characteristics of drumlins and associated streamlined forms, relevance of studying them and their global distribution. Chapter—2 is aimed to provide the background knowledge of the study area; their geography, geology, climate and other essential physiographic characteristics in the light of present study, and the glacial chronology of the study and other cryospheric characteristics of the region. In Chapter—3 the general characteristics of glacigenic sediments and their comparison to the Himalayan region is first discussed, followed by the methodologies and approaches suitable so far in this realm is mentioned critically. Chapter—4 is dedicated to the methodologies applied in the present study to analyze the drumlins in the present study area, both morphologically and geologically, and the limitations of the present study. Chapter—5 discuss the geographical distribution of drumlins and their pattern of long-axes distribution in the Chandra valley and Yunan valley and on the basis of their geography, the location of the ice-divide during their formation is reconstructed along with the ice-flow direction in the main Chandra valley. The different morphological types along with their distribution are also discussed in this chapter. In Chapter—6, the detail sedimentological analysis is done using fundamental lithofacies techniques. Based on the sedimentological analysis couple with the previous morphological analysis, a hypothetical model of the genesis and evolution of the drumlins in the Chandra Tal area is lastly proposed. The Chapter—7 conclude the important inferences of the present study. Some of the future scope of studying drumlins in this area is proposed at the end.

Chapter—2

INTRODUCTION TO THE STUDY AREA

".. an understanding ... is fundamentally important in reconstructing the evolutionary history of the high mountain landscape of Central Asia."

——Derbyshire and Owen (1996)

2.1. Introduction:

The greatest concentration of glaciers outside the polar realm in the Himalayas, Transhimalayas, and Tibetan Plateau (Qinghai Xizang) (Owen et al., 1995, 1996, 1997, 2001, 2002; Benn and Owen, 2005; Owen, 2009; Hedrick et al., 2011) brings the conspicuous name of "*Third Pole*" to this region. Being the world's greatest relief feature, the Himalayas play a great interactive role as a '*geodynamo*' in circulating energy and mass through tectonic uplift and wide range of denudational and/or erosional processes. In the words of Derbyshire (1996), *"The world's greatest relief is a locus of enormous geodynamic energy consisting of a complex interplay between tectonics and glacial and fluvial erosion associated with widespread and frequently catastrophic mass wasting"*, (pp-153). The Himalayan orogeny, thus, have long been fascinating the workers, especially in the light of late Cenozoic (~55 Ma.) uplift and the consequent possible role in influencing regional and global climate during late Tertiary and Quaternary times (Owen et al., 1995, 1996; Mitchell et al., 1999; Hedrick et al., 2011). Major studies in this archetype natural laboratory, therefore, are focused on several interdisciplines of

Earth Sciences, especially on tectonics (exhumation, Isostatic adjustments etc.), geomorphology (large scale glacial e.g. over steeped valleys, moraines, glacial dam outburst etc., paraglacial and periglacial, fluvial, and mass wasting processes e.g. different forms of avalanches, slides, flows, falls, and creep etc.), geology (petrology, dendrochronology, paleontology etc.), climatology and meteorology, biology and ecology, and various other subdisciplines. The present study is focused on glacial geomorphology and Quaternary geology. It has enormous implication interms of the global and regional climatic interplay and response to extensive valley glaciation. The study area, chosen for studying '*Drumlins in the Himalayas*' are located in the Lahul Himalaya and the Zanskar region (Fig. 13). While the nature and timing of glaciation is considered to be highly variable across the entire stretch of the Himalayas, Karakoram and the Tibetan Plateau[1] (Owen et al., 1996; Hedrick et al., 2011) and the Lahul Himalaya, being considered as the transition zone to the two major climatic system i.e. the southwesterly summer monsoon and winter westerlies of mid-latitudinal origin (Owen et al., 1996, 1997, 2001; Hedrick et al., 2011), is therefore the most suitable study area (Fig. 13) for reconstruction the palaeoenvironmental condition and the complex interplay between climatic-cryospheric systems. Drumlins, as previously discussed (see chapter 1), are the subglacial streamlined morphological forms and their detail morphological and sedimentological study may provide the valuable linkages between the subglacial dynamics of basal ice, in particular, and overall glacial regime, in general, and the possible palaeoenvironmental condition. Furthermore, such analysis is not only helpful in future climate modeling at the global and regional scale, but also bears a huge implication to the society and the economy by an large as well, since many of the country's economy, in one way or the other, is

[1] The Himalaya including the Tibetan plateau stretch eastwest for ~2000ka. from Burma to Afghanistan and for ~1500 km. from India into Central China (Owen and Benn, 2005; Owen, 2009). This includes from south to north the main ranges of Siwaliks, ser Himalaya, Greater Himalaya, Karakoram mountains, Hindu Kush, Kunlun Shan, Nianqentanglha Shan, Tanggula Shan, Nianbaoyeze mountains, Qilian Shan, and La Ji mountains (Benn and Owen, 2002; Owen and Benn, 2005; Owen, 2009).

still dependent on the rainfall characteristics of summer monsoon and snow and ice melt fresh water resources.

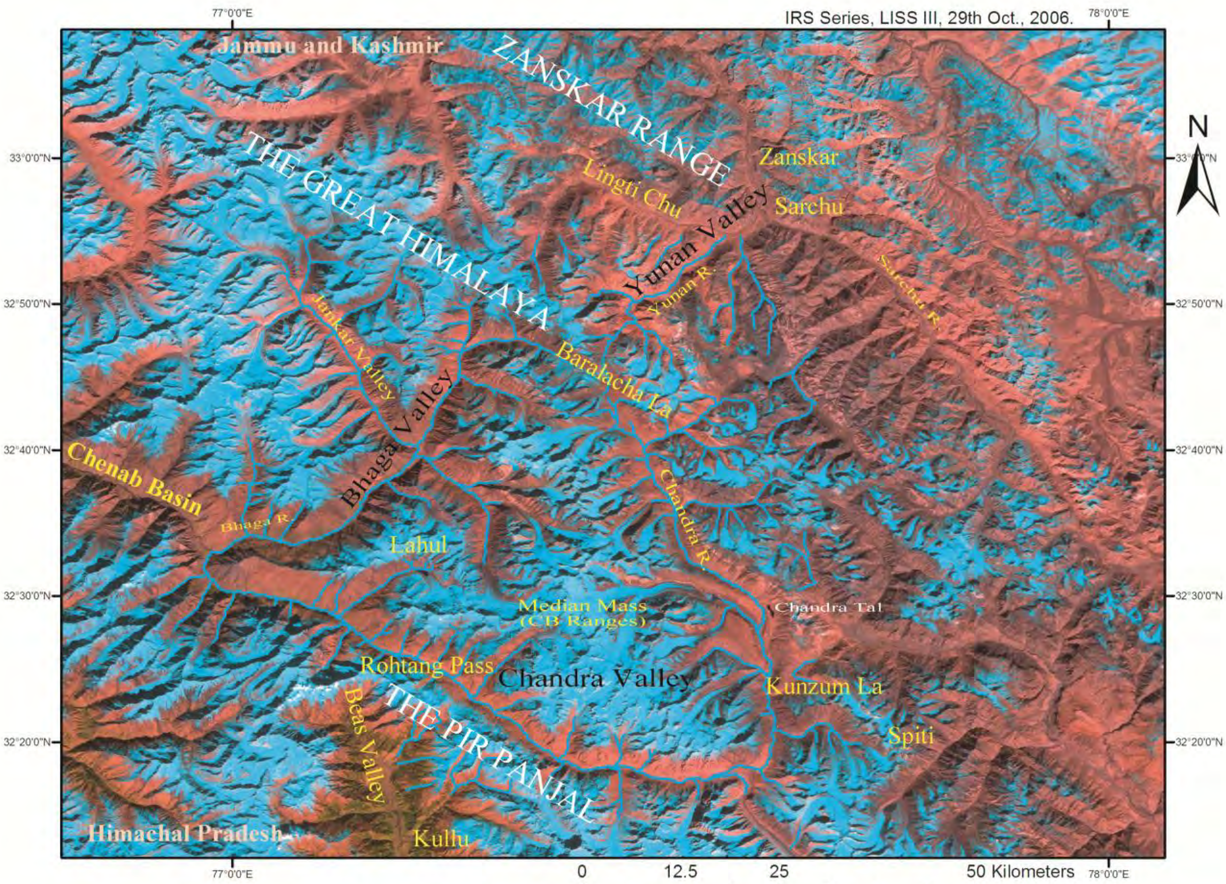


Fig. 13 Map Showing the Lahul Himalaya and Zanskar Range.

2.2. The Study Area:

The present area of concern is located in the arid countries of Chandra Tal area of Chandra-Bhaga basin (32.085°-32.989°N/ 77.013°-77.748°E, area ~4,121 km^2), the Kunzum la (32.395°N/77.636°E, ~4,550 m asl.) of the upper Spiti basin and the Yunan basin (32.725°-32.912°N/ 77.373°-77.562°E, area ~221 km^2) of Zanskar valley (Fig. 14). The Chandra-Bhaga (CB basin) and Kunzum La come under the Lahul and Spiti district of Himachal Pradesh, India, whereas the Yunan basin falls in the Zanskar district of Zammu and Kashmir, India. The CB basin is bounded by northwest to southeast trending Pir Panjal range in the south and the Greater Himalaya in the north, and the Yunan basin by the Greater Himalaya in the south and the Zanskar range in the north (Fig.14). These ranges are formed during late Cenozoic period due to collision between Indian continental plate with Asian continental plate (Owen et al., 1995, 1996) and is still in the very early phase of their mountain building process. Both the three ranges are consisting of lofty mountain peaks, with average height of the Pir Panjal is ~5,000 m asl. and the that of the Greater Himalaya and the Zanskar range is >6,000 m asl. Connectivity across these ranges is maintained by the high altitudinal mountain passes. For example, the Rohtang Pass (32.371°N/77.246°E, 3,980 m asl.) connects Kullu and Manali with rest of the Lahul and Spiti. Hamtah Jot (Jot=Pass) (32.270°N/77.351°E, 4,130 m asl.) is another trek route to connect both these regions. Kunzum La (La=Pass) (32.395°N/77.636°E, 4,550 m asl.) connects Lahul with the Spiti region. Connectivity between the Zanskar and Leh and the Himachal Pradesh is maintained through the famous Baralacha La[2] (32.758°N/77.414°E, 4,930 m asl.) Pass. Baralacha La (4930 m asl.) is also very important in the present context because it is source region of the three main rivers of the study area i.e. Chandra, Bhaga, and Yunan river, and the possible location of the ice-divide during the extensive glaciation in the late glacial interstadial or younger (Owen et al., 2001, 2002). Three drumlins fields (sites) are chosen for mapping and detail sedimentological study, with the major focus is mostly around the Chandra Tal area which is coded in this study as *'site 1'* (32.438°-32.511°N/77.586°-77.644°E, ~4,300 m asl.). The site in Yunan basin is the second one i.e. *'site 2'* (32.821°-32.862°N/77.435°-77.516°E, ~4,450 m asl.) and that in the Kunzum La is coded as *'site 3'* (32.398°-32.422°N/77.627°-77.657°E, ~4,430 m asl.). The

[2] The Baralacha La Pass is a Tibetan name meaning "pass with cross roads on summit" i.e. in Tibetan, "Para Lá rtsé" because of the fact that roads from Zanskar, Ladakh, Spiti and Lahul meet on the top (Kangra district Gazetteers, 1917).

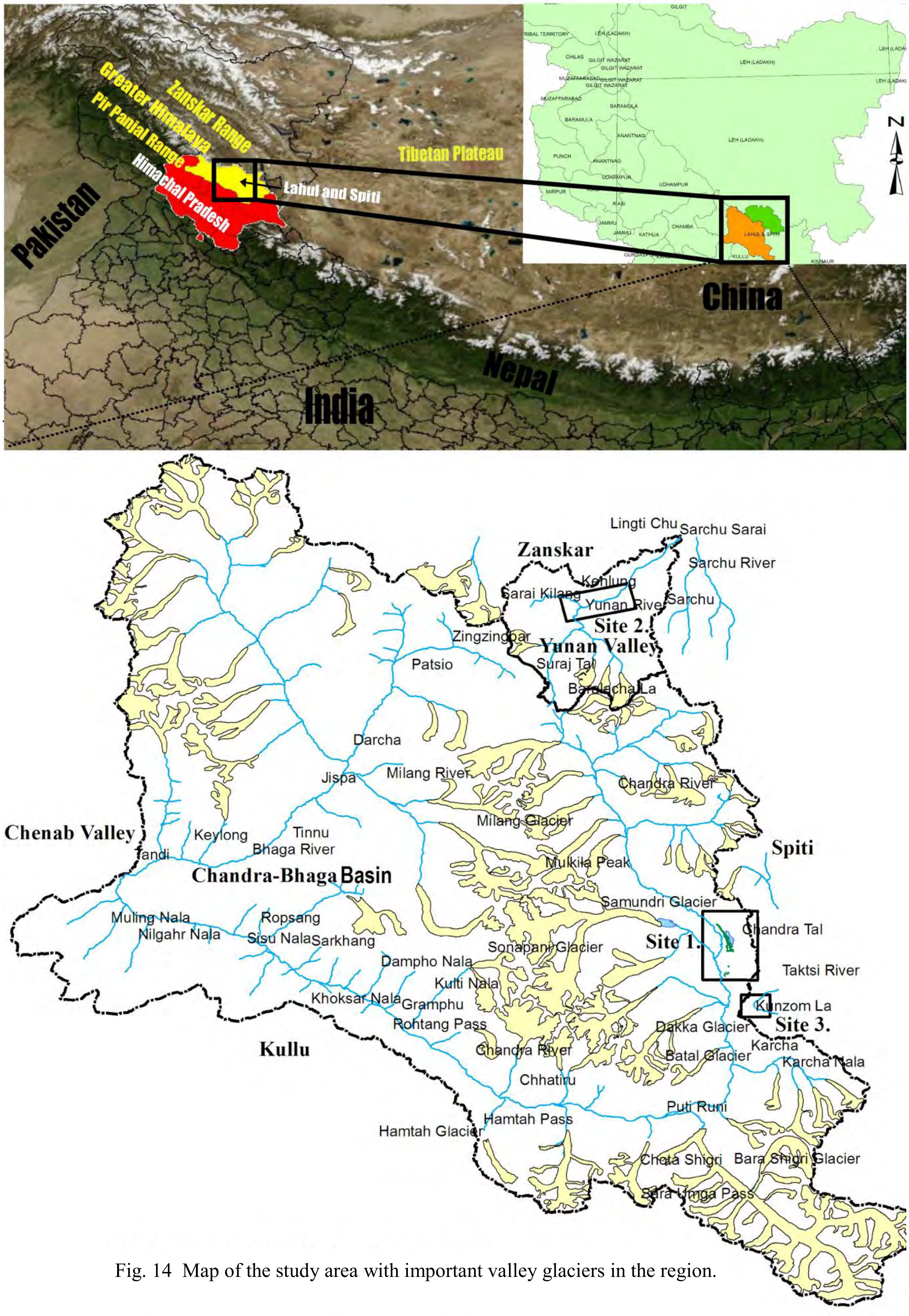


Fig. 14 Map of the study area with important valley glaciers in the region.

general description of three drumlin swarms –in the Himalayas and their surroundings may be discussed as follows under three headings, viz.

2.2.1. The Lahul Himalaya

2.2.2. The Upper Spiti Valley at Kunzum La

2.2.3. The Yunan Basin of the Zanskar Range

2.2.1. The Lahul Himalaya:

The Lahul Himalaya is politically consisted of Lahul and Spiti district of Himachal Pradesh and is traversed by two main NW-SE trending mountain ranges i.e. the Pir Panjal to the south and the Greater Himalaya to the north (Fig.14). It is however, enclosed by Kullu valley to the southeast, Kangra in the south and Ladakh in the north. The vernacular name of the Lahul actually comes from the Tibetan '*Lho-yul'* meaning *'southern country'* applied by *'early Ladakhis'* whereas to the local people the country is known as *'garzha'* (Kangra district Gazetteers, 1917). However, the Lahul Himal, a part of northwestern Himalaya, marks the junction between the monsoon-influenced southern flanks of the Pir Panjal (Lesser Himalaya) and mid-latitude westerly-influenced the Greater Himalaya (Derbyshire and Owen, 1996) and hence environmentally (especially climatically) a very important transition zone (Fig. 14). The relative seclusion of the region both environmentally as well as socio-culturally is, thus, due to the potential physical barrier imposed by these two mighty mountain ranges of the earth. Both the ranges possess peaks in excess of 5,000 m asl. to 6,000 m asl. (Owen et al., 1995, 1996) and highest being the Mulkila Peak (32.545°N/77.412°E, 6,517 m asl.). Hence, both orographically influenced climatic systems and altitudinally determined lapse rate determine the temperature and precipitation gradient of the region. The region, however, mostly receives rainfall in the form of snow during winter months due to Westerlies and very less rainfall during summer monsoon seasons. Due to this contrasting moisture supply the permanent snowline varies as high as >4,260 m asl. in the Greater Himalayan part of Lahul to as low as ~1,500 m asl. on the southern slopes of the Pir Panjal range (Owen et al., 1995). The summer temperature although, feels scorching, but never goes very high.

Tectonically the Lahul Himalaya is active too during the entire Quaternary period, although the tectonism is rather episodic (Adams et al., 2009). The Pir Panjal range is enclosed by Main Boundary Thrust (MBT) in the south and Main Central Thrust (MCT) in the north whereas the Greater Himalaya is bounded by MCT in the south and Zanskar Normal Fault (ZNF) in the north. According to Brookfield (1993), although slower uplift of Pir Panjal range has taken place between 3.5 and 0.4 million year (Ma), a phase of rapid upliftment has experienced in the following periods. According to Burbank (1982, cf. Owen et al., 1995) Pir Panjal was highly active over the last 0.8 Ma, which involves a minimum of 1,400-1,700 m differential uplift between the southern and northern margins of the Kashmir basin with minimum upliftment rate is about ~4mm. a^{-1} (a = year) (Brookfield, 1993). If this rate of upliftment of Pir Panjal is extrapolated in the Lahul Himalaya and compared with the rate of upliftment rate of the High (Greater) Himalaya which is ~1mm. a^{-1} [3]at least for the last ~2.5 Ma (Taylor and Mitchell, 2000), there is unequivocally a very contrasting tectonic and/or exhumation history of this transition zone, which further adds to the significance of the region for detail study of every

[3] Recently Adams et al. (2009) have also found exhumation rate of the High Himalayan crystalline series (HHCS) in the Lahul, from shallow crustal levels to the surface, was ~1-2 mm a^{-1}. This study also corroborates the highly active geological and geomorphological processes of the region.

aspects in order to understand the possible influence of Cenozoic uplift of the Himalayas on the global climatic system. Geologically the major part of the Lahul Himalaya, however, consists of metamorphic and crystalline rocks (due to volcanic activities) and only a small area near the junction of the Bhaga and Chandra river is formed of primeval unfossiliferous sedimentary rocks (see section 2.3) (Kangra district Gazetteers, 1917).

The Lahul Himalaya entitled with two major river system at the head of Chenab River which enclose a '*Great Triangular Mass'* (Fig. 13), popularly known as CB ranges. They are Chandra system and Bhaga system. The river Chandra and Bhaga confluence near Tandi (32.551°N/77.414°N, 2,864 m asl.) and later flows as Chenab River. However, both the high altitudinal river systems along with Yunan system originate at the Baralacha La (4,930 m asl.). The Chandra river first flows southwesterly and southerly and take a sharp westerly turn at Bara Shigri glacier (32.309°N/77.608°E) and ultimately meet Bhaga river at Tandi (2,864 m asl.). The river first flows as anticedent river and later its course may be directed by structural and topographic adjustments (Adams et al., 2009) because the initial southeasterly and southern course is seemingly 180° different from the northwesterly course near confluence. The Chandra river has a total length of ~138 km. which is >14% of the total length of Chenab river. On the other hand, Bhaga has a total length of ~60 km. (>6% of the total length of Chenab). Both the river system has a tremendous geomorphological and socioeconomic importance to the region. According to Adams et al. (2009) the rate of incision of the Chandra river was 12 to 5.5 mm a^{-1}, especially during the post glacial adjustment in the region and although river discharge follows seasonal and diurnal rhythmic cycles, the sediment yield can be very high at times[4] due to predominant paraglacial activities, leaving apart the fact that the river flows through relatively

[4] One time measurement indicates that the total suspended sediment discharge can be as high as ~462 kg s^{-1} (Owen et al., 1995; Adams et al., 2009)

hard metamorphic crystalline beds of HHCS. Both the Chandra and Bhaga river valley have the average height of more than 3,000 m asl. (Adams et al., 2009). Apart from the highly active river systems other noticeable water bodies are ephemeral streams (e.g. the one emanating from the Chandra Tal and joins the main river south of the Tal) and gullies (on the debris cones and fans) and two attractive lakes, viz. the Chandra Tal (Tal = lake) (32.481°N/77.616°E, 4,314 m asl.) and the Suraj Tal (32.757°N/77.403°E, 4780 m asl.).

The Lahul Himalaya is gemorphologically also very active because of the stronger glacial[5], paraglacial and periglacial, mass wasting and fluvial processes. Barring from roches moutonnees at the Baralacha La (4930 m asl.) and Chandra Tal area, to drumlins, impressive moraines of past and present glacial advances, lake deposits, smoothly glacially scoured rock benches and striations at high altitudes, horns and arêtes, pro and supra glacial lakes, hanging valleys, ice-contact fans and other glacial landforms, debris and talus cones of paraglacial origin and patterned ground, rock glaciers of periglacial origin etc. A large suit of landforms are preserved in this relatively barren arid region. The site 1 (32.438°-32.511°N/ 77.586°-77.644°E, ~4,300 m asl.) around Chandra Tal area where field mapping is conducted, the following landforms and features are identified and mapped (Fig. 49). These are drumlins, roches moutonee, whale-back bedrock ridges, bedrock outcrops, striations, erratic, debris and talus cones, rock glaciers, river incised gorge, shallow ponds and peat bogs, lake shoreline and flood plain deposits, point bars and sandurs, and deltaic deposits. This indicates that within a small reach a variety of geromorphological forms can be encountered which is the result of both active formation and preservation. There is also a spatio-temporal gradation of the formation of these

[5] The Lahul Himalaya contains a number of imprerssive glaciers of Northwestern Himalaya. They are Samundri Glacier, Dakka Glacier, Batal Glacier, Chhota Shigri Glacier, Hamtah and Gagloo Glaciers, Sonapani Glacier, Kao Rong Glacier, Mulkila Glacier, Milang Glacier etc.

landforms such as the roches moutonnees, whale-backs, and drumlins are essentially subglacial streamlines forms whereas the debris and talus cones are predominately paraglacial in origin. Similarly rock glaciers are the product of contemporary aridity of the region and large scale suit for periglacial processes due to very low temperature, especially during winter (active freeze and thaw regime). Detail and systematic study of these landform assemblages in this dynamic region hence is worth require to understand the environmental change and the evolutionary history of the landscape of the Lahul Himalaya. Since Bhaga valley does not contain any such Drumlin like landforms of interest, not much discussed here, although the major geomorphological processes remain same for both the valleys, except the fact that Bhaga valley is relatively narrower and having more steeply dipping general gradient than the Chandra Valley.

2.2.2. The Upper Spiti Valley at Kunzum La:

This region located southeast of site 1 and is although a part of Lahul Himalaya but it is discussed here separately in order to describe the surroundings of site 3 (32.389°-32.422°N/77.627°-77.657°E, ~4,430 m asl.) (Fig. 14). The Spiti valley is locally pronounced as *'Piti'* which is also derived from Tibetan language, meaning '*Middle Province'*. Upper Spiti valley is separated from Lahul by the Kunzum range (Fig. 13) which runs roughly parallel southwards for ~48 km. before it merges with Pir Panjal near Batal, where Karcha Nala joins the Chandra river (32.349°N/77.622°E, ~4,028 m asl.). The roadway connectivity between rest of the Lahul and Spiti is maintained through Kunzum La (Pass) (~4,551) avenue. The site 3 study area is traversed by Taktsi stream (from 1:250,000 Topographical Sheet, Survey of India) which joins the Spiti river downstream. The average elevation of mountain ranges in the Spiti valley is more than 5,500 m asl. and the valley lies somewhat ~600 m higher than the surrounding Chandra valley in the west (Kangra district Gazetteers, 1917). The Upper Spiti valley, however, is also more wind dominated than the surrounding valley. Near Kunzum La (4551 m asl.) already Owen et al., (1995, 1996, 1997, 2001) have identified and dated the glacially polished and striated bedrock surface of Kunzum range and mentioned about the existence of drumlin (~4,600 m asl.) having similar trend along with striations. The author traverse and mapped the area with special emphasis to drumlin streamlined forms which is somewhat lower than (~4,430 m asl.) that mentioned by the above authors. A more elaborative discussion regarding these drumlins is given in section 5.4. Here it must be kept in mind that the evidences of the existence of drumlins and striations across Kunzum range denotes and corroborate the statement of Owen et al., (1997) that one of the extensive valley glaciers possibly, during late glacial interstadial time (Owen et al., 2001; Hedrick et al., 2011), over topped the then shallow Chandra Valley and spread in the Upper Spiti valley. Since drumlins are mostly formed along the margins of ice-sheets/mass (section 1.3.1), hence bringing such logical relation may not be wrong for this study area as well although the magnitude could be highly different. It is possible to demarcate the margin of former extensive valley glacier(s) on the basis of the distribution of drumlins, at least in the Upper Spiti valley. The broad opening of the valley near the Chandra Tal area and reconstructed thick ice mass (see section 2.5.1 and 2.7) further supports the conducive conditions for drumlin formation (see section 1.2 , Fig. 1a.) in this part of the Himalayas.

2.2.3. The Yunan Basin of the Zanskar Range:

The Yunan basin, as discussed before, is bounded by the NW-SE trending Greater Himalaya in the south and the Zanskar range in the north. This part of the Zanskar range is a broad arid belt of mountains which is in sharp contrast with the monsoon dominated southern slope of the Pir Panjal in many respect. The Yunan valley is mostly uninhabited and uncultivated barren wasteland type with general elevation of the valley is ~4,300 m asl. (Kangra district Gazetteers, 1917). The summit level range between 5,500 m asl. and 6,000 m asl., highest being the Nimaling (~6400 m asl.) (Taylor and Mitchell, 2000). The modern Equilibrium Line Altitude (ELA) for the Zanskar range is ~5,500 m asl. (Taylor and Mitchell, 2000) which is comparatively higher than the surrounding Lahul Himalaya. The climate is analogous to that of Leh according to Osmaston (19945, cf. Hedrick et al., 2011), although anecdotal data suggest precipitation amount is slightly higher in this region than Leh. Thus, relatively more aridity and low temperature for the most part of the year favours the extensive permafrost creation and periglacial activities. It is impressively reflected through the prominent distribution of rock glaciers while traversing the valley from Baralacha La (4930 m asl.). Since only fragmentary and limited extent glaciers are present currently in the valley heads of the Yunan basin (Fig. 14), they are not discussed here. However, among the other prominent geomorphological land features, notable are, drumlins, glaciated palaeosurface (>280 m above present river level), augen gneiss erratics, fragmentary and inset lateral moraines (Taylor and Mitchell, 2000), point bars, sandurs, outwash plain, alluvial and debris fans, talus/scree cones, glacio-fluvial deposits etc. Hence both periglacial and paraglacial processes overwhelm in the Yunan basin at the contemporary time.

The present study is focused in the area enclosed by site 2 (32.821°-32.862°N/77.435°-77.516°E, ~4,450 m asl.). This area is traversed by the Yunan river which has an origin at

Baralacha La (4930m ASL.). It has a length of only ~30 km. before joining into the Lingti Chu river (Fig. 14). Both the rivers are then joined subsequently by the Sarchu river. The Sarchu river rans northwestward and ultimately meets the Tsarab river before flowing into the river Zanskar. Tanglang La (5,200 m asl.) separates the tributaries of the Zanskar river from the main Indus river which is the climax drainage system of the northwestern Himalayas.

The above description intends to touch the general aspects of all the three sites studies so far. However, there are many physiographical aspects which require further detail elaboration for understanding the evolution of the landscape system in this region, couple with the timing and nature of glaciation, which is in fact the major focus for the present study. These aspects therefore, are discussed as follows.

2.3. Geological Characteristics and their Significance in the Present Study:

The regional geological setting play a key role in the present study, especially in terms of acting as natural obstacles (bed rock knoll) to the flow of the ice in basal ice regime, supplying subglacially derived local bedrock clasts and supraglacial clasts, determining clast shapes (mostly elongated and blade shape clasts) and sizes etc. They are further helpful in understanding the variable exhumation versus incision rates, both spatially and temporally and also in terms of the degree of susceptibility of these rocks to periglacial processes and weathering.

The regional geological setting of the study area precisely incorporates the Lahul and Zanskar orogeny i.e. the Zanskar range in the north, followed by the '*High Himalayan Crystalline Series'* (HHCS) in the middle and the Pir Panjal range in the south (Fig. 13). These ranges are trending northwest to southeast fashion and are the product of very complex thrusting, faulting and folding orogenesis with frequent instructions. The former northern edge of the Indian continental crust is represented by the Tso Morari crystalline series (Nimaling Massif) of HHCS and is separated from the Tethyan self sediments by *'Indus Tsangpo Sature Zone'* (ITSZ), lies north of the study area (Mitchell et al., 1999; Taylor and Mitchell, 2000; Hedrick et al., 2011). The ITSZ is structurally very complex and polyphasic in origin and incorporates three main linear thrust belts, each of them are separated by major fault zones or ophiolitic belts (Taylor and Mitchell, 2000). The Zanskar range however, exposes both the rock of the ITSZ and HHCS. In fact, it is the '*Zanskar Normal Fault*' (ZNF), which maintains the contact between high-grade gneiss, migmatites and leucogranites of the HHCS and the low-grade unmetamorphosed sediments of the Tethyan Zone (Taylor and Mitchell, 2000) . Greater part of the Zanskar range therefore is composed of Tethyan shelf sediments deformed by folding and thrusting (Hedrick et al., 2011, Mitchell et al., 1999).

Traversing the Lahul is a part of HHCS. This is extensively composed of Precambrian Chandra-Bhaga series and Palaeozoic metamorphic rock, intruded by large stocks and sills of porphyritic k-feldsper granite of Cambrian-Ordovician-Silurian age and leucogranite of Miocene age (i.e. early Miocene [22-23 Ma] and Middle Miocene [12-13 Ma] in age (Sharma , 1986; Adams et al., 2009). Hence the region is entitled with unbroken series of rocks barring from Pre-Cambrian to Cretaceous age, with recent overly of Pleistocene and Holocene (Quaternary) deposits. Already Sharma (1986) has compiled the detail stratigraphic record of the Lahul Himalaya (especially the Chandra-Bhaga basin and Yunan basin) (Fig. 15 and Fig. 16) from various sources of Geological Survey of India (GSI). Repetition is not intended and only important aspects are given stressed here with progressive geologic age (i.e. old to young). The

Precambrian rock distribution is extensive in the region (Central, Northern, and Western part of Chandra-Bhaga and Yunan basin) which includes the Chandra-Bhaga group of metamorphosed arenaceous sediments, Quartzites, Slates, Phyllites, Schists, crystalline Limestone, Dolomite Quartz, Schists, Migmatites and Gneiss (the major part of the province of the site 1 ans site 3); the Killer Gneiss formation; and the metamorphic group of Schist, Granite, Amphibolites and Graboo (Fig. 15 and 16; Sharma, 1986). The Ordo-Silurial and Muth Quartzite system of Palaeozoic era, which incorporates rocks like Sericitic (red) Quartzite, Porphyritic Granite, Amphibolite, Silt, Biotite, whitish Quartzite and Limestone bands (Fig. 15 and 16; Sharma, 1986). This zone is where the site 1 and site 3 (Fig. 14) is located. Manjir formation and mainly the Lipak series of Carboniferous period which having rocks of Muth Quartzite, Shale, Siltstone bedded crystalline Limestone, is the location of Site 2 (Fig. 14 and 16). Following this geologic system is the Pangi Slate formation of Permian age, (Sharma, 1986 cf. Kumar 2003). According to Kangra district Gazetteers (1917), the upper Permian series consists dark micaceous Shale, called *'Productus Shales'*. Overlying the Permian series is the narrow Tandi formation of Mid-Triassic period which mostly contains Limnestone, intercalated with Phyllite, Slate, Quartzite, and Calcites (Sharma, 1986 cf. Kumar 2003). This system of Limestone rocks is succeeded by the well known Spiti-Shale of upper Jurassic age (Kangra district Gazetteers, 1917). Recent Pleistocene and Holocene formations, however, includes morainic glacial till deposits, lacustrine and fluvial deposits, thin soil cover, scree, and valley fills, respectively (Owen et al., 1995, 1996, 1997; Sharma, 1986 cf. Kumar 2003).

A summery can be drawn from the above analysis that the present focused area has predominance of Quartzitic and Shale, Slate rock assemblages. These rocks can be account for the effective obstacles to the flow of ice and also clast shape and size determination, since it has been found in the present study that the blade shaped clasts of local shale/slate origin, predominate the matrix followed by elongated clasts of mostly Quartzite or Gneiss etc (see section 6.2.2.1). The indurated Quartzites around Chandra Tal area (site 1) also shows deep red brown rock varnishes on many of the roches moutonnee and whale-back streamlined forms. Hence, the geology is believed to play one of the key roles in the formation of drumlins in this part of the northwestern Himalaya, and may also influence the deformation/erosion/depositional processes to a considerable extent.

2.4. Geomorphological Characteristics and their Significance in the Present Study:

In terms of superficial processes and landforms, the Lahul Himalaya consists of some of the very well developed and preserved glacial landforms. Lahul is an impressive, rugged and highly spatially variable landscape comprising broad u-shaped valleys and tributary hanging valleys, glacially eroded benches and truncated spurs, moraines, drumlins and roches moutonee etc. produced during the former glacial advances, in the region and also containing extensive paraglacial and periglacial landforms and fluvial and lacustrine deposits and landforms. The Zanskar range i.e. the Yunan basin on the northern side of the Greater Himalaya, however, shows somewhat different set of geomorphological setting because of the major reason of precipitation shadowing on the outboard wedge[6] i.e. the northern slope of the Great Himalayan range (Mitchell et al., 1999). Mitchell et al. (1999) have already mentioned about some of the significant points of geomorphological differences between the southern and northern flanks of

[6] Mitchell et al. (1999) distinguished the region north and south of the Greater Himalayan range as inboard wedge and outboard wedge respectively in order to interpret the different suits of environmental and landform assemblages in these two relatively contrasting areas of the Northwest Himalayas, and further to reconstruct the Quaternary glacial chronology of the Zanskar region.

the Great Himalayan range, which according to them reflecting the external forcing mechanism, such as tectonics and climate, but since drumlins are given major emphasis in the present study, and only Yunan valley is studied, therefore the assemblages of landforms in the valley is discussed here; although description of the geomorphological landforms in the Zanskar range is already given in Mitchell et al. (1999), and Taylor and Mitchell (2000). According to their observation the small tributary valleys of Zanskar range are very complex in nature and have been modified by glacial and glacio-fluvial processes. The lack of glacial evidences in the high mountain passes (>5,000 m asl.) in the north of Zanskar further complicates some of the inferences. However, according to Hedrick et al. (2011), the increasing aridity and restrictive glaciation in the late glacial interstadial period in the Zanskar and Ladakh range unlike that in the Lahul Himalaya, may explain some of the complicate nature of the landscape evolutionary history of this region. However, few of the general geomorphological attributes and landforms may be listed as follows.

2.4.1. Glacial Geomorphology:

Extensive late Quaternary glacial advance (more than 100 km. beyond the present termini of glaciers) in the Lahul Himalaya has resulted in the formation and preservation of impressive glacial landforms throughout the region (Hedrick et al., 2011), which is in sharp contrast to the Yunan valley beyond (north of) Baralacha La (4,930 m asl.). Drumlin is one of such impressively preserved landforms in both Lahul and Zanskar; the main interest of the present study. The glaciers in the Lahul however, are high activity type or *'D-type'* consisting of extensive supra glacial debris covers (Owen et al., 1989, 1995, 1996), steep gradients and well developed ablation valleys and paraglacial reworking. Mostly glaciers of the Lahul and Zanskar are avalanche feed *'firnkessel'* type (Benn and Owen, 2002) where Steep ice-fall or avalanche tracts often separate the glacier accumulation zone from the ablation zone (Plate: 1). Besides, due to very high rate of reworking of glacigenic sediments due to mass movement (till slide and till flow etc.) and glcio-fluvial processes, the preservation potentiality of primary signatures is very low. During the field survey in Batal (4,239 m asl.) a complex assemblage of lateral and end moraines (Plate: 2), ice-contact fans (Plate: 3), heavy supra glacial debris cover in the ablation zone, ice-fall and eroded recent pair of lateral moraines with their continuous base erosion etc. have been observed. Impressive lateral morainic assemblages have also been at Hamtah (Plate: 4) and the latero-frontal moraines at the Kulti valley mouth (Plate: 5) along with well recognized trimlines few kilometers downstream of Chhatiru (3,316 m asl.) have also been observed (Plate: 6). In the Yunan valley glaciers are very small (>1 km^2) and fragmented, hence did not observed while traversing the region and is also not very clear in literature.

2.4.2. Periglacial Geomorphology:

The region both Lahul and Zanskar shows very high periglacial activities in the form of rock glaciers, patterned ground etc. In fact, beyond Baralacha La (4,930 m asl.) in the Yunan valley a number of impressive rock glaciers have been observed (Fig 23) along side of the road (NH 21). At the Chandra Tal area of Lahul a rock glacier has been mapped (Fig. 49). Owen et al. (1995) have provided detail description of the rock glaciers at the Milang valley of Lahul Himalaya, and their contribution to the sediment load of the stream. However, most of the rock glaciers in this region are caterpillar type and lobate form and are periglacial in origin. Predominantly formed talus cones and scree also flank the steep hill slopes, especially more extensive in the Yunan basin and mostly found in the northern slope of Pir Panjal in the Chandra basin. The progressively arid climatic condition, from south of the Pir Panjal to Zanskar and beyond, and sufficiently low temperature (Fig. 32) condition, for substantial period of the year, allow the periglacial processes to dominate and formation of these landforms. According to Owen (2009) decline in snow avalanche activities due to precipitation reduction leads to long term negative mass balance and may lead to transformation of the glacier into rock glacier. Therefore, in terms of changing environmental conditions over space and time, the study of rock glaciers and other periglacial landforms and their spatial distribution is very important especially in this dynamic transition zone of the Himalayas.

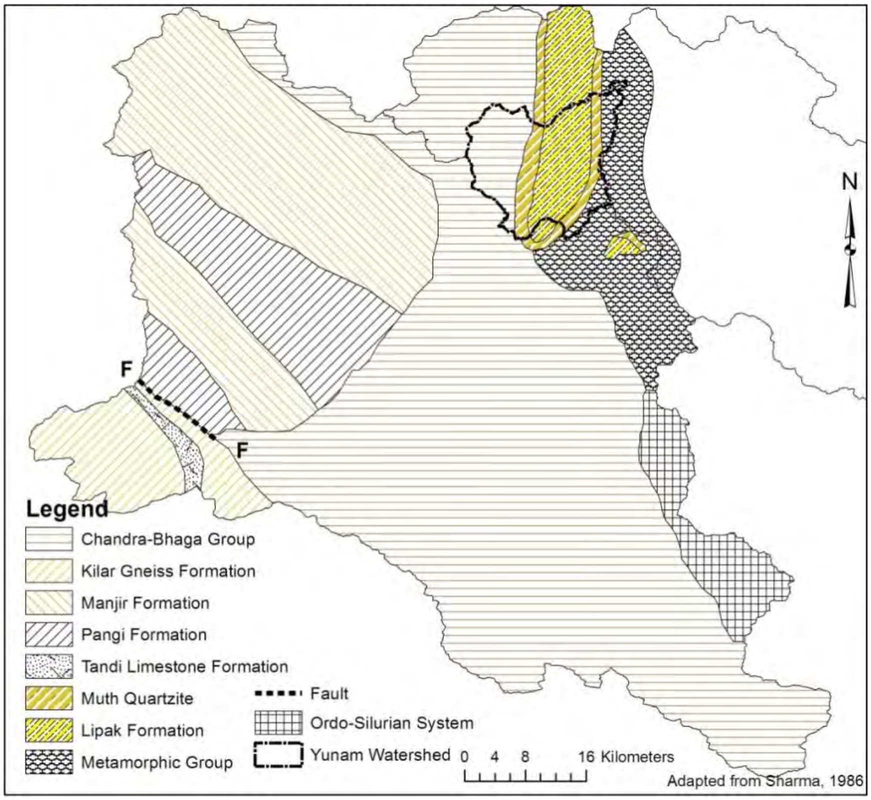


Fig. 15 Geology of the Chandra-Bhaga and Yunan Valley

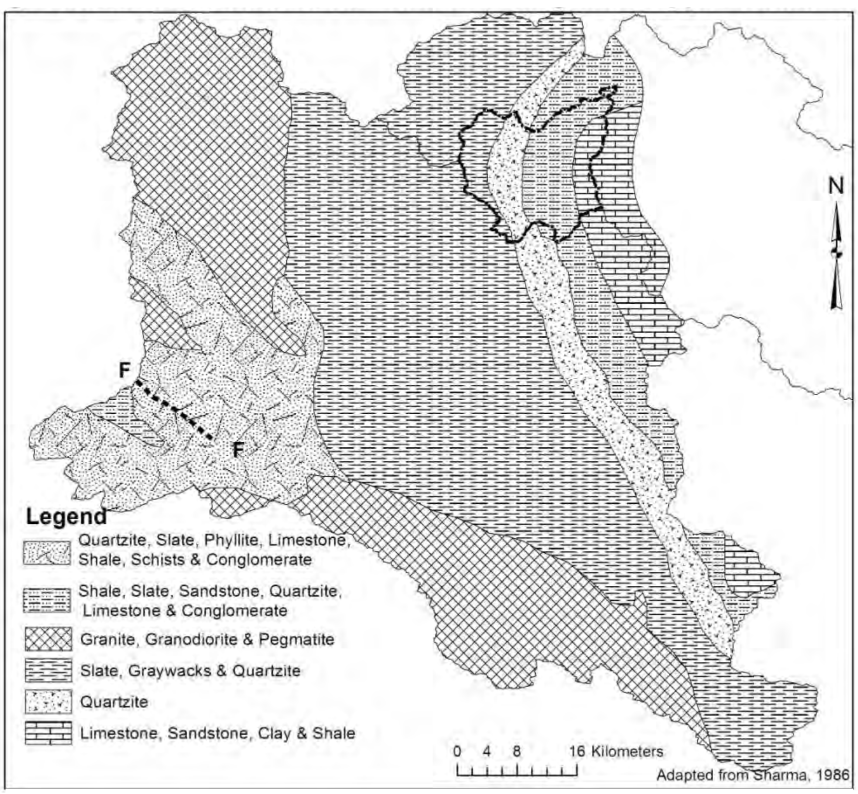
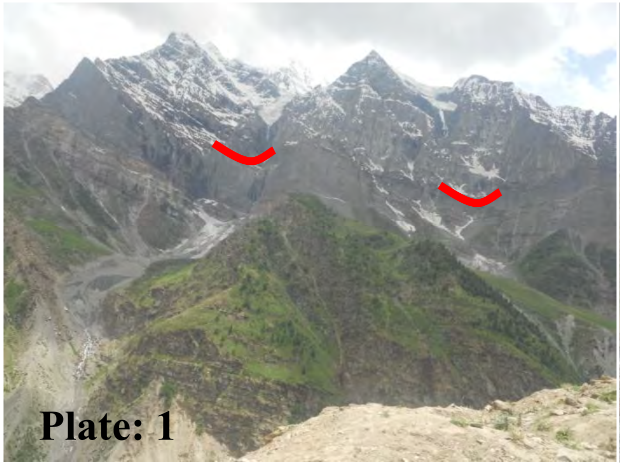
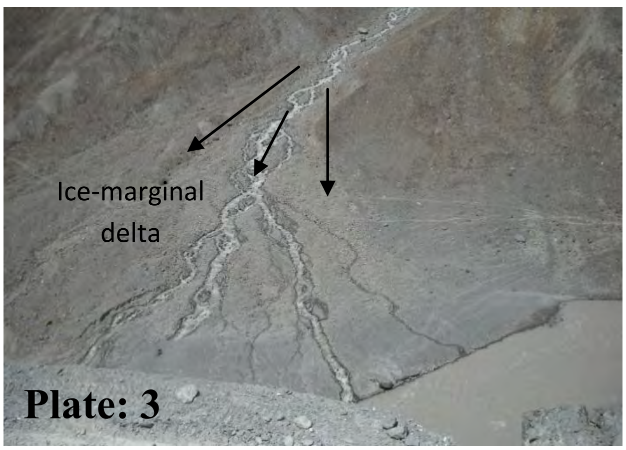
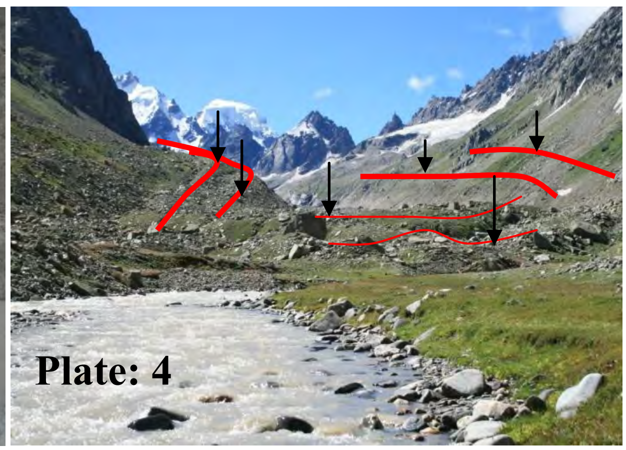
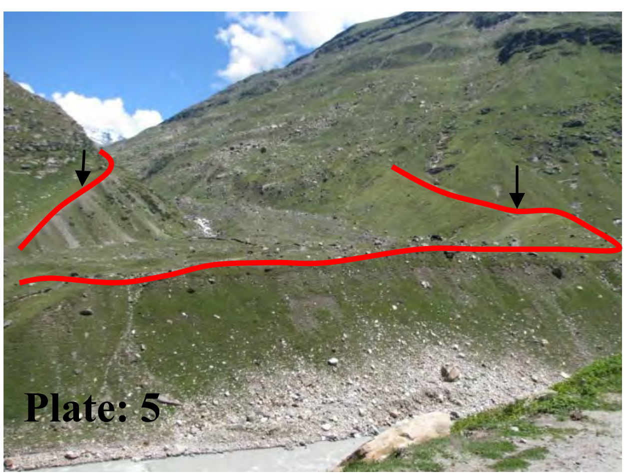


Fig. 16 Rock distribution of the Chandra-Bhaga and Yunan Valley









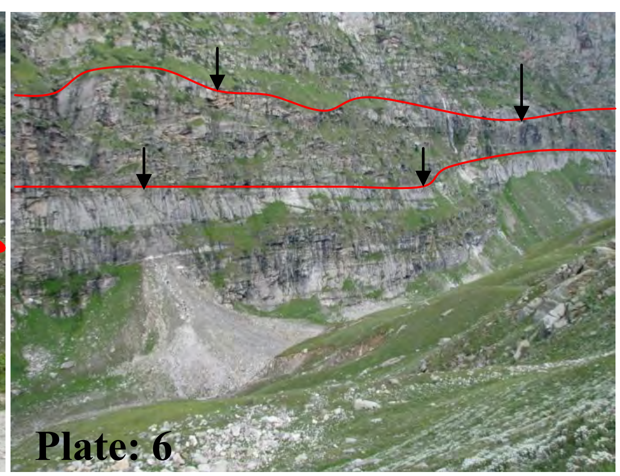
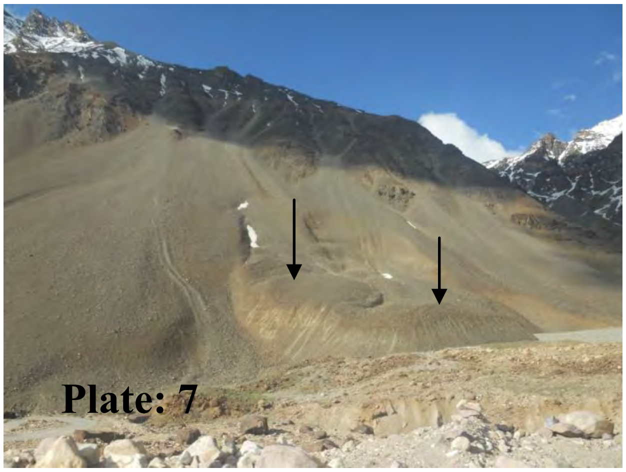
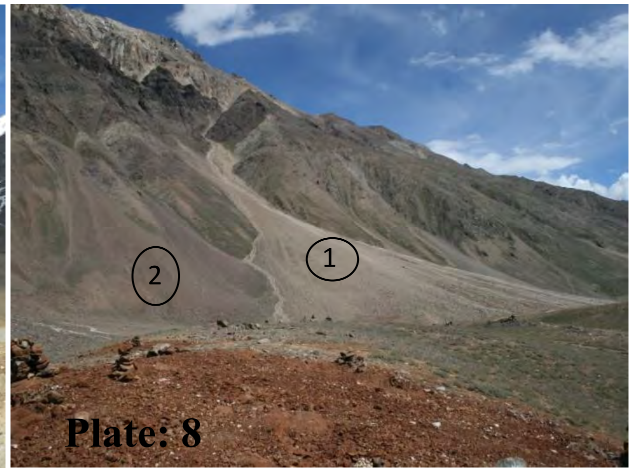
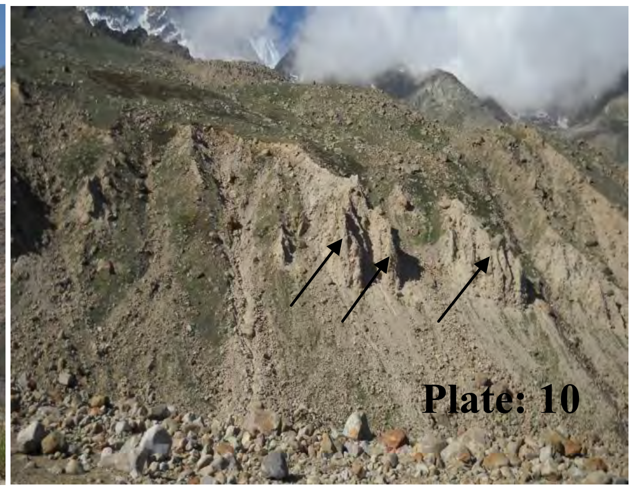


Plate: 1 The typical hanging valley glaciers in the Bhaga valley; popularly known as 'Double Deck' glaciers. The ice falls (red lines) separate the accumulation zones from the ablation zones which is typical in this valley and most common as well.







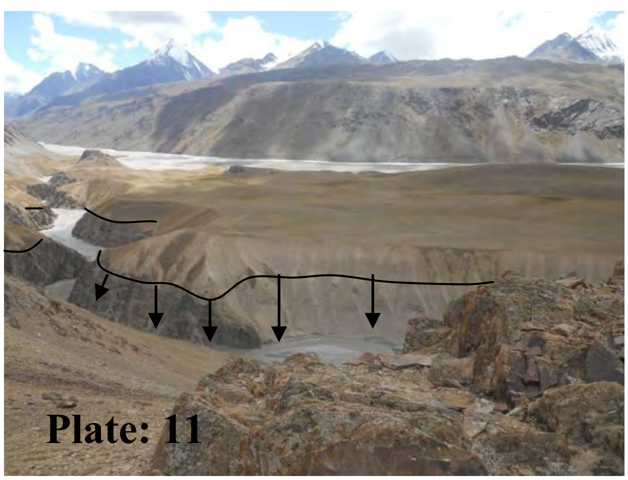


Plate: 2 Well developed Batalmorainic complexes (arrows) at Batal, Lahul Himalaya. View looking towards Karchanala (towards east).

Plate: 3 Ice marginal(or ice contact) delta in the terminoglacialsubenvironment of Batal glacier, Himachal Pradesh, India. The ice marginal delta is dissected by the stream emanating from the glacier snout.

Plate: 4 Three pairs of lateral moraines clearly indicate three phases of glacier advances also in the Hamtah glacier; a tributary glacier in the Lahul valley, with end morainic complex in the frontal zone. Inset small indistinct moraines are also common. Here in the photograph two older moraines (red lines and arrows) can only be displayed.

Plate: 5 Kulti stage sharp crested terminal moraine (red lines and arrows) is clearly preserved in the Kulti valley. Evidences of this stage of glacial advance are preserved only in some tributary valleys only.

Plate: 6 Glacialtrimlines are well developed in the main Chandra valley, Lahul Himalaya. The lines and arrows are indicating them in the plate. It is taken few kilometers before Chhatiru, Himachal Pradesh.

Plate: 7 Alobate type small rock glacier (arrow) is identified in the right of the Chandra Tal, Lahul Himalaya. This is a periglacial landform and signature of the aridity (cold desert) of the region in the post glacial period.

Plate: 8 Extensive debris fans (1) and talus or scree (2) are developed presently in the Chandra valley indicating the predominance of the post glacial paraglacial activities.

Plate: 9 Largeflowslide deposit (arrow) at Jispa, Bhaga valley, Lahul Himalaya. Local slope failure causes this scale of mass movement deposits after glacial retreat.

Plate: 10 Earth pillar structures (arrowed) are well developed all along the valley. Spatially variable incision rates augment their development along the banks of the main river Chandra.

Plate: 11 Mini-gorge like landform developed in the upstream reach of the Chandra river. The incision rate possibly is very high after recent deglaciation in the main valley to develop such an impressive mini-gorge (black lines and arrows). View towards downstream of the valley looking at south.

Plate: 12 Well developed point bar deposits along the upper reach of the Chandra valley owing to reduced river gradient and spatially variable aggradation rates, and both seasonally and diurnally defined high and low rates of sediment yield and temporary deposition; high discharge at times and extensive paraglacial activities are responsible for. View looking upstream towards north from the Bhagabridge.

2.4.3. Paraglacial Geomorphology and Mass Movement Processes:

Paraglacial and mass movement processes are another set of very active geomorphological processes of the region resulting into the formation of very huge number of debris fans and large flow slide deposits. According to Owen et al. (1995) rapid deglaciation of the main trunk valley and tributary valleys in the recent past has resulted into release of large quantities of sediments into fluvial system through paraglacial processes. Rectilinear debris fans, parallel retreat of the gully heads, variety of slope processes (e.g. falling, rolling, sliding, and bouncing of clasts) and highly active mass movement processes such as debris flow, rock fall, snow avalanching, slumping, rotational failure, catastrophic flow slides (Plate: 9), creep (Owen et al., 1995) and impressive earth pillar structures visible in the mass wasted and incised valley fill deposits (Plate: 10) etc. are extensively observed while traversing the Lahul valley and Zanskar range. Some of the very large debris fan deposits along with rockfall and avalanches are very well preserved all along the Kunzum range while looking at the Chandra valley and few of them are also mapped (site1). In the Zanskar region (Yunan valley) some of the bedris fans are huge and possibly buried the lateral moraines and small drumlins of previous glaciations. They may be traced along the left bank of Yunan river and further verification is required.

However, very high relief, sharp slopes with frost shattered Shale and Slate composition, ephemeral streams and gullies (feed by snowmelt water) and possibly rapid deglaciation (Owen et al., 1995, 1996; Owen and Sharma, 1998; Hedrick et al., 2011) may result into (as like in other parts of Central and Western Himalayas) the initiation of *'Paraglacial Time'* (Bernard et al., 2004) with large scale *'disequilibrium'* condition in the region (Adams et al., 2009). And this fact has huge environmental significance of landscape evolution in the present study area when compared with the period of extensive valley glaciation (Hedrick et al., 2011) and impressive drumlin formation.

2.4.4. Fluvial Geomorphology and Lacustrine Deposits:

Both the Chandra-Bhaga and Yunan valley exhibit spatially variable incision and aggradation evidences. Near Chandra Tal of Chandra Valley narrow mini incised gorge like features (~4,131m asl.) are developing (Plate: 11) and can also be found further downstream. Equally important features are point bar deposits and braided river system (Plate: 12) along the upstream reach of the Chandra Tal, especially noticeable where Samundri nala joins the Chandra river and continue downstream beyond Batal (4,239 m asl.). There are impressive gorges along the Bhaga reach as well. According to Adams et al. (2009), the incision and depositional history of the valley in recent times are highly spatially variable, although very rapid (with 12 mm to 5 mm a^{-1} rate of incision) due to post glacial adjustment (disequilibrium). Extensive lake deposits are also found. According to Owen et al. (1995) a large moraine/ice dammed lake may have formed between Bara Shigri glacier (~3,900 m asl.) and Batal glacier (~4,300 m asl.), possibly during little ice-age. Local folk story says in 1836, the Bara Shigri glacier burst and dammed the Chandra river to form a huge lake and local guards were appointed on the Kunzum pass to watch at least that the water should flow over into Spiti (Kangra district Gazetteers, 1917). This lake later breached (catastrophic flood by Coxon et al., 1996) and presently the lake deposits are extensively found downstream from Batal (Plate: 13). At the present time, however, two big lakes in this area are Chandra Tal (32.48°N/77.616°E, 4,314 m asl. and with area of <0.5 km^2, length of ~1.7km., and width of ~0.3 km.) Suraj Tal (32.757°N/77.403°E, 4780 m asl.). a proglacial lake is also identified at the Samundri glacier front (~4157 m asl.). Other than these, aeolian processes also dominate in this arid zone, especially in the Spiti valley. However, no impressive landforms is indentified in this region, which is entirely dedicated to aeolian activities, although wind is an active agent of reworking and transporting distant finer grains. The relative contribution of each of these processes in Lahul Himalaya, however, is compiled in the Fig. 17, adopted from Owen et al. (1995). This is certainly supports the dynamic contemporary geomorphological activities in this region.

Plate: 13 Batal Lake deposits shown (arrows) at Batal, Himachal Pradesh, India. View looking from Batal Glacier end moraine towards the Karchanala.

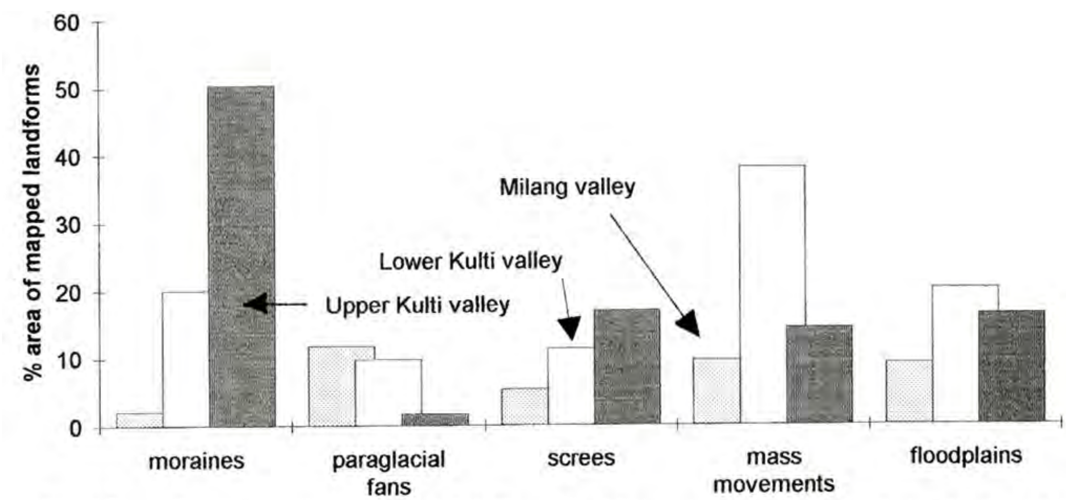


Fig. 17 Percentage contribution of different landforms types for Milang, lower Kulti area, Lahul Himalaya. The predominance of paraglacial and mass movement processes are well exhibited through their share of landforms. Adapted from Owen et al. (1995).

Drumlins are Quaternary landforms and linked to subglacial to submarginal processes. In the Himalayas where high activity glaciers with thick supraglacial deposits and very thin subglacial materials (less than a meter, Owen et al., 1989) predominate, formation of such impressive landforms certainly develops a lot of curiosity. Hence a deep knowledge of timing and extent of glaciation in the Lahul Himalaya and Zanskar range is indispensable when reconstructing the platform for the evolution of *'drumlins in the Himalayas'* along with geological and geomorphological settings of the region. This further helps in reconstructing the palaeoenvironmental condition during the evolution of the landform.

2.5. The Timing and Extent of Glaciation in the Lahul Himalaya and Zanskar Range:

In the recent years with the extensive use of the numerical dating techniques[7], it is now clear that the glaciation in the Himalayas, Karakoram and Tibetan plateau was asynchronous, that is the timing of the maximum extent of the glaciers are different in different ranges and parts of the Himalayas and adjacent high relief countries (Owen et al., 1989, 1995, 1996a, 1996b, 1997, 2001, 2008, 2005, 2008; Derbyshire et al., 1989; Holmes, 1993; Cronin and Johnson, 1993; Owen and Derbyshire, 1993; Shroder et al., 1993; Derbyshire, 1996; Sharma and Owen, 1996; Mitchell et al., 1999; Taylor and Mitchell, 2000; Owen and Benn, 2005; Owen, 2009; Adams et al., 2009; Hedrick et al., 2011). During the last two and half decades a massive resurgence in research into glaciation of this vast, high relief Central Asian Mountain region has been observed. And it is the fruit of these early workers, both native and abroad, that new glaciation and glacial advance history for the vast region is known to a certain extent, although the data base is not extensive and rarely account for detail coverage of entire area except fewer parts of the Himalayas and Karakoram (such as the Pakistan part of Karakoram and Nanga Parbat area; Gangotri of Garhwal Himalaya etc.). Apart from these limitations, newer research is

[7] Dating techniques possess severe constrains in the Himalayan environment, such as absence of fossils, artefacts, organic materials etc. for ^{14}C dating and also lack of suitable sediments properties for palaeomagnetic dating (Owen et al., 1996, Derbyshire and Owen, 1996; Owen and Benn, 2005) limit the extensive numerical dating. Similarly it is now widely believed that the relative weathering techniques are good for differentiating and correlating landforms and stratigraphy within small space with similar microclimate but their use is very limited across broad space (Owen et al., 2001). However, the Optically Stimulated Luminescence (OSL) dating and cosmogenic radionuclide (CRN) dating are the two robust dating techniques which are now extensively used in the Himalayan environment for establishing chronology and period of formation etc. (Benn and Owen, 2002).

coming and at least sufficient to broadly correlate the nature and extent of glaciation/glacial advances in the presently studied Lahul Himalaya and Zanskar region and also for the Ladakh region. The history of glaciation in these adjacent regions is very important in the present context because Lahul demarcates the transition between two broad regional climatic systems i.e. summer time southwestern monsoon coming from the Indian Ocean (Fig. 18a) and winter westerlies travelling a long way from mid-latitude and bringing moisture from the Mediterranean, Caspian, and Black Sea (Fig. 18b) (Owen et al., 1995, 1996; Derbyshire and Owen, 1996). Aridity gradually increases as one move northwards, especially away from the Pir Panjal. The interplay between these two climatic systems is very important and possibly responsible for the bulk of the glaciation in this region. However, the debate related to the relative role of the Tibetan Plateau as high level pressure regulator (Fig. 18a & b) and the uplift of the Pir Panjal during the Pleistocene in modifying the regional as well as global climate is not much discussed here since it is not the purpose of the present study. Few important concepts although require attention and therefore stressed here. It is believed that even during the past the precipitation gradient (Fig. 19) remain more or less similar in pattern for the entire region as like present time, although magnitude may differ. For example, according to Shi et al. (2001 cf. Hedrick et al., 2011) the geochemical and paleontological proxies suggest that the strength of the South Asian summer monsoon has fluctuated considerably over the entire late Quaternary and at times increased in intensity, with 40 to 100% more precipitation than today. However, present numerical dates for the Zanskar and Ladakh indicates that progressively increasing aridity is observed throughout the Quaternary in these regions, as the glacial advances were more restricted with the passage of time (Derbyshire and Owen, 1996; Derbyshire, 1996; Hedrick et al., 2011). Although this pattern of glaciation is more or less common in other parts as well e.g.

in Lahul and Garhwal Himal, Hunza, and Skardu valley of Karakoram etc., but recent OSL and CRN dates from different areas of this high mountain ranges indicate that their timing and extent were largely variable across space (Owen et al., 2005, 2008; Owen, 2009; Hedrick et al., 2011). However, an overview of glaciation in these two adjacent areas (inboard wedge and outboard wedge, after Mitchell et al., 1999) may be given as follows.

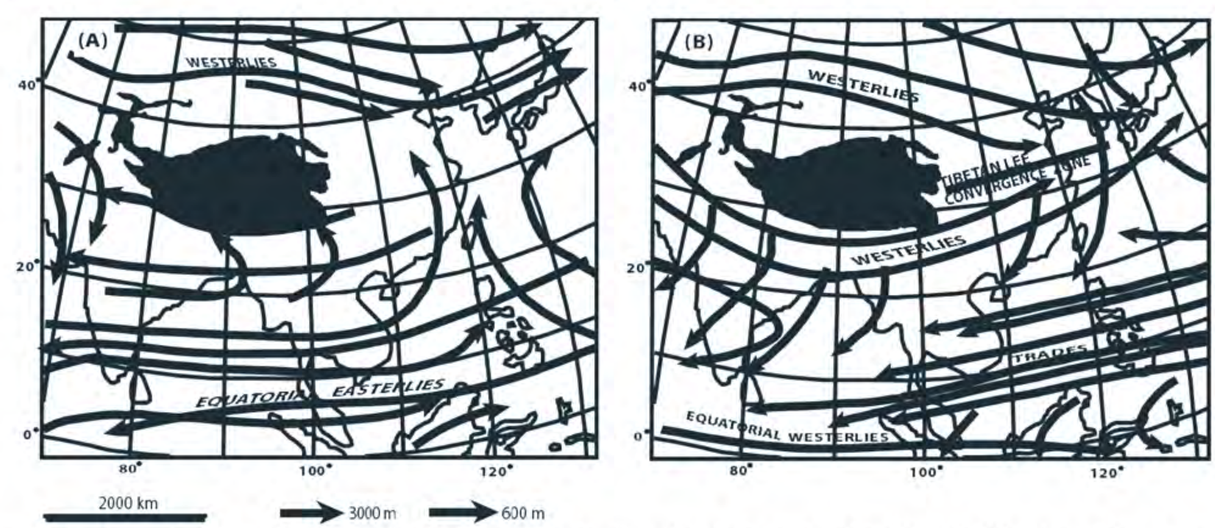


Fig. 18 Characteristics air circulation over the eastern hemisphere for (A) Summer (July), and (B) Winter (January). The solid lines indicate airflow at ~600 m. in (A) and (B). Names refer to air systems. The area of Tibet and the Himalaya is show in black. Adapted from Barry and Chorley (2003 cf. Owen et al., 2008).

2.5.1. Timing and Extent of Glaciation in the Lahul Himalaya:

The glaciation in the Lahul Himalaya and Zanskar region is asynchronous, as far the numerical dates given till date and although Taylor and Mitchell (2000) have applied similar names to these glaciation in the Zanskar as that in the Lahul but the recent ^{10}Be and ^{26}Al dates indicates that the extensive glaciation took place in the Lahul Himalaya during the late glacial warmer interstadial period (~14-16 ka; Owen et al., 2001) whereas it was sufficiently older in the neighboring Zanskar and Ladakh (Taylor and Mitchell, 2000). The ^{10}Be and ^{26}Al exposure ages for the Lahul is given from some of the lodge boulders on the crests of the drumlins near Chandra Tal area which is believed to represent deglaciation times (Owen et al., 1997, 2001), as they are supposed to deposit subglacially at the submarginal environment and expose only after the glaciers had retreated; and also from the stable boulders of morainic complex at Batal (4,239 m asl.) and from the exposed and polished bedrock surface at Kunzum La (4551 m asl.). These numerical dates provide timing of the two glacial advances viz. Batal and Kulti glacial advances (Owen et al., 2001), whereas the geomorphological mapping and relative dating techniques helped previously in determining the older extensive Chandra glacial stage, followed by Batal I and Batal II stage, Kulti stage and minor Sonapani I and Sonapani II glacial advances in the valley (Owen et al., 1996, 1997). These may be briefly discussed as follows.

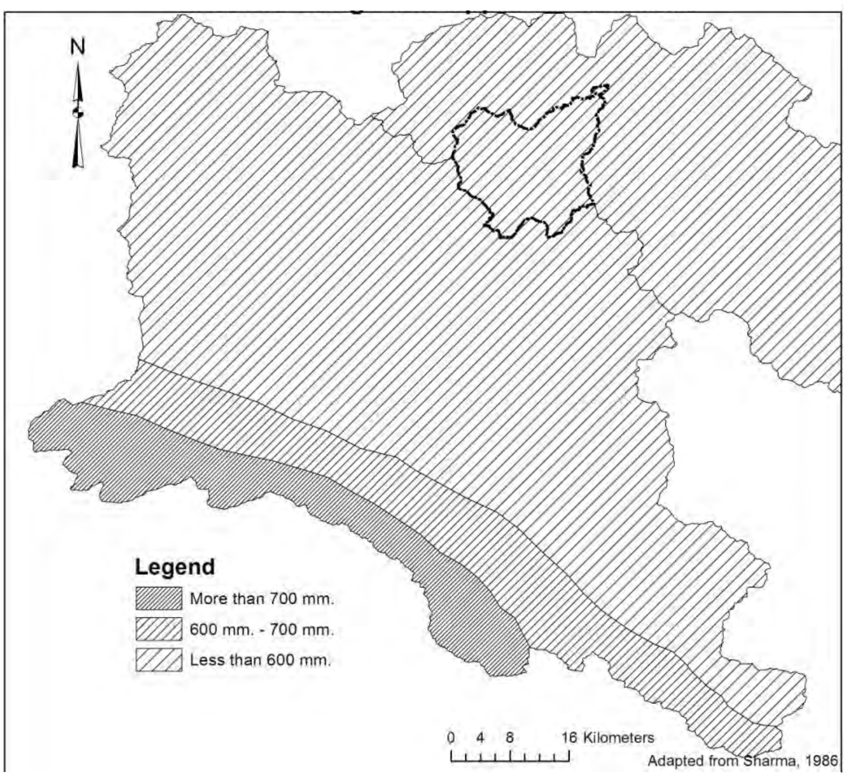


Fig. 19 Precipitation gradient of the Chandra-Bhaga and Yunan valley.

2.5.1.1. Chandra Stage Glacial Advance:

This is possibly the oldest extensive glaciation in this region as far the evidences are concerned (Owen et al., 1995, 1996, 1997, 2001). The trimline of possibly this stage was found between 4,500m and 4,000 m in Chandra and Bhaga valley (Fig. 20) (Owen et al., 1997). Glacially polished[8] and streamlined bedrock benches, roches moutonee, erratic[9], and eroded drumlins, bedrock outcrops at the altitude of >4,300 m asl. are the other evidences of this extensive broad valley type glaciation (Owen et al., 1995, 1996, 1997, 2001). Beside, deeply abraded and well preserved glacial striations, and well developed red brown rock varnish, subduced moraine ridge fragments having well developed vegetation, and an indurated tillite of possibly the Chandra age at Baralacha La (4.930 m asl., Shroder et al., 1993 cf. Owen et al., 1997) etc. also support a broad and shallow valley glaciation which predates the incision of Chandra river to its present level (Owen et al., 1999, 1997). These evidences however, are well preserved near the Chandra Tal (4,314m asl.) and north Dakka glacier. Presently no date is available for this glacial advance in the valley (Owen et al., 2001), although it is believed that the glaciation in this stage was extensive and inundated the local topography, leaving a few of the higher reaches as nunataks (Owen et al., 1997). Rock benches (roches moutonee and whale-back forms) and striations however, trend NW-SE which is in contrast to the N-S trending present valley in the upper reaches (Owen et al., 1997).

The timing and extent of this glacial advance stage, therefore, has not been reconstructed till now because of the inaccessibility of suitable sites for dating. However, the glacially polished surface at Kunzum La which was previously believed to belong to Chandra stage (Owen et al., 1997), the CRN ages indicates that they actually polished (or possibly overridden) during Batal stage (Owen et al., 2001), therefore leaving mystery of this stage of glaciation on in the Lahul Himalaya.

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[8] In the lower Bhaga valley, around keylong, a high level erosion surface at 4,000 m is attributed by Owen et al. (1997) as belong to Chandra glacial advance.

[9] Erratic generally belong to Quartzite, sandstone, and granite.

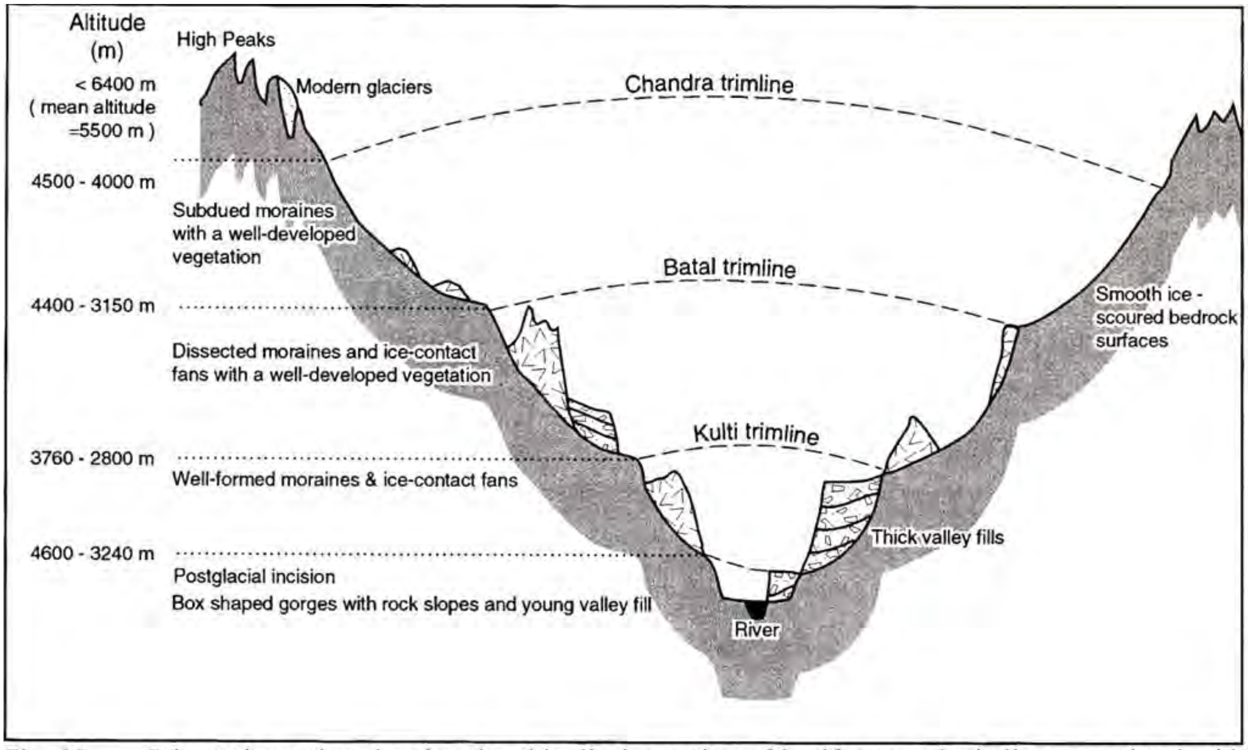

Fig. 20. Schematic section showing the altitudinal zonation of landforms and trimlines associated with different stages of glacial advance in the Lahul Himalaya. The possible palaeo surface and thickness of glacier ice can be inferred from this schematic diagram. Adapted from Owen et al. (1997).

2.5.1.2. Batal Stage Glacial Advance:

The highly weathered and dissected complex assemblage of lateral moraines, well preserved at Batal (4,239 m asl.), and superimposed and small drumlins at Chandra Tal (~4,300m asl.), are the major evidences of the second extensive phase of valley glaciation in the Lahul Himalaya (Owen et al., 1995, 1996, 1997, 2001). Batal stage moraines are found at ~4,000 m asl. to 4,400 m asl. (Fig. 20) and mostly are well vegetated and having less boulders. However, on the basis of the superimposed forms of drumlins[10] and clearly distinguished two

[10] At the Chandra Tal area (~4,300m asl.) the younger and smaller drumlins are often found superimposed upon older, relatively large form of drumlins. These two set of drumlins with variable sizes are possibly formed during two different phases of extensive glacial advance in the Lahul Himalaya.

different phases of moraines, especially on the basis of relative dating criteria, Batal I glacial advance followed by Batal II glacial readvance was previously hypothesized (Owen et al., 1997). However, no dating practice of the two different phases of Batal stage glaciation is conducted till now (Owen et al., 2001). Rather the Batal glacier stage clustered at ca. 12 to 15.5 ka (Owen et al., 2001), which is analogous to the Northern Hemisphere late-glacial interstadial period. The exposure ages on boulders on the crest of drumlins at Chandra Tal area (~4,300 m asl.) range between 11.4±0.8 and 14.0±0.4, which is likely to represent deglaciation times. According to Owen et al., (2001), these lodged boulders are deposited subglacially and exposed only after the glaciers had retreated. The exposure ages of the samples from the glacially polished surface at the Kunzum La area also range between ca. 13.2 and 14.3 ka (Owen et al., 2001). These CRN dates thus, also support that the minimum age distribution of the Batal glacial advance took place during ca. 12 to 15.5 ka. i.e. warmer late glacial interstadial period and the glaciation was extensive as well as thick enough to overtopped the Kunzum range. Some of the similar dates also came from the moraines which belong to Batal stage (Owen et al., 2001). As far these dates, deglaciation of this stage was completed by ca. 12 ka. However, given the thickness of the moraines and the large drumlin fields, and relatively older CRN dates of some moraines (Owen et al., 2001), it can be postulated that the Batal glacial stage may have reached its maximum glacial extent substantially earlier than 15.5 ka. and according to Hedrick et al. (2011) the maximum glacial extent during this period was > 100 km. from the present glacial termini. The inferred Equilibrium Line Altitude (ELA) during this period was probably ~4,000m asl. with 800 m of ELA depression from the present (Taylor and Mitchell, 2000). Hence, the Batal stage glaciation, with possibly two phases of advances (i.e. Batal I and Batal II; Owen et al., 1997), for which no dates are available, was extensive and occurred during late glacial period in the Lahul Himal.

2.5.1.3. Kulti Stage Glacial Advance:

The 3rd glacial stage, well preserved at Kulti valley and also elsewhere in some tributary valleys only, the Kulti stage, does not actually a readvance of previous Batal, but according to Owen et al. (1997) a distinct stage of glaciation with sharp contrast with earlier ones and occurred during the early Holocene i.e. between ca. 10.6 and 11.4 ka. The ^{14}C date from the base of a peat bog also support the similar period of deglaciation by 9160±70 yr BP (Owen et al., 1997). However, this stage of glacial advance was limited within the tributary valleys and also topographically constrained (Owen et al., 1995, 1996, 1997, 2001) as the well preserved and sharp crested lateral and end moraines indicates, especially in the Kulti valley, Kao Rong and Batal valleys (Owen et al., 1996, 1997). The ice extended up to ~12 km beyond the trmini of modern glaciers (Owen et al., 1997) and thickness of the ice was not more than 60 m from the present glacier surface as it appears from the height of the lateral moraines (Owen et al., 1996). The evidence of this stage of glaciation is absent in the main trunk valley in the Lahul Himalaya. The ELA during this stage was possibly at ~4,900 m asl. (Taylor and Mitchell, 2000).

2.5.1.4. Sonapani I and Sonapani II Glacial Advance:

Small sharp-crested moraines within 4.3 km. of the present glacial termini, sparse vegetation, small lichens (<10 m in diameter) and poorly developed rock varnishes sufficient enough to indicates a limited glacial advance (Owen et al., 1996, 1997). This set of moraines is followed by another set of sharp crested moraines within 2.75 km. from the present termini of the glaciers and its attributed to the next phase of minor glacial advance (Owen et al., 1997). The previous one is termed as Sonapani I and the later is termed as Sonapani II glacial advances. The relative dating criteria suggest that the Sonapani I is of Neoglacial in origin (i.e. 4,500 yr BP to Present), whereas on the basis of photographic evidences[11] the Sonapani II advance is therefore, attributed to a late 19th century advance, possibly during the culmination of the Little Ice Age (Owen et al., 1997). However, Owen et al. (1997) also stated a third set of moraines in the Batal valley (~4,239m asl.) inset within the Sonapani II moraines. These form a small end moraine approximately 400m from the present snout of the Batal glacier and may be attributed to 3rd advance or may be recessional moraines. No work has been done on these recent morainic complexes in the Chandra Valley.

2.5.2. Timing and Extent of Glaciation in the Zanskar Range:

There is marked difference in ages of glacial advance between Lahul Himalaya and Zanskar Range and glaciation was not only asynchronous between these two regions but also their extent varies widely along the north and south of the Greater Himalayan range. Taylor and Mitchell (2000), although, follows the names of the glacial stages given by the Owen et al., (1996,1997) for the adjacent Lahul but the glacial stages of the Zanskar do not fit with the refined ages of the Lahul region (Owen et al., 2001), which is based on extensive CRN dates.

[11] On the basis of the photographs published by Walker and Pascoe (1970 cf. Owen et al., 1996, 1997) it can be found that the Sonapani glacier was only a few 100 meters up-valley from the lowest Sonapani II moraines in the 1905 and since then retreated back approximately 2.6 km. It is therefore, attributed to a late 19th century advance, probably the culmination of the Little Ice Age (Owen et al., 1997, 2001).

Hence usage of the same terminologies creates problems when correlating the glaciation style and timing of these two adjacent regions. At the same time the recent numerical dates provided by Hedrick et al. (2011) for the Karzok valley of Zanskar range correlate well with the dates already given by Taylor and Mitchell (2000). Therefore, it is clear that although use of similar names create problem in correlating glacial timing and extent, but the glacial stages by Taylor and Mitchell (2000) for the Zanskar is confirmed by more than one study. Hence to reduce the confusion and better correlation, here different names are used along with the original names used by Taylor and Mitchell (2000) for this region.

Taylor and Mitchell (2000) have, so far, recognized three glacial stages and a minor advance in the region. They are –

2.5.2.1. Chandra Stage Glacial Advance or Zanskar 1:

2.5.2.2. Batal Stage Glacial Advance or Zanskar 2:

2.5.2.3. Kulti Stage Glacial Advance or Zanskar 3:

2.5.2.4. Sonapani Minor Glacial Advance or Zanskar 4:

They are briefly discussed as follows:

2.5.2.1. Chandra Stage Glacial Advance or Zanskar 1:

Possibly the oldest and extensive broad valley glaciation in this region is the Chandra Stage glaciation (Zanskar 1). Palaeo surface remnants at ca. 200 to 300m above the present river bed and associated augen gneiss erratic at high surfaces in the Yunan basin, Sarchu plain, down up to >100 km. along the main valley (Taylor and Mitchell, 2000) are the major evidences of this stage of extensive glaciation although their ultimate limit and timing still not precisely known. The Sarchu mountain, above the presently studied site 2, is a broad surface at an altitude of ~5,200 m asl. and is possibly glacially polished (Taylor and Mitchell, 2000). However, Taylor and Mitchell (2000) also talked about the carbonate-rich matrix, the erratic clast content, edge rounding, faceted glacial shape of clasts etc. which possibly belong to Zanskar 1 stage, but betray the glacial origin, as far their interpretation. According to them this is probably due to resedimentation. Similar matrix characteristics have also been observed from the present drumlins exposures (Exposure 1 and Exposure 2; see the section 6.2) at the Yunan basin (4,448 m asl.) and may possibly have some linkages among them.

2.5.2.2. Batal Stage Glacial Advance or Zanskar 2:

The second most important but relatively confined glacial advance took place during the Batal stage (Zanskar 2). Glaciers during this stage emanated basically from the two most elevated areas i.e. High Himalaya in the south and the Nimaling massif in the north (Taylor and Mitchell, 2000). Broad U-shaped valley with much of filling followed by V-shaped narrow rock gorges with only local filling is possibly the major evidence of this stage of valley glaciation and marked the lower limit as well (Taylor and Mitchell, 2000). Subdued moraines and associated landforms also accompany this change in some of the valleys (Taylor and Mitchell, 2000). Besides, the subtle changes in the valley floor width (increasing from 100 to 200 m to >500m.) and decrease in the angle of the valley (up-valley) (from 70° to vertical to 40°-50°) northern conglomerate valley, alluvial terraces (paraglacial) and erratics also indicate the limit of this stage of glaciation. Other evidences of Zanskar 2 glaciation include the impressive kame terraces and lateral moraines with large and deeply weathered gneiss erratic at Padam (3,600 to 3,700 m asl.), and a large moraine on the northeast side of the Kurgiakh river (3,980m asl.) etc. (Taylor and Mitchell, 2000). Other valleys also have similar but dissected moraines. However, in terms of numerical dates, the tentative TL dates from the loessic deposition on the Padam kame terrace come around 50 to 70 ka. (Taylor and Mitchell, 2000), whereas around Reru village (3890 m asl.) where the bed rock gorge creation provided the excellent preservation of moraine ridges (some of which also cross-cut each other), the lacustrine sediments indicates the OSL dates of ~78.0±12.3 ka BP and 40.0±9.3 ka BP[12] (Taylor and Mitchell, 2000). Given the location and the sediment type (lacustrine sediment), it thus can be inferred that prior to this time the Zanskar 2 glaciation was at its maximum extent. During this stage the ΔELA was ~500m; ELA was possibly ~5,000m asl., compared to the present ~5,500m asl. (Taylor and Mitchell, 2000).

2.5.2.3. Kulti Stage Glacial Advance or Zanskar 3:

The glaciation during this stage was much more restricted and confined to high tributaries only leaving the main valley and many other tributary valleys ice free (Taylor and Mitchell, 2000). Ridges and mounds of Zanskar 3 (Kulti glaciation) stage, however, are well formed at few places and found as inset chevron ridges up-in some valleys. At other places these ridges are partially modified by fluvial erosion. In the Yunan basin (i.e. Upper Tsarp basin) these moraines are possibly buried beneath sandur and paraglacial (debris cones, alluvial fans, talus and scree etc.). However, the OSL dates from fluvio-glacial sediments from the moraine complexes

[12] Taylor and Mitchell (2000) have place lesser confidence in the age— ~40.0±9.3 ka BP, because of high degree of Scatter (33%) along the dose curve.

associated with maximum glacier position in Yunan and Markha valleys, give age estimates of 16.2±5.6 and 12.2±4.8 ka BP (Taylor and Mitchell, 2000). Two further age estimates are given from a recessional landforms close to the palaeoglacier maximum position, which comes at 13.1±4.9 ka and 10.2±2.1 ka BP (Taylor and Mitchell, 2000). Taylor and Mitchell (2000) interpretated these dates as close to Global LGM, although admitted the fact that the true ages may lie younger than Global LGM. Owen et al. (2002) criticized Taylor and Mitchell (2000) and stated that the timing of Golbal LGM was 18-23 ka and that the Kunzum 3 (Kulti stage) glacial advance took place during the last glacial interstadial. It is also required to mention that the morainic complex or mounds, in the Yunan basin, of Taylor and Mitchell (2000), possibly may denote the drumlins studied so far in this paper. The absence of locational and altitudinal data of the sample sites in Taylor and Mitchell (2000) makes it difficult for direct comparison. However, the timing of glaciation in the Lahul Himalaya (the Batal glacial advance) associated mostly with the drumlin formation, supports the view that possibly during the same time i.e. the late glacial interstadial, ice might also flowed in to the Zanskar range, especially at the Yunan valley, north of Baralacha La (4,930m asl.), and might extended enough to form the drumlins or the drumlins of the Yunan valley are much younger in age as the recent ages of the drumlins at the Milang valley suggests and may distinctly different from the timing of drumlin formation in the Chandra valley. Without controlled numerical dates the correlation is unsatisfactory and is not establishedin the present paper, but tentative age limit can be suggested. Similarly it is to be kept in the view that the Zanskar dates are OSL dates (Taylor and Mitchell, 2000), whereas the numerical dates of Lahul are CRN (Owen et al., 2001). Unlike OSL method of numerical dating CRN dating method indicates the minimum age distribution. Hence, great care must be taken while comparing these two sets of dates; but from the interpretation of Hedrick et al. (2011) is can be assumed that the age difference is within the comparable limit. During the Zanskar 3 (Kulti) glacaial stage, however, the ELA was possibly at ~5,200 m asl. (Taylor and Mitchell, 2000).

2.5.2.4. Sonapani minor Glacial Advance or Zanskar 4:

The fourth and minor glacial advance in the Zanskar range was named by Taylor and Mitchell (2000) as the Sonapani (Zanskar 4) advance. Sharp crested morainic ridges of this advancement, is found within less than 2 km from the present glaciers. The morainic ridges are generally 5-10 m in height except the two glaciers at the head of the Nimaling plain, which border the tributary glaciers and more than 100m in height (Taylor and Mitchell, 2000). However, these moraines in few places indicate complex assemblage. No numerical dates are given yet, although according to Taylor and Mitchell (2000) they possibly belong to Little Ice Age (LIA).

Apart from the above glaciation chronologies of the Zanskar range, Damm (2006 cf. Hedrick et al., 2011) further extended the glacial chronology of this region using geomorphic evidences, and recognized eight glacial advances in the Marka valley and northern Nimaling mountains. These glacial advances from oldest to youngest couple with the possible ELA depression (ΔELA) during these respective advances are: the i) Skio I (ΔELA- >1,000m), ii) Skio II (ΔELA- >1000m), iii) Chaluk (ΔELA- ~670m), iv) Hankar (ΔELA- ~510m), v) Nimaling I (ΔELA- ~400m), vi) Nimaling II (ΔELA- ~350m), vii) Gapo Ri I/Dzo Jongo I/ Kang Yaze (ΔELA- <70m), and viii) Gapo Ri II/Dzo Jongo II/ Tasken Ri II (ΔELA- <70m) (Damm, 2006 cf. Hedrick et al., 2011). Recently numerical dates (TCN dates) are also given for the Karzok and

Puga valleys (Hedrick et al., 2011) which flank the southern Zanskar range. While the dates at Karzok valley corroborate largely with the dates already provided by Taylor and Mitchell (2000), the dates for the adjacent puga valley differ in many respect. It has also been found that no early Holocene glacial advances occurred in both the Karzok and Puga valleys of Zanskar range and is in sharp contrast to not only the adjacent Lahul Himalaya, but to other areas of the Himalayas as well. This also increases the importance of developing the numerical dates of drumlin formation in the Yunan valley which if comes much younger, will certainly contribute hugely in reconstructing the glaciation chronology of the valley or otherwise is believed to strengthen the already present chronological base.

2.6. Palaeoenvironmental Implication of Glaciation in the Study Area and Their Importance to Present Study:

The changing nature and timing of glaciation during the late Quaternary in the Himalayas, is now considered as a regular feature. The timing of glaciation was mostly asynchronous over time and space across the entire stretch of the Central Asian high relief realm. However, they are closely linked with palaeoclimatic conditions during the period of glaciation and largely driven by the climatic interplay between the Indian summer monsoon (southwesterly) and winter mid-latitude westerlies. Couple with the palaeoclimate, tectonic uplift of the Tibetan plateau in China and the Pir Panjal range in the Himalayas, and their possible influence in determining global climate in general and regional climatic gradient in particular, also has tremendous bearing in determining the nature of glaciation and the landscape evolution in this abode of god—the Himalayas. Equally significant is the role played by topography of these mostly rugged mountains in constraining glaciation of younger times over the late Pleistocene and Holocene. This fact leads Derbyshire (1996) to conclude that although *"Ice extent may have progressively decline with increasing contrasts on glaciation limits through time, but the total ice volumes during glaciations may have shown less variation as valley systems enlarged in the conditions of qusi-balance between uplift and incision"* (pp-147). However, the volumetric analysis is rarely done until now in the Himalayas and requires further understanding about the nature, timing and extent of glaciations over period of time, although it is clear from the above discussion that climate, tectonics, and topography, in one way or the other, play a tremendous role in determining the nature, timing, and extent of glaciation in this high relief realm. Following points can be conceptualized in this context.

i) The glaciation becomes less extensive over time and with progressively increasing aridity, in general, in the Himalayas, Karakoram, and Tibetan Plateau during the Quaternary (Owen et al., 1996). During the late glacial (~16-14 ka) period glaciers only advanced few kilometers from their present positions in the Transhimalaya, whereas the Lahul Himalaya experienced extensive broad valley glaciation which extended more than 100 km. from their contemporary position (Hedrick et al., 2011; Owen et al., 2001). During the Zanskar 3 (Kulti) stage glacial advance which is analogous to late glacial interstadial advance in the Lahul, only restricted glacial advance had experienced in the Zanskar valley; especially evidences are preserved in the tributary valleys rather than in the main valley. According to Hedrick et al. (2011) also during the same period very restricted glacier advance (only a few kilometers) can be found in Ladakh range. Similarly, unlike Lahul Himal and many other parts of the world, Ladakh and Zanskar ranges do not actually consist any evidence (till now) of early Holocene glaciation (Hedrick et al., 2011), further pointing the abrupt geographical transition of glaciation in this dynamic region. But if the formation of drumlins in the Yunan valley is found analogous to the drumlin formation in the Milang valley i.e. ~4ka (suggested by M.C. Sharma), then a younger stage of glacial advance can be postulated for the Yunan valley of Zanskar as well and this may remodify the existing knowledge base.

However, when comparison between the timing of maximum extent of glaciers is done across different parts of the Himalayas, and Transhimalaya (and Tibetan Plateau in Fig. 21) based on the existing literature, it is found that maximum dated glacial extent took place during 12 to 16 ka (Late glacial Batal stage) in the Lahul (Owen et al., 2001; Hedrick et al., 2011), whereas the maximum extent in the Zanskar range occurred during ~40 to 78 ka (i.e. during MIS 3 and MIS 4[13] (Mitchell et al., 1999; Taylor and Mitchell, 2000); in Garhwal (The Central Himalaya) maximum extent occurred at 63 ka (Sharma and Owen, 1996; Derbyshire and Owen, 1996; Owen et al., 2001); and in Swat Kohistan and Nanga Parbat region it occurred during 35-65 ka (i.e. MIS 2) (Derbyshire, 1996; Derbyshire and Owen, 1996; Owen et al., 2001). Hence, Lahul is the only sharply contrast area from the rest in terms of presently available numerical dates , which exhibit extensive late glacial advancement, incomparably more than 100 km from the present glacier's termini. In contrast, according to Owen et al. (2006 cf. Hedrick et al., 2011), glacial advances was ~15 km from the present glaciers during the past ~130 to 200 ka in the Ladakh range. In Zanskar during the past 100 ka, the maximum glacial extent was ≥10 km. from the present glacier margins. These data further increases the curiosity of studying this transitional area in detail in order to reconstruct the palaeo environmental condition which stimulate

[13] Marine Oxygen Isotope Stage 3 and Marine Oxygen Isotope Stage 4.

extensive glaciation in this area in late glacial time, and the development of massive drumlin streamlined forms, which otherwise cannot be found in adjacent areas in the same time frame.

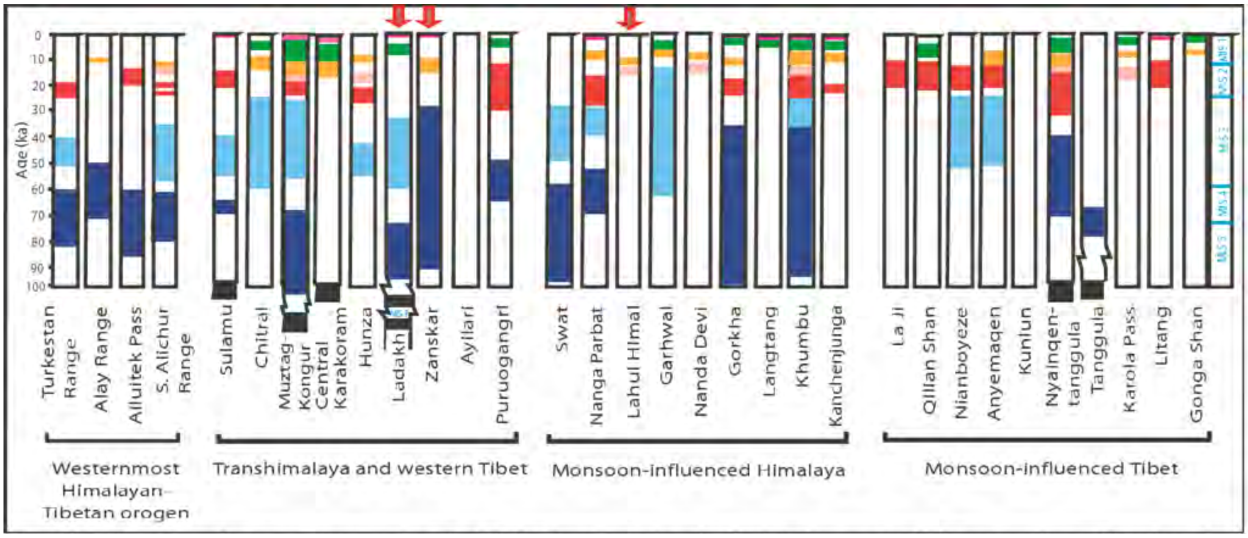

Fig. 21 Thecolour bars are representing the likely duration of each glacial advance in their respective valleys based on the best estimate of the ages of moraines presented in the original publications. A tentative correlation is suggested by applying similar colours to the bars (expected from Owen et al., 2005, and data from Shiraiwa, 1993; Sharma and Owen, 1996; Phillips et al., 2000; Richards et al., 2000a,b; Owen et al., 2001; 2002a,b, 2003a,b,c, 2005, 2006a,b; Schafer et al., 2002; Tsukamoto et al., 2002; Yi et al., 2002; Finkel et al., 2003; Zech et al., 2003, 2005; Barnard et al., 2004a,b, 2006a,b; Meriaux et al., 2004; Spencer and Owen et al., 2004; Chevalier et al., 2005; Abramowski et al., 2006; Colgan et al., 2006; Seong et al., 2007, 2008a—cf. Owen et al., 2008). Marine Isotope Stage (MISs) are taken from Martinson et al. (1987 cf. Owen et al., 2008) and Shackleton et al., (1990 cf. Owen et al., 2008). Present areas of interest are marked as red down arrows. Adapted from Owen et al. (2008).

ii) The Lahul Himalaya, as mentioned previously, is a transitional zone in the northwestern Himalaya between the monsoon influenced Pir Panjal and the high altitude desert areas of the Higher Himalayas, Transhimalaya, and Tibetan plateau (Owen et al., 1995, 1996; Derbyshire and Owen, 1996). While there is no ambiguity regarding the Cenozoic uplift of the Himalayas and Tibetan Plateau and their possible role in stimulating global climate, their magnitude of influence is still greatly debated (Derbyshire, 1996). Tibetan plateau (Qinghai-Xizang) being a high relief (~5,000 m asl.) elevated area, acts as a major stimuli in operating the high level streams of Westerlies and easterlies (Fig. 18) and this upper climatic system in general determines the climatic gradient of this region (Fig. 22). The reconstructed ELAs in Lahul, Zanskar and Ladakh also support the view, along with glacial timing and extent across these areas that the similar climatic gradient also persists in the past. And according to Owen et al. (2002) and Owen's (2009) interpretation it is possibly that during the insolation maxima (i.e. warmer late glacial interstadial time i.e. 12 to 15.5 ka) the South Asian summer monsoon strengthen and resulted into increased precipitation as snow, and consecutive positive glacial mass balances over sufficient period of time, especially in the Lahul Himalaya. This increased the albedo, weathering rates and associated meltwater fluctuation (Derbyshire, 1996; Derbyshire and Owen, 1996). Ice possibly thus, achieved a greater thickness to overtop Kunzum La and flew down valley for more than 100 km. Ice in the Yunan valley also possibly extended extensively during the same time period or may be at much younger time of ~4 ka. Since no numerical dates are available for comparison, tentatively it can be proposed that the drumlins of site 2 have formed during the late glacial to historical time. Hence this time frame is very much critical and needs much better understanding, especially in the light of palaeoclimatic condition and extensive valley glaciation, and consequent drumlin formation in the study area (Lahul and Zanskar region). The study made by Shi et al. (2001 cf. Hedrick et al., 2011) also supports that during the late Quaternary the South Asian summer monsoon at times increased in intensity and possibly contributed 40-100% more precipitation than today. Hence this '*Pluvial Period'* in the in the Lahul Himalaya and adjacent regions retains the key to many of the palaeoclimate related questions in this regions. The late glacial extensive glaciation largely negate the possibility of rapidly uplifted Pir Panjal range in the south in defining the glaciation characteristics in this region, although orographic influence undoubtedly must have had pronounced impact.

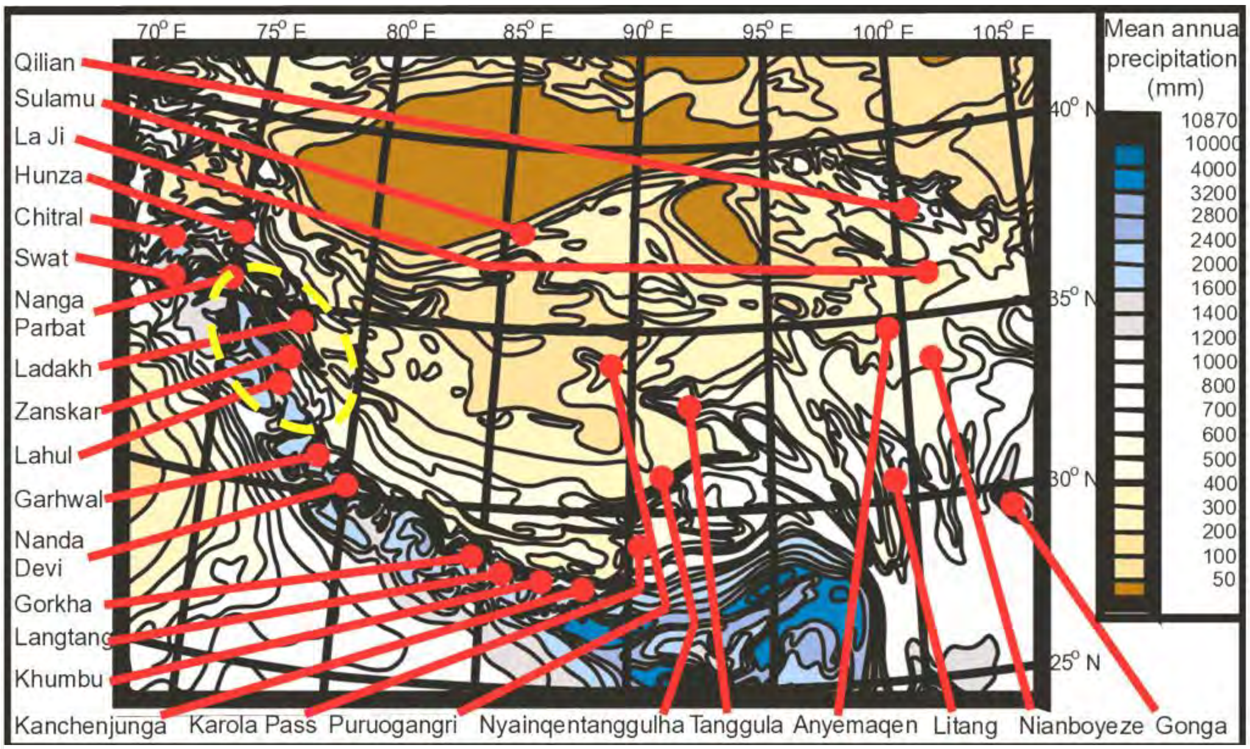

Fig. 22 The map is representing the distribution of contemporary mean annual precipitation (precipitation gradient) across the Himalayas, Trans Himalaya, and Tibetan Plateau. The red dots highlight the regions where TCN surface exposure dating has been undertaken originally by Owen et al. (2008). Here they are circled (dashed yellow) to highlight the present study area. Adapted from Owen et al. (2008).

iii) Despite apparent diversity in the estimates of ELA depression and large disagreement[14], for the last glacial maximum, it is still widely used even for the Himalayan and Transhimalayan mountains. ELA is sensitive to perturbation in the

[14] Large disagreement exist regarding the use of ELAs for the entire Himalayas and Transhimalaya because of extreme topographic control, micro-climatic variability, low preservation of former ice limits, very thick supraglacial debris cover (Owen and Benn, 2005; Owen et al., 2002; Taylor and Mitchell, 2000), avalanche feeding of glaciers (firnkessel type) (Benn and Owen, 1995) and also due to the use of different methods (Sharma and Owen, 1996) and different individual (Derbyshire, 1996). These limit the use of ELA in this high mountain realm.

climate; hence ELA reconstructions provide the potentiality to quantify the palaeoclimate as well as former precipitation gradient and moisture and moisture sources along with atmospheric circulation patterns (Taylor and Mitchell, 2000). According to Derbyshire (1996) the ELA depression values for the Northwest Himalaya, Greater Himalaya, and Swat Kohistan tend to cluster in the range 800-1000m., leaving individual diversities apart. Shi et al. (2000 cf. Owen and Benn, 2005) have already given the ELA depression pattern for the entire Himalayas, Transhimalaya, and Tibetan Plateau during global LGM, which also indicates similar pattern of ELA depression as discussed above (Fig. 23). Although, Owen and Benn (2005) have cautioned about the use of these ELA depression values, but according to them although these ELA depression values are incorrect, the distributional pattern of variation remained more or less realistic in this High mountain realm. Similarly, Taylor and Mitchell (2000), using '*Toe-Headwall-Altitude-Ratio*' (THAR) of both 0.4 and 0.5, have found a rise in ELA from the southwest i.e. Pir Panjal to northeast i.e. the High Himalayas and Zanskar, which again dip to the Indus valley for both Batal and Kulti stage glacial advance. Since there is age confusion related to the Lahul Himalaya and Zanskar range, hence they can't directly compared using Taylor and Mitchell's (2000) ELA or GEI (Glacier Elevation Index) values but the broad pattern possibly remains the same. The present ELA values indicate ~4,800m asl. in the southwest to ~5,500m asl. in the northeast, agreeing well with the maps of the Climatic snowlines (Fig. 24) (Taylor and Mitchell, 2000). However, during Batal stage (12 to 15.5 ka) the ΔELA was ~800 m from the present, and during Kulti stage (10.6 to 11.4 ka.) the ΔELA was possibly ~300 m from the present in the Lahul

Himal (Taylor and Mitchell, 2000; Owen et al., 1997). On the other hand in the Zanskar, the ΔELA ranges between ~500 m. to 300 m. during Zanskar 2 and Zanskar 3 glacial advances, respectively (Taylor and Mitchell, 2000). Zanskar 3 advance is possibly analogous to the Batal advance in the Lahul Himalaya. According to Burbank and Fort (1985 cf. Derbyshire, 1996) the ELA depression (ΔELA), however, in the Ladakh range appear to have been ~400m lower than the adjacent Zanskar range and this is also supported by Taylor and Mitchell (2000). Taylor and Mitchell (2000) interpretated this is probably due to channeling effect of westerly depression in the Indus valley region (Owen and Benn, 2005). Hence broadly speaking, as far these evidences the regional climatic transition and sharp precipitation gradient possibly remains similar during in the late Quaternary time as well in this broad region with gradually older evidences of extensive glaciation northwards and very limited late glacial advance in the both Ladakh and Zanskar region. The Lahul, although, remains as a puzzle because of its very extensive glaciation during the

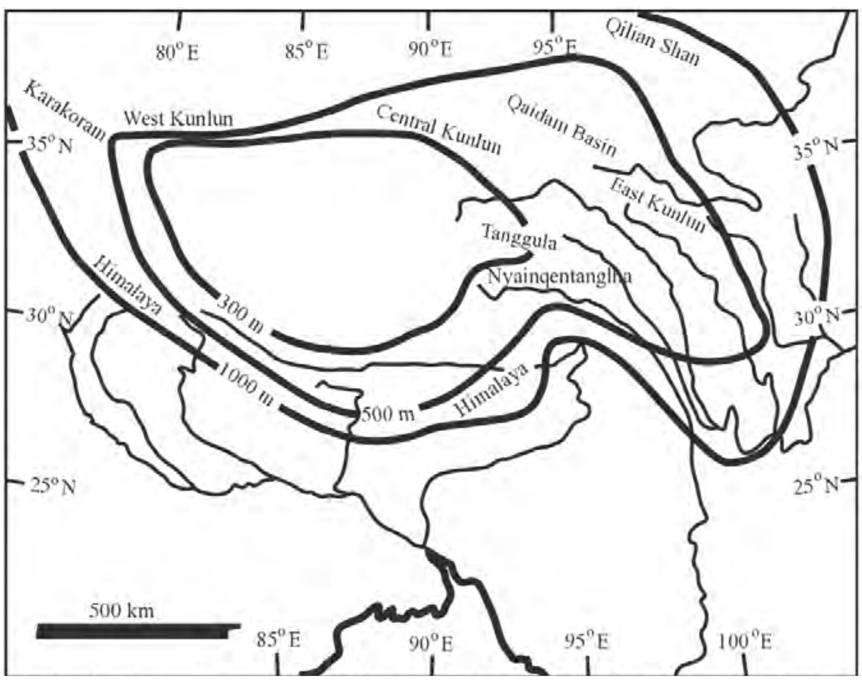

Fig. 23 Map showing the Equilibrium Line Altitude (ELA) depression for the Global LGM across the Himalayas, Trans Himalaya, and Tibetan Plateau. According to Owen and Benn (2005) although the ΔELA values are probably not correct, the general pattern of variation is probably realistic. Adapted from (Shi et al., 2000 cf. Owen et al., 2005; and Shi, 2002 cf. Owen et al., 2005).

late glacial interstadial. The evidences of extensive glaciation in the Yunan valley during the same period or younger time also needs to be proved with the use of numerical dates and only then the puzzle can possibly be solved to a certain extent.

Fig. 24 Map showing the contemporary regional snowline (ELAs) variation across the Himalaya, , Trans Himalaya, and Tibetan Plateau. Adapted from Benn and Owen (2005).

However, the analysis of these three points thus indicates that the landscape evolution in the Lahul Hiamalya is very much rapid and mostly has been taken place after deglaciation. Although the glacial landforms are well preserved in the main valley and mostly in the tributary valleys, this allows the glacial history of this region to reconstruct. The tectonic uplift and exhumation does play some role through orographic influence, weathering and geomorphological processes, but the evidences mostly point to the strengthening of the Indian summer monsoon during insolation maxima as the major driving force of landscape evolution. Topography did play a major

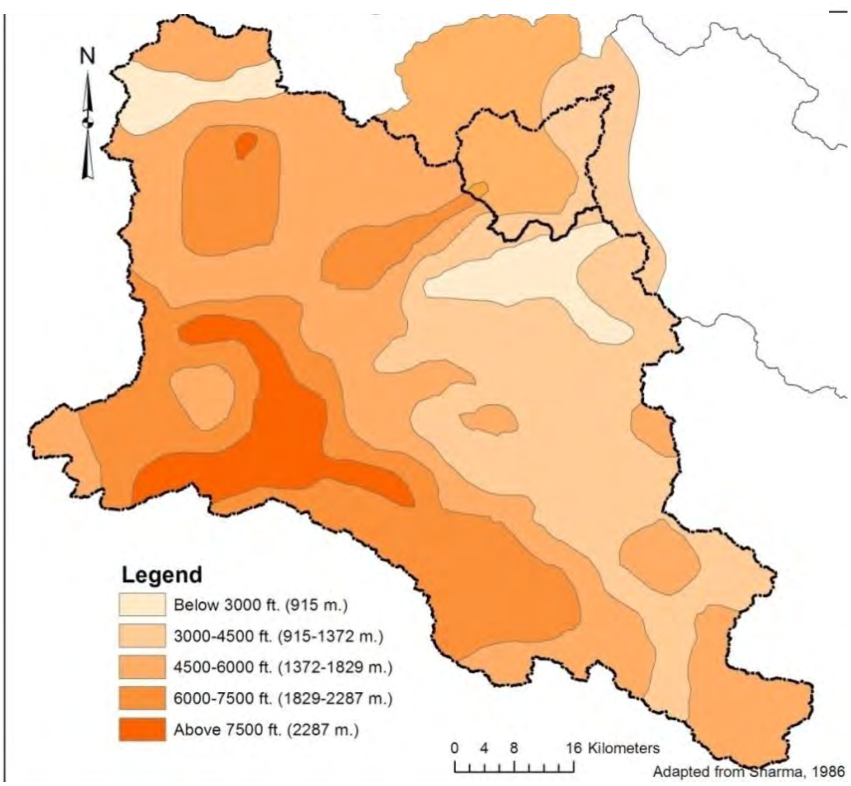

Fig. 25 Relative relief distribution in the Chandra-Bhaga, and Yunan valleys.

role but they are more relevant in the younger phases of glacial advances in this region which were topographically more restricted and allowed negative feedback[15] to operate along with. However, much better understanding is aimed through the detail study of the drumlin in this region which may provide some more meaningful insight of the palaeoclimatic condition during their formation. Since drumlins are large subglacial landforms and mostly formed beneath the former ice-sheet covered areas, dynamic subglacial processes alongside favourable topographic condition and thick ice cover etc. are the perquisite for their formation. How well the present study fits into this framework will decide the viability of studying *"drumlins in the Himalayas"*.

2.7. Physiographic Setting of the Study Area and their Relevance in the Present Study:

The Chandra-Bhaga basin of the Lahul Himalaya and Yunan basin of the Zanskar range are physiographically very diverse and complex at the same time. High mountain summits (>6,000m asl.), rugged topography, spatially variable incision-aggradation activities, both extensive periglacial and paraglacial activities, and large seasonal snow cover and gullies and ephemeral streams characterize the physiography of the study area. Already a great deal of the physiographical attributes is covered in detail by Sharma (1986) and Kumar (2003) in their dissertations. So only the relevant points are discussed here.

This is one of the high **(absolute) relief** country of the Himalayas and Transhimalaya with average height of both the Chandra-Bhaga valley and Yunan valley is >3,000m asl. in general to 4,900m asl. at the Baralacha La. More than one third of the area is fallen between

[15] The negative feedback operates as confined glaciers lead to less surface are for albedo and less reflection as well as more supraglacial debris accumulation. They consequently increase the temperature regime and couple with Late Quaternary relatively drier climate, augments more restricted glaciation (Derbyshire, 1996; Derbyshire and Owen, 1996).

3,000 to 4,500m asl. height, whereas two third is confined between high altidunal areas of 4,500m asl., and 6,000m asl. (Kumar, 2003).

The **relative relief** map (Fig. 25) (i.e. Highest-Lowest elevation) of the area, however, indicates very low to moderately low relative relief in the study sites i.e. near the Chandra Tal area (site 1), Kunzum la (site 3), and in the Yunan valley (site 2). The relative relief increased downstream of both Chandra and Bhaga indicating greater fluvial incision in this part in contrast to the relatively less dissected areas upstream.

The **slope** of the study area is also shown in the Figure 26.a. It is generated from Bhuvan Cartosat 1 Digital Elevation Model (DEM) data. Apart from the complexities, few general characteristics can be extracted. These are—the site 1, site 2, and site 3 of the study area (Rectangular areas in the Fig. 26a) generally indicates gently sloping ground, with mostly 0° to 20° slope angle, along with broad valley aspect (Fig. 26b and Fig. 26c). Both the upper Chandra (~4,300 m asl) (Fig. 27 c) and Yunan valley (~4,450 m asl.) (Fig. 26b) possess ≥100m. of broad flat valleys, just after few kilometers distance of confined valleys in the upstream section. The opening of the mouth of the valleys is clear from three dimensional terrain diagrams (Fig. 26b and Fig. 26c) and form the slope map (Fig. 26a) of the study area, especially where drumlins are identified and mapped (site 1, site 2, and site 3). Rather than **aspect** (Fig 27), it seems that the contemporary glaciers are more responded to the general climatic gradient of the region (Fig. 19), which shows increasing aridity north-westward and the more restricted type of glaciers.

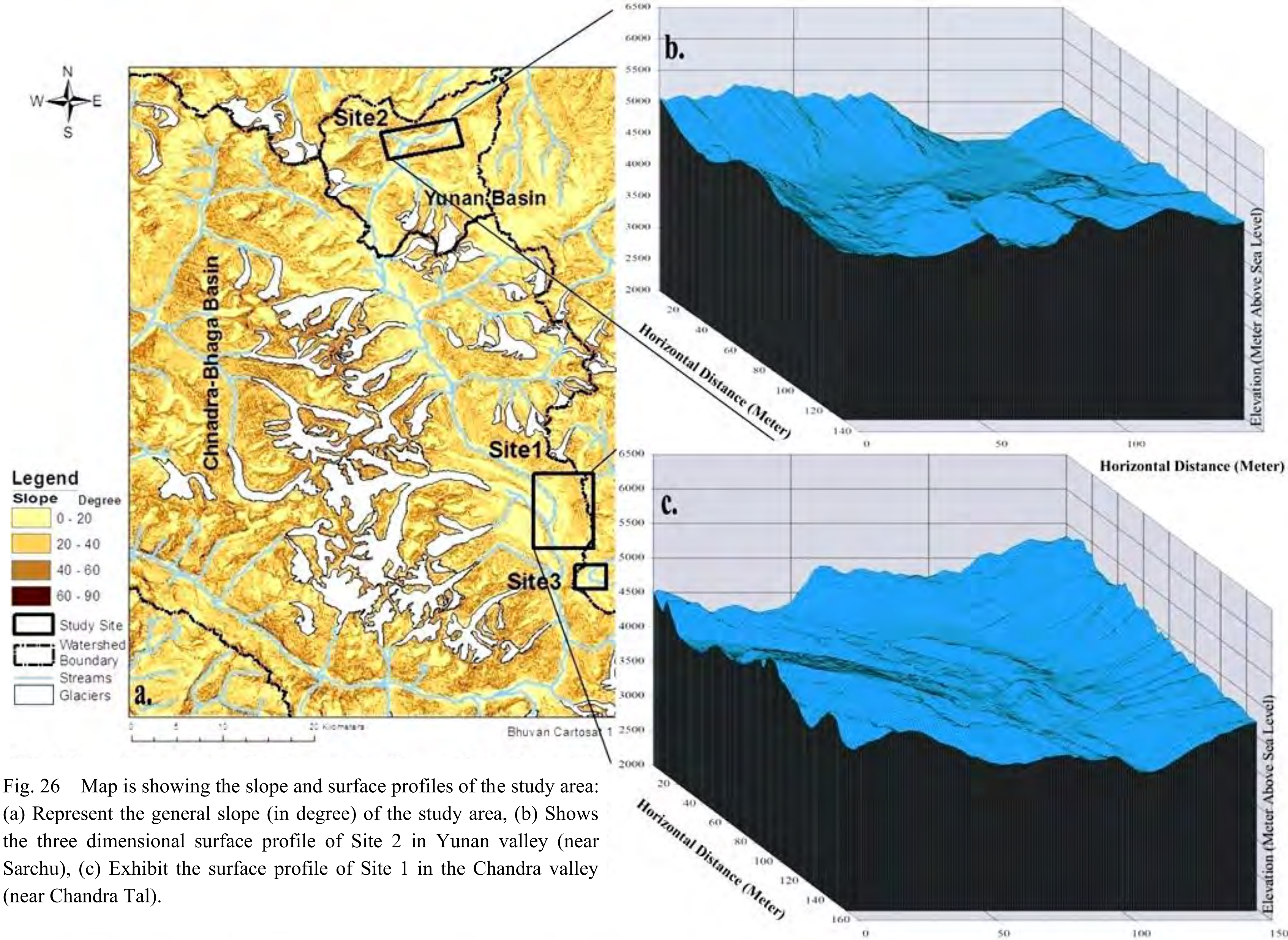

Fig. 26 Map is showing the slope and surface profiles of the study area: (a) Represent the general slope (in degree) of the study area, (b) Shows the three dimensional surface profile of Site 2 in Yunan valley (near Sarchu), (c) Exhibit the surface profile of Site 1 in the Chandra valley (near Chandra Tal).

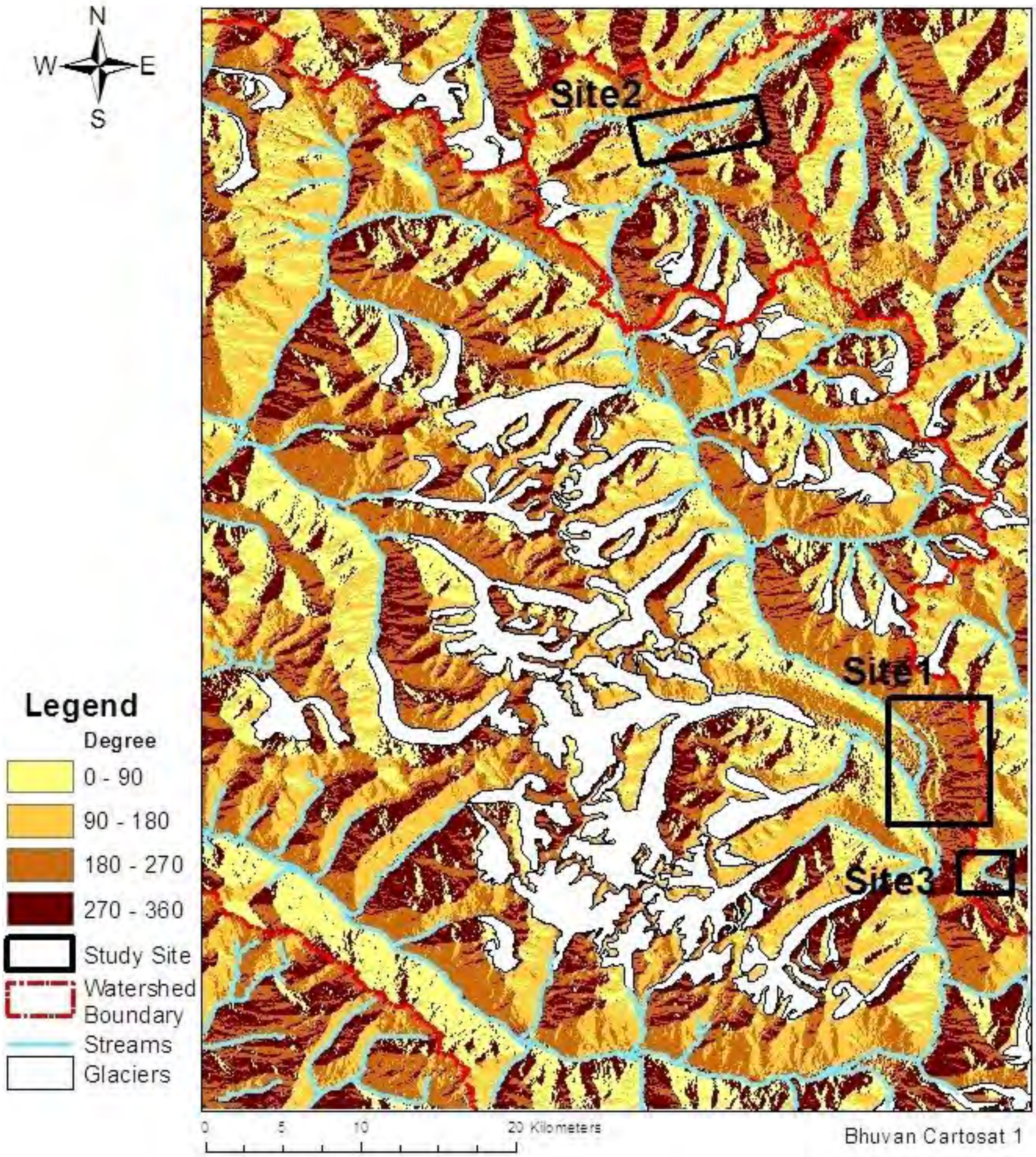

Fig. 27 Map showing the aspect of the study area.

Three main rivers viz. Chandra (with ~138 km. length up to Tandi), Bhaga (with ~60 km. length up to Tandi), and Yunan (with ~30 km. length up to the confluence with Tsarap Chu), characterize the **drainage** of the region; with a number of dissections also occur due to the ephemeral streams and gullies. The Chandra-Bhaga river has more than 150 tributaries (Kumar, 2003) in the basin and according to 1:250,000 topographic sheet the river is a third (stream) order basin (using Strahlar method). However, the average fall of the Chandra River is 12.5m per km., whereas that of the Bhaga River is 28m. per km. (Sharma, 1986). The number of impressive gorges at the Bhaga valley tells why the fall of the Bhaga river is more than the river Chandra. It is also because of the fact that the Chandra valley is more flat and gentle-broad valley type, especially in the upstream section (Fig. 26), unlike the narrow Bhaga valley with relatively higher Gradient (Fig. 26a). Trellis drainage pattern is the characteristic pattern of the structurally adjusted drainage system—Chandra and Bhaga. Both the **drainage density**[16] (Fig. 28) and **stream frequency**[17] (Fig. 29) maps, however, indicate that the moderate density and frequency prevail in the study sites. This is possibly because few of ephemeral streams dissect the area, like for example, the streams flowing from the Chandra Tal and adjacent western flanks of Kunzum range around the Chandra Tal (4314m asl.). Detail description of these maps is given in Kumar (2003). Since these physiographic characteristics do not show any significant linkage, hence only glimpse of them is discussed here.

The study area generally lacks well developed **soil types**. Figure 30 shows the distribution of three major soil types. They are entisols, histosols, and mollisols (Sharma, 1986). The **land-use and land-cover** pattern also indicates (Fig. 31) mostly barren wasteland cover

[16] Drainage Density (DD) is calculated as, DD= ΣL/A, where ΣL = the total length of all the segments of the stream in a region, and A= the area of the region (Kumar, 2003).

[17] Stream Frequency (SF) is calculated using Horton's method (1945 cf. Kumar, 2003) as, SF = N/A, where N= number of streams in an area, and A= area.

with mostly small flowering herbaceous plants and grasses and lichens at the upstream areas. Well developed scrubland, and arable land coupled with scattered (and planted) forest patches generally develop in the downstream areas of Chandra and Bhaga rivers. Yunan is mostly uncultivated and wasted (barren) land.

The notable **flora** in this study area are Blue Pine, Bird Cherry, Walnut, Juniper, Woody nut, Spruce Fir, Silver Fir,, Willow (Kangra district Gazetteers, 1917) and mostly herbal species, grasses and flowering species at the high altitudes (Kangra district Gazetteers, 1917; Chauhan et al., 2000). The forest cover also indicates the climatic gradient in this region both latitudinally and altitudinally. For example, according to Owen et al. (1995, 1996) the southern slope of the Pir Panjal is densely forested with thick cover of Juniperus, Pinus, Betula, Salix, Populus, Picea, and Pyrus, whereas the north of it being a precipitation shadow zone, has <16 percent of the total area under forest (Fig.43) with major dominance of scrubs, grasses, and alpine plants. Altitudinally, the area between 2,450m asl. and 3,550m asl. possess mainly those forested plants discussed above, followed by the area between 3,550m asl. and 4,850m asl. where alpine vegetation including rhododendron as shrubs can be found (Owen et al., 1995, 1996). The area above this only contains lichens and few flowering species.

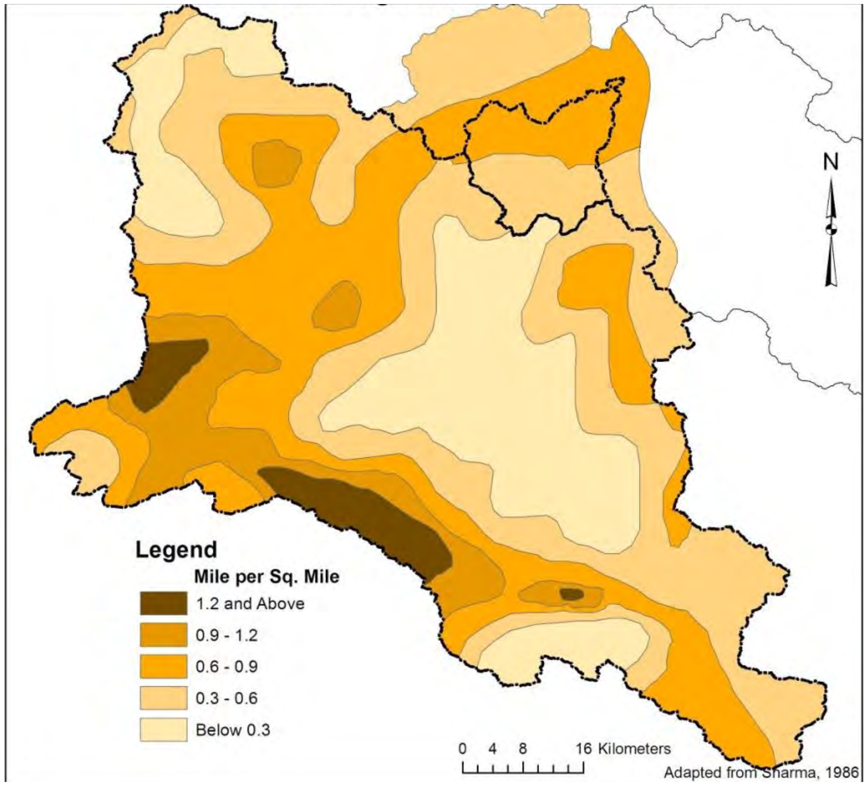

Fig. 28 Drainage density distribution in the Chandra-Bhaga, and Yunan valleys.

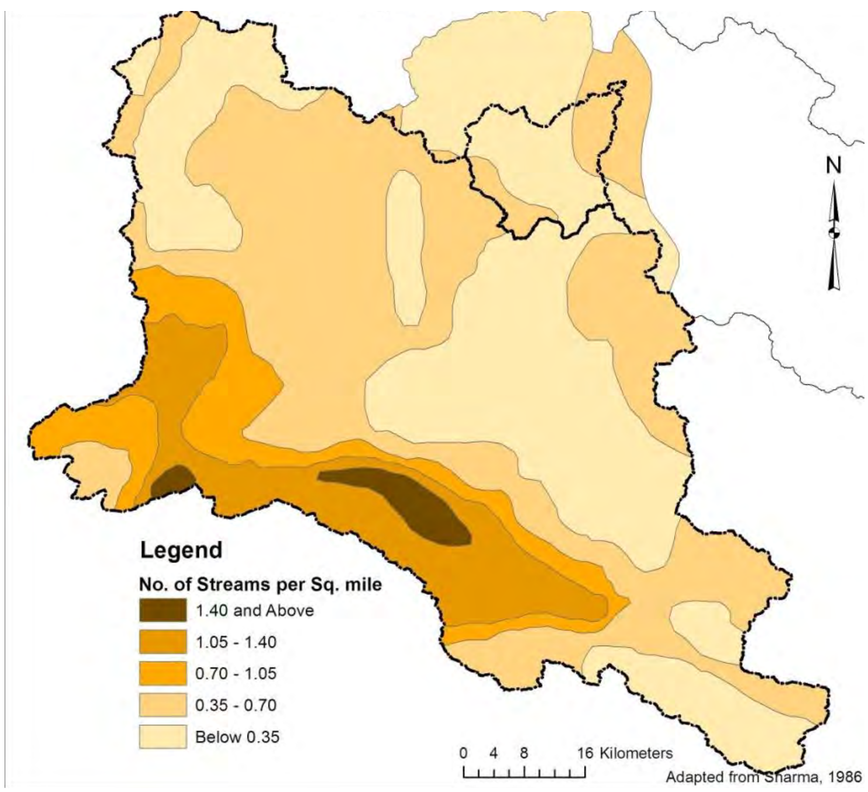

Fig. 29 Stream frequency distribution in the Chandra-Bhaga, and Yunan valleys.

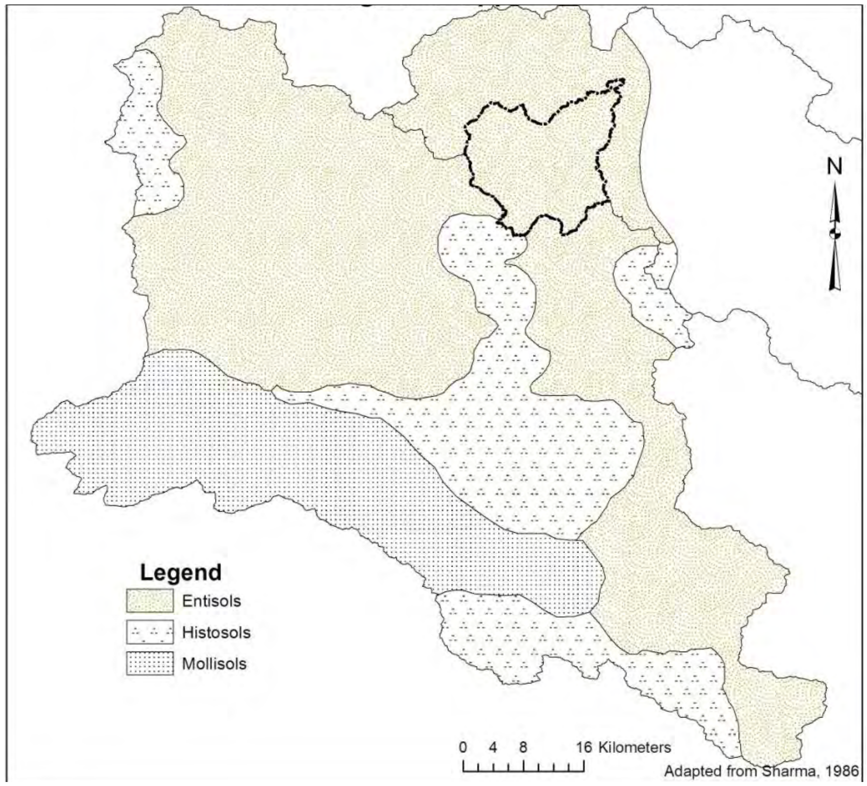

Fig. 30 Soil distribution in the Chandra-Bhaga, and Yunan valleys.

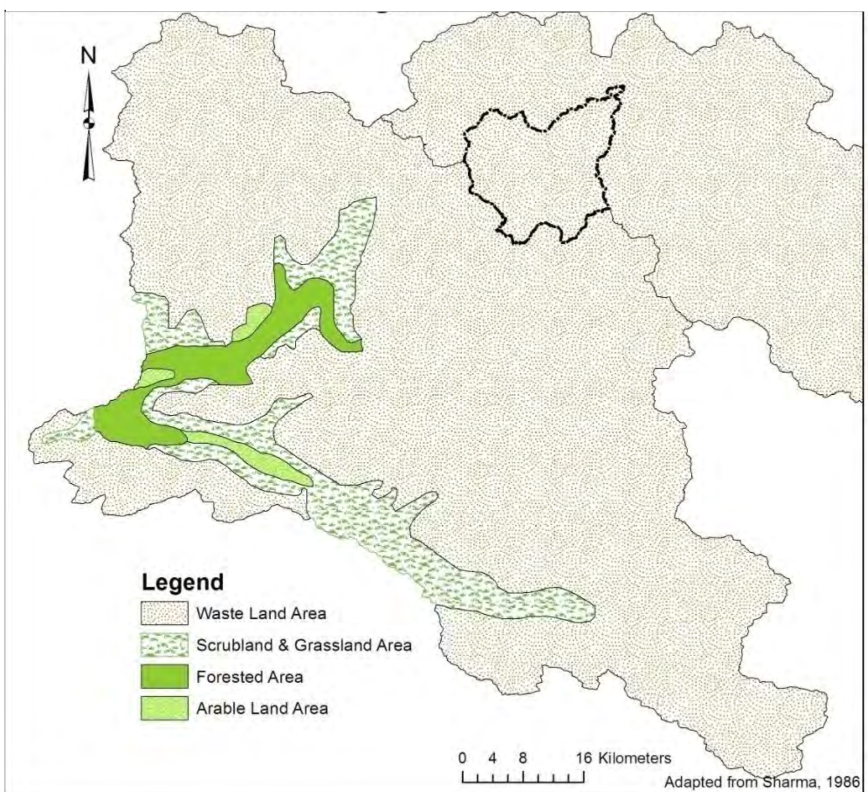

Fig. 31 Land use and land cover pattern in the Chandra-Bhaga, and Yunan valleys.

The **climatic condition** of the region indicates that during the winter months the temperature remains below subzero; from December to April. Lowest temperature recorded at Keylong is -22° C during 2003 in the month of January, the coldest month of the season (Fig. 32.a). Winter spread from mid-November to even up to April. May is the short spring and summer extends for June to the end of September. Autumn is very short lived in the valley. The summer, as stated before, is scorching but the mean monthly temperature rarely goes beyond 15° C (Fig. 32.a). The region is mainly dominated by two major climatic systems and orographic effect is most pronounced. These are Southwesterly Indian monsoon during summer, bringing moisture from the Bay of Bengal, and the mid-latitude westerlies during the winter months, bring the moisture from the Mediterranean, Caspian, and Black Sea. Presently the

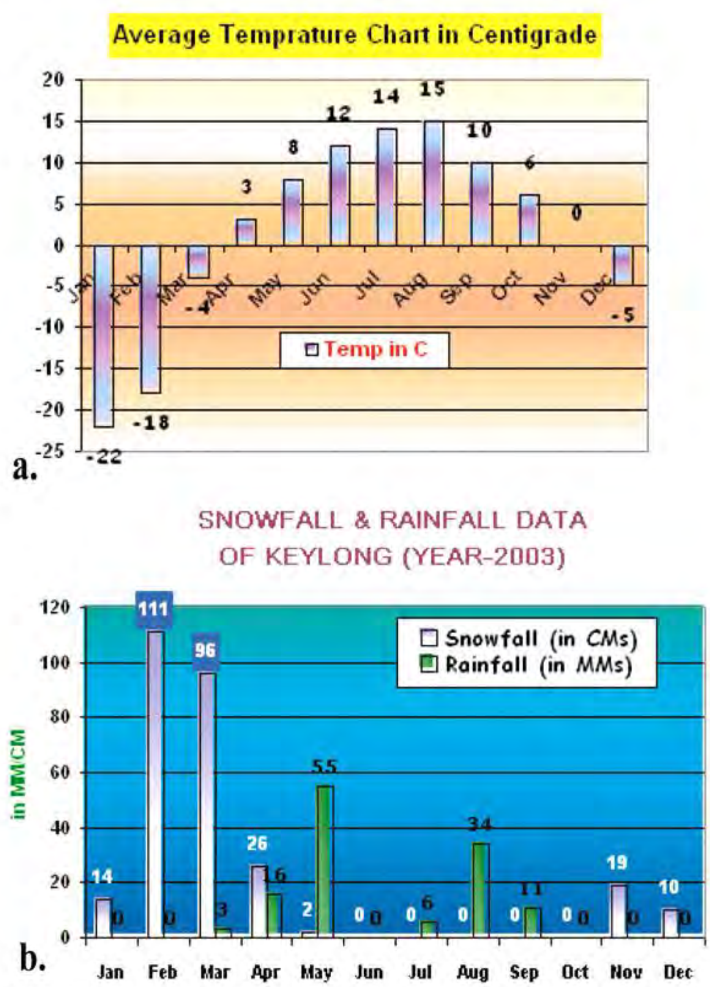

Fig. 32. Average monthly Temperature and Precipitation distribution of Lahul Valley. **a.** Shows the average temperature (°C) and **b.** Represents the snowfall & rainfall, in the whole valley. The charts are based on the data recorded at Deputy Commissioner Office, Keylong for the year 2003, and believed to be representative of the entire Lahaul & Spiti. Supplied by Dr. M.C. Sharma.

winter months receive more precipitation than June to September (Fig. 32.b) i.e. the contribution from the westerlies during winter are more dominative at present than the southwesterly monsoon during the summer. February and March receive relatively more snowfall whereas May to April is the period when rainfall mainly dominates (Fig. 32.b). The general climatic condition at the present is similar in Chandra-Bhaga valley, Spiti valley, and even in the Yunan Valley beyond Baralacha La. All these areas presently receive heavy snowfall during winter months whereas summer rainfall is scanty—cold arid desert type.

Hence from the above analysis the essential characteristics of the present study area and its surroundings become clear. Several key notes in general can be restated in the summary. That is the region is still in the early phase of landscape evolution. Geology plays a major role in the valley interms of high orography and mountain building, hard metamorphosed rocks and typical incision and denudation rates, faulting and thrusting and folding activates and also interms of the Quaternary glacial depositional characteristics. The rate of fluvial aggradation and incision is highly variable across the space and time. Glacial geomorphological activities and landforms, although still dominates in the region but was more pronounced during the periods of glacial advances. Among the other geomorphic activates, both paraglacial and periglacial processes predominate the present valley environment. Aeolian and fluvial activities are also prevalent and together with geomorphic activities influence the landscape evolution of the region. The palaeoglacial landforms and features are still preserved well in the valley, especially due to the apparently arid climate and more due to the still early phases of valley evolution during the post glacial regime. Climate is still largely crafted by the two major climatic systems. They are the southwesterly monsoon during summer months and westerlies during winter months. The present and also possibly the past ELAs are showing gradual rise *from the south i.e. Pir Panjal range to the north i.e. Zanskar range, after which it again falls in the Indus valley in Ladakh. This kind of ELA distributional patterns agree well with the regional snow line distribution and to some extent precipitation gradient of the region. Precipitation gradient, however, is showing progressive aridity towards north. The drainage density and texture along with the agriculture and other land use pattern is well developed, however, only in the downstream section of the Chandra-Bhaga valley near Tandi and less developed and largely barren and uninhabited in the upstream sections. Soil cover of the study area is more or less in the early phase of their development and is still immature. The Chandra and Yunan valley in general is broad and gentle, compared to the relatively narrow and high gradient Bhaga valley. The timing, extent, and nature of glaciation in both the Lahul Himalaya and Zanskar range is asynchronous and four to five glacial advances are reported from both the valleys. Over all the entire study area of the Himalayas and Transhimalaya is very much dynamic and unique as well interms of its sharp transition to more arid counterparts in the north of Great Himalaya and more moist part in the south of Pir Panjal.*

Chapter—3

GLACIGENIC SEDIMENTARY CHARACTERISTICS AND METHODOLOGICAL APPLICATIONS

"Interpretation of ancient sediments and landforms … (must be) …based on detailed, systematic observation and guided … by sound theory …".

——Douglas I. Benn and D. J. Evans.

3.1. Introduction:

Understanding of the glacigenic sedimentological problems started late in the history of geological sciences. The often chaotic nature and structural complexities, as well as harsh climate, keep researchers away for long to conduct detail sedimentological study in glaciated and glaciarized terrain; even when other disciplines of Earth sciences have already been explored in detail. In fact, the study of glacigenic sediments started during late 19th century, especially after the pioneer work of Venetz De Carpentier and Agassiz in European Alps, on erratic, striae, and moraines (Hallam, 1983; Powel, 1998). Although, already, as early as 18th century, the *'Drift Theory'* emerged, and De Saussure's useful contribution to glacial theory and mechanism of erratic transport provided the early impetus to the geologists and geomorphologists alike (Hallam, 1983). Over the last six decades, however, glacial sedimentology has experienced huge overall upsurge in understanding, technical applications, and methodological sphere. The upsurge is mostly attributed to modern technological development. Many glaciated areas, even the once remote Antarctic continent, now have already been explored in some details using modern technologies, and especially in the light of greater urge to understand our global climatic system and response to cryosphere. The Himalayas, Transhimalaya, and Tibetan Plateau constitute the highest concentration of glaciers outside polar realm (Benn and Owen, 2002). Over the past 15 yrs. the understanding of glacigenic sedimentology in this Central Asian High relief region is improving. Although our understanding of Himalayan cryosphere is still in early phase, especially the subglacial and submarginal subenvironments, hence more rigorous works are the requirement of time. Already Owen et al. (1995, 1996, 1997), Benn and Owen (2002), Derbyshire and Owen (1996) etc. have successfully been explained the need of integrated facies-landform association (land system model) analysis in the Himalayan realm. The present chapter largely deals with the general characteristics of glacigenic sediments with special emphasis to the Himalayan conditions and general methodology applied satisfactorily in this environment. This chapter hence, intends to prepare the platform on which the present work is entirely framed.

3.2. Rationally Behind the Lithofacies Study in the Himalayas:

The modern concept of facies deals with a body of sediment or rock unit[1] with a distinct combination of properties which bears the imprints of a particular environmental condition of their formation (Benn and Evans, 1998). Generally five types of facies analysis are found in literature. They are lithofacies, genetic facies, sedimentary facies, biofacies, and geochemical facies. These facies are differentiated from each other on the basis of the use of unique set of

[1] The 'rock unit' varies from any soil or unconsolidated sediment to consolidated hard rock (Spock, 1953).

parameters and the objectives behind their study[2] (Broadzikowiski and Van Loon, 1991). Here emphasis is paid on the *Lithofacies* analysis because in active glaciers like the Himalayan glaciers, often interpretated as *D-type* (Owen et al., 1989), the '*process-dominated facies'* identification i.e. *genetic facies,* from the geological records is utmost difficult, if not uncommon. And equally difficult is their correlation in a broad area. Similarly, the biological evidences are rarest and chemistry is mostly immature to provide effective facies correlation and understanding. In fact the relative weathering criteria varies as much within a single basin that the micro climatic influence seems to be far more important than the regional (Owen et al., 2001). Since the glacigenic sedimentology in the Himalayan cryosphere is mostly chaotic and often the product of more than single processes, lithofacies study, perhaps, is most likely and discuss as follows.

Study of physical characteristics of a sedimentary unit with no reference to the depositional processes is called lithofacies analysis (Benn and Evans, 1998). Although, the analysis of processes are not directly discussed under lithofacies study, which is actually discussed under genetic facies study, some way or the other the aim of lithofacies study is not only to develop facies association of different adjacent facies but also to come up with the interpretation of prevalent process characteristics to construct palaeoenvironment. However, the Walther's Law of vertical and lateral facies transition and their correlation of events/set-cosets, thus, still remains one of the most important basic guidelines in facies analysis (Brodzicowiski and Van Loon, 1991). The study of lithofacies study, however, includes the detail analysis and

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[2] The study of *lithofacies* includes the analysis of physical parameters without considering processes; *genetic facies* study does consider the processes in operation; *sedimentary facies* incorporates the combined characteristics of both lithofacies and genetic facies; *biofacies* study considers the study of biological parameters common in different sedimentary units for correlation and inferring the condition of deposition and palaeoclimate as well, like fossil study etc.; *geochemical facies*, on the other hand, considers the common geochemical properties for correlation of different facies (Brodzikowiski and Van Loon, 1991).

interpretation of grain size, grain shape, sorting, fabric, surface features, physical state, colour, mineralogy and petrography, roundness, density and porosity, inventory sedimentary structures and of early diagenetic deformations, geometry and size of the various units, contact surface characteristics and palaeocurrents and ice movement directions etc. (Brodzicowiski and Van Loon, 1991). These lithological and textural components are discussed latter in detail in the section 6.2. Examples like, poorly sorted diamictons, cross bed-ripple drift structures, lenses of silt/clay etc. can be formed by more than one process.

However, focus only on lithofacies may not be very much helpful in the glaciated terrain where preservation of geological records is found majorly in terms of landforms, especially in the present study area of Lahul Himal and Zanskar range. Hence, the most effective approach must incorporate both geomorphology and facies together i.e. the lithofacies and landsystem model (Owen et al., 1989, 1995, 1996, 1997; Derbyshire, 1996; Owen and Sharma, 1998; Benn and Owen, 2002; Owen 2009). In the words of Benn and Owen (2002), *"Some misinterpretations result from a lack of geomorphic and sedimentological analysis and a desire to assign landforms to either glacial or non-glacial origin to support a hypothesized model for glaciation.* (Hence) ... *researchers must support their interpretation with convincing geomorphic and sedimentological data…"* (p- 4). Similarly Benn and Evans (1998) stressed that, *"Facies association and sediment-landform association place facies within a context, indicating the local stratigraphy, structural and genetic relationship between closely associated facies"*. However, the contemporary depositional environment in the Himalayas are very diverse and active in nature[3]

[3] The Himalayan orogeny is highly diverse and controlled by rigged topography, deep and seep valleys, steep scarp faces, very high relative relief, continuous uplift and consequent incision of valleys, seasonal and diurnal fluctuation in temperature and melt water discharge (with a lag of 3-5 hrs., Owen et al., 1995), changes in precipitation, extensive periglacial and paraglacial processes, weathering and high mass movement activities,

and developing lithofacies-landform system model to reconstruct the evolutionary history of the landscape and further to infer the possible environmental condition in the past, thus, is the biggest challenge to any researchers working in this high terrain realm.

Since the Himalayan and Transhimalayan glaciers contains large quantities of supraglacial debris cover[4], and in general supraglacial path predominate over the subglacial path. Rarely thin basal till in the Himalayan glaciers exceeds few meters of thickness (Owen et al., 1989, 1995); further makes it interesting for the present study of drumlins. For drumlins to form, the glaciers must contain sufficiently thick subglacial tills and or at least supply of some supraglacial materials are required at the submarginal subenvironment of glaciers which may be over ridden by ice in the later stage. That means subglacial and submarginal cover must predominate over supraglacial cover. However, at the contemporary time, the major processes that operates to form glacigenic sediments in this high mountain region are, direct melt-out from ice, flow sliding, debris flow, flow till, avalanche, rock fall and other mass movement processes, gully erosion by meltwater stream, supraglacial and subglacial stream erosion and deposition, tunneling, basal sliding[5], and lodgement, deformation, ice contact abrasion or comminution, events of meltwater flux, and lake outburst etc. (Owen et al., 1989). These ranges of processes often produce polygenetic sediment deposits and landforms. Hence care must be taken while not only differentiating between glacial and non-glacial deposits, but also deposits of polygenetic glacial origin and monogenetic origin. Owen et al (1989) have identified two different sets of characteristics supraglacial landform assemblages. They are a) ***Ghulkin type***, and b) ***Pasu type***, in the Karakoram, Pakistan. The Ghulkin type contains more of thick supraglacial debris cover

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active and warm characteristics of glaciers, mostly avalanche feeding *'firnkessel'* type of glaciers, very high ablation, and relatively high rate of glacier movement etc. (Owen et al., 1989).

[4] They are generally called debris-mantled glaciers or D-type glaciers (Owen et al., 1989).

[5] Large polished and striated rocks provide very good evidences of basal sliding of ice.

with polygenetic sedimentary origin. Episodic melt water fans with boulder gravels (slope ≤ 25°), termed as '*Ice-contact fan'* (Fig. 33), is the most common feature along with *latero-frontal moraines,* and *ablation valley features* (Fig. 33) etc. Besides, other actively formed features incorporates, *glacio-fluvial outwash fans* (Fig. 33.4), *slide moraines* (Fig. 33.5), *slide-debris cones* (Fig. 33.6), *slide modified lateral moraines* (Fig. 33.7), *abandons lateral outwash fan* (Fig. 33.8), *melt-water channels* (Fig. 33.9), *meltwater fans* (Fig. 33.11) etc. (Owen et al., 1989). The Figure 33 includes the sketch of the distribution of all these landforms along with graphic logs which mostly contain massive composition. Post depositional meltwater modification is also found to be most prevalent in these types of glaciers.

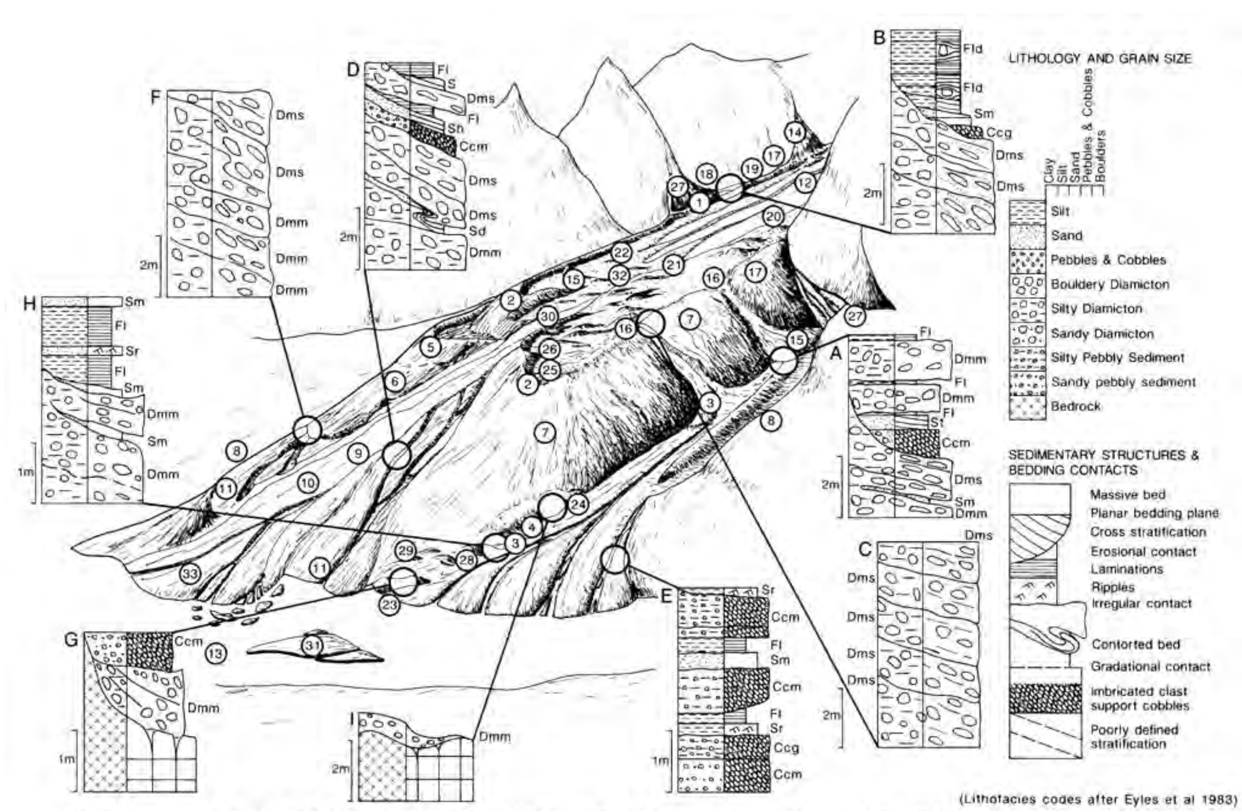

Fig. 33 Facies model for a debris-covered glacier with latero-frontal moraines and ice-contact fans. This model is based on the Ghulkin Glacier after Owen et al. (1989). The major landforms are listed 1-33. 1. Truncated scree, 2. Latero-terminardump moraines, 3. Lateral outwash channels, 4. Glaciofluvial outwash fan, 5. Slide moraine, 6. Slide and debris flow cone, 7. Slide-modified lateral moraine, 8. Abandoned lateral outwash fan, 9. Meltwater channels, 10. Meltwater fan, 11. Abandoned meltwater fan, 12. Bare ice area, 13. Trunk-valley river, 14. Debris-flow, 15.Flowslide, 16.Gullied lateral moraine, 17. Lateral moraine, 18. Ablation valley lake, 19. Ablation valley, 20.Supraglaciallake, 21. Supraglacial stream, 22.Ice-contact terrace, 23. Lateral lodgement till, 24. Roche moutonnee, 25.Fluted moraine, 26.Collapsed latero-frontal moraine, 27.High-level till remnant, 28.Bedrock knoll, 29.Hummocky moraine, 30.Ice-cored moraine, 31.River terraces,

32.Supraglacial debris, 33. Dead ice. The lithofacies association is labeled A to I. A. outwash channel sediments and fan associated with lateral moraine, B. lateral moraine and ablation valley sediments, C. lateral moraine sediments, D. latero-frontal moraine and glaciofluvial outwash fan sediments, E. proglacial outwash fan sediments, F. Frontal moraine sediments, G. bedrock, supraglacial till and outwash, H. frontal till and proglaciallacustrines, I. exposed bedrock and subglacial till. Adapted from Benn and Owen (2002).

The Pasu type of glaciers, on the other hand, does not have ice-contact fans rather they are characterized by hummocky moraines, pits, and glacio-flivial outwash plain (Owen et al., 1989). Roches Moutonnees are also reported from these kinds of glaciers; commonly reported from Karakoram. Beside the above two sets, surging glaciers are also reported (Owen et al., 1989; Bhambri et al., 2012), especially from the Karakoram. These glaciers generally develop features like, steeper older lateral moraines adjacent to rock steps, high trimline, convoluted shape of medial moraines, and stranded avalanche cones of talus and ice hanging at height in tributary glaciers etc. It is therefore, clear that the glacigenic sedimentary environment in the Himalayas and Karakoram is highly diverse and complex in nature and mostly produce hybrid deposits. The most common structure observed in these conditions is mainly massive in appearance. Wide ranging sedimentary compositions are also very common. For example, the grain size vary mostly from fine sands to gravels and boulders (mostly depleted of clays) i.e. polymictic; mostly poorly sorted and positively skewed, mostly, towards coarse gravel; clasts vary from angular to subangular type; and very high void ratios characterize the matrix etc. (Owen et al., 1989). The fabrics are mostly found diffusive with the exception of push morainic features which generally have strong dipping up-valley fabric pattern (Osborn, 1978; Owen et al., 1989). Beside, parallel surface fabric orientation is often considered as the diagnostic to basal sliding processes (Brodzicowiski and Van Loon, 1991). These widely variable sedimentary compositions with mostly polygenetic nature, therefore, limit the identification of genetic signatures in the Himalayas and favours the lithofacies study couple with landsystem model; although, Owen et al. (1989) have successfully differentiated the subglacial deposits[6] from the supraglacial deposits on the basis of grain size distribution in Karakoram, Pakistan (Fig 34.). They are also able to differentiate between different flow deposits—glacial and non-glacial (Fig. 35) and tills of different origin (lodgement till, basal till, englacial meltout till, subglacial meltout till etc.) (Fig. 36). Since these are mostly from contemporary glaciers where environmental conditions are known, finding such signatures from the Quaternary geological deposits may be more difficult and can be tricky at times. This further supports the lithofacies study in the Himalayas over genetic facies. Keeping all these problems in mind, here in the present study mostly lithological and textural analysis is adopted. At first geomorphological analysis is done in detail, followed by the detail sedimentological analysis, as suggested by Benn and Owen (2002).

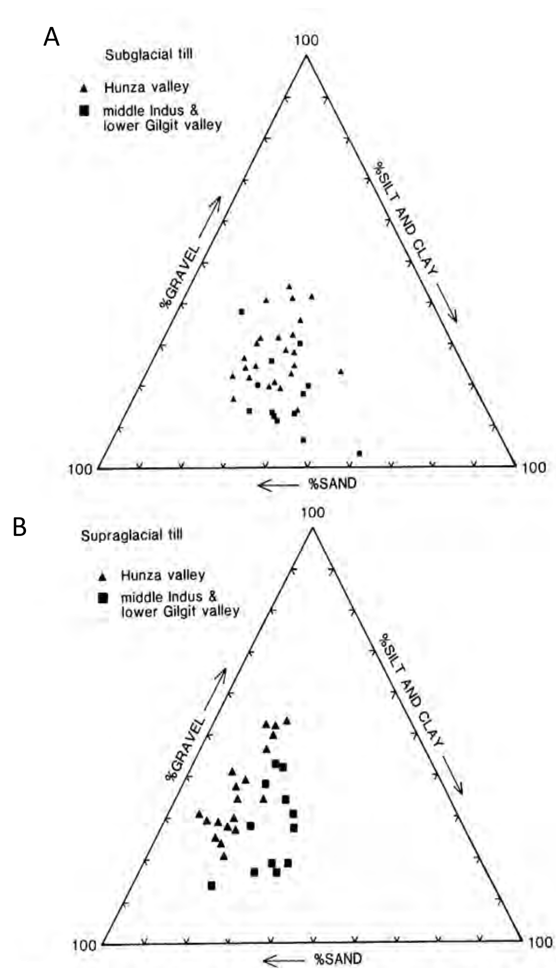

Fig. 34 Ternary plots comparing the subglacial and supraglacial till sediments of the middle Indus and lower Gilgit valleys with the till sediments from the Hunza valley. (A) consists of subglacial tills, (B) consists of supraglacial tills. Adpated from Owen et al. (1989).

However, before proceeding to characterize different types of

6 Subglacial tills are more matrix supported and greater degree of edge rounding and less faceting and have more striations than supraglacial and mass movement deposits (Owen et al., 1989).

glacigenic sediments, general terminological dilemma in the contemporary glacial sedimentology, must be clear. They are discussed as follows.

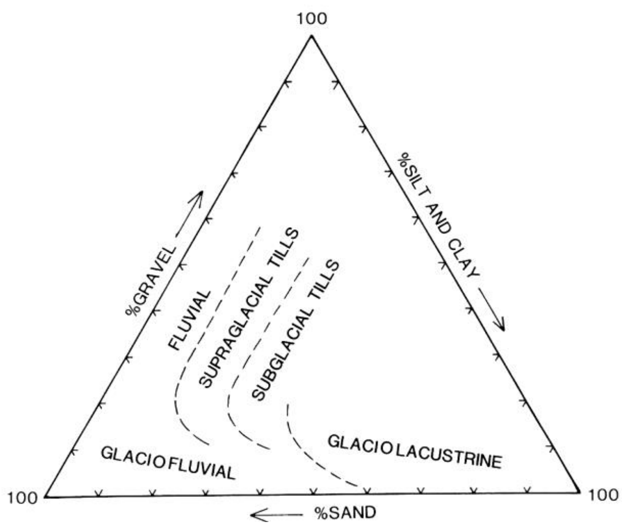

Fig. 35 Ternary diagram showing the range of different sediment types in the Hunza, Gilgit and middle Indus valleys. Adpated from Owen et al. (1989).

3.3. Terminological Dilemma in Glacial Sedimentology:

One of the major general problems in interpretation of glacigenic sedimentation worldwide is the differences in the universality of terminology and corresponding understanding. There are terminologies which are necessarily genetic but often use in literature as descriptive, such as *'Till'* (Brodzicowiski and Van Loon, 1991). Previously the term '*Diluvium*' has been used in literature which used by Lyell as '*Drift*'. Gradually the term '*Till*' is favoured by researchers. The popularity of the term also creates lot of dilemma in interpretation of glacially deposited sediments. The term '*Till*' is, actually by definition, is genetic term which restricted to all the sediments deposited directly by ice (Brodzicowiski and Van Loon, 1991; Flint, 1971). But the practical application of the term is rather difficult because in most cases these deposits are modified by other allied processes like glacio-fluvial processes in ablation areas, aeolian and/ mass movement processes etc. Due to this dilemma in application of the (genetic) term *'Till',* instead, the term *'Diamicton'* (Diamictites for lithified rocks) is introduced which is a descriptive term and is applied extensively in present literature (Benn and Evans, 1998; Evans et al. 2006; Brodzicowiski and Van Loon, 1991).

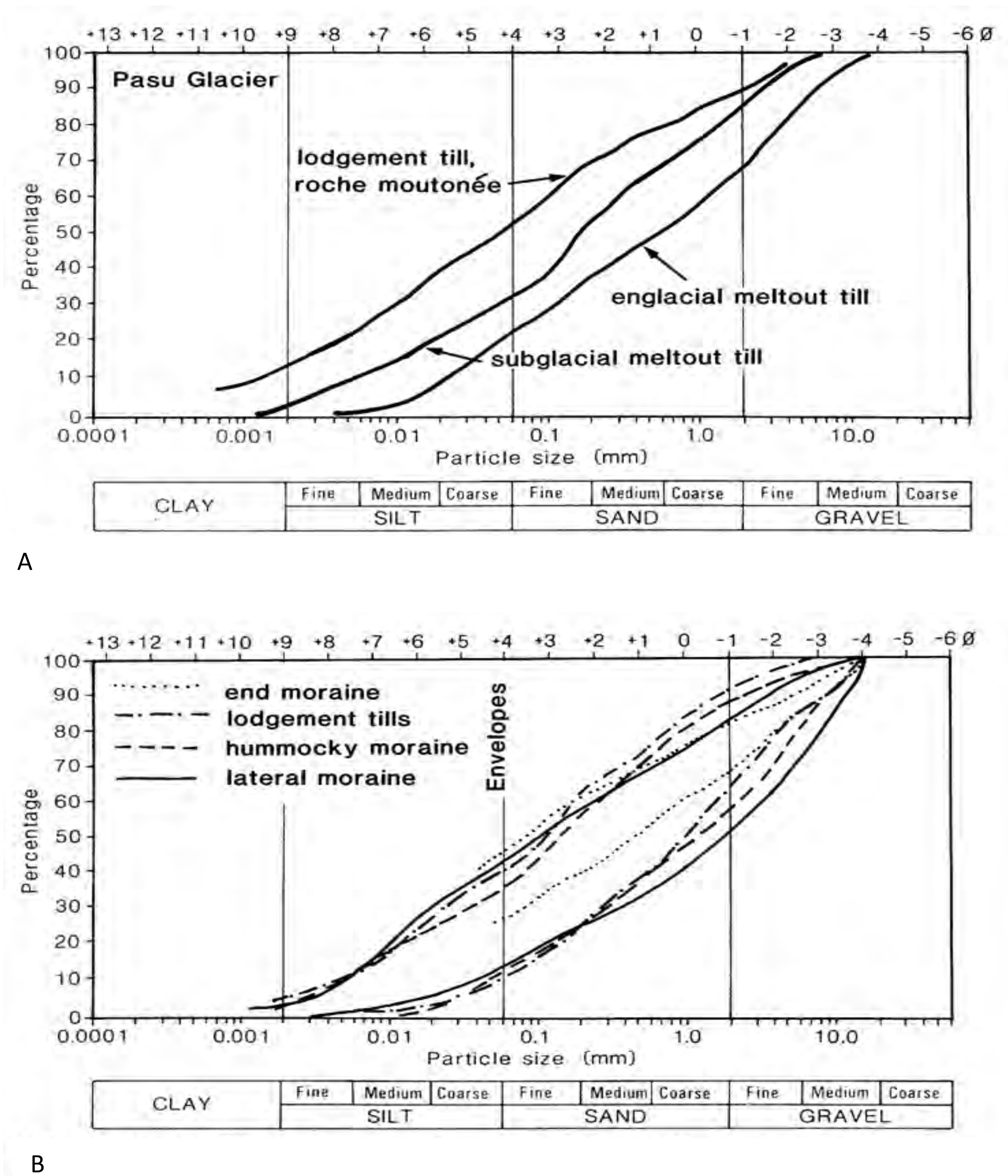

Fig. 36 Particle size distribution through semilog diagram. (A) particle size distribution curve for lithologically similar tills produced by different modes of deposition from the Pasu glacier. (B) particle size distribution envelopes for tills from different glacial landforms. Adpated from Owen et al. (1989).

Similarly often morphological terms are used in sedimentological interpretation, such as *'esker deposits'*, '*ice-pushed ridges sediments*', *'supraglacial morainic deposits'* etc. (Brodzicowiski and Van Loon, 1991). The misuse of these terms often leads to misunderstanding in interpretation but more over limits the universality of correlation among sedimentary deposits. They, although, improve our knowledge but are more confusing than scientific (Brodzicowiski and Van Loon, 1991). Hence, sedimentological interpretation should avoid confusing usage of morphological terms together but rather use should includes morphological features or landforms in one hand and detail study of their sedimentology on the other.

3.4. General Methodological Application in Glacial Sedimentology:

For characterizing and deciphering the important glacigenic sedimentary properties of different types, for example supraglacial, englacial, and subglacial till characteristic, and glacio-fluvial, lacustrine, aeolian, and mass movement deposits etc. and their subclassifications, detail lithological and particle morpho-textural analysis are conducted both at the field and in the laboratory. These analyses have huge implication in the Himalayan glacigenic environment where lithological and landsystem model is largely advised (Owen et al., 1989; Benn and Owen, 2002). Before venturing into the general methodologies applied to so far in the present study (see chapter 4), an over view of these analysis, relative merits and demerits, must be first discussed so as to compare the feasibility of using some of the techniques in relation to others and limitations of the present study and future scope as well.

3.4.1. Lithological Analysis:

Detail lithological analysis largely helps in correlating various sedimentary deposits and their vertical and lateral transition in space-time context. These essentially incorporates grain size analysis, mineralogy, sedimentary structures, contact characteristics, size and geometry of the unit, palaeo-current analysis etc. (Brodzicowiski and Van Loon, 1991).

3.4.1.1. Grain Size Analysis:

The Udden-Wentworth's logarithmic and millimeter grade scale is extensively and universally applied to granulometric study to determine grain size distribution in sample size (Nichols, 2009; Tucker, 1988; Hubbard and Glasser, 2005; Brodzicowiski and Van Loon, 1991; Lindholm, 1987; Selley, 2000; Bogg, 2006; Blott and Pye, 2001). In this scale the boundaries between successive size classes differ by a factor of two but not much suitable actually for graphical presentation. However, to facilitate graphical presentation and statistical manipulation of grain size frequency data, Krumbein (1934 cf. Blott and Pye, 2001) further transformed these millimeter scale values into phi (φ) values using the expression $\varphi = -\log_2 d$, where d is the grain diameter in millimeters (Blott and Pye, 2001). Presently the phi (φ) (log normal) scale is in most usage (Table: 1). This simple particle size analysis generally provides insight of the mechanism that lead to the deposition, processes and the energy regime and also differentiating or correlating different lithofacies (Brodzicowiski and Van Loon, 1991). For example, as previously mentioned, Owen et al. (1989) have successfully used grain size distribution in semilog scale to differentiate subglacial and supraglacial diamicts (Fig. 36). Ternary diagram, thus, has been widely in application for graphical representation and for characterizing unique properties of different sedimentary units; it is constructed on the basis of proportion of mud-sand-gravel mixtures or sand-silt-clay mixtures (Fig. 34.a and 34.b). However, Folk and Ward (1957) further modified grain size analysis using their log-normal scale for statistical analysis. They proposed four parametric analysis, viz. grain size distribution (Mz)[7], sorting or standard deviation (σ_1)[8], skewness (Sk_1)[9], and kurtosis (K_G)[10] techniques. These modifications using mathematical 'Methods of Moments' (Blott and Pye, 2001) certainly have large importance and it is up to future works on glacigenic sediments in the Himalayas to correlate the already reported (Owen et al., 1989) common signatures of grain size distribution for different sedimentary deposits. It also

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[7] Mean, $Mz = \frac{\Phi16+\Phi50+\Phi84}{3}$......................10. where, Φ is the grain size in Phi (Φ) unit. **It measures the average grain size in the unit.

[8] Sorting or Standard Deviation, $\sigma_1 = \frac{\Phi84+\Phi16}{4} + \frac{\Phi95-\Phi5}{6.6}$ ....11. **It measures the dispersion or spread within grain sizes relative to average grain size (Blott and Pye, 2001).

Scale for σ_1,		
	Very well sorted -	<0.35
	Well sorted -	0.35-0.50
	Moderately well sorted -	0.50-0.70
	Moderately sorted -	0.70-1.00
	Poorly sorted -	1.00-2.00
	Very poorly sorted -	2.00-4.00
	Extremely poorly sorted -	>4.00

[9] Skewness, $Sk_1 = \frac{\Phi16+\Phi84-2\Phi50}{2(\Phi84-\Phi16)} + \frac{\Phi5+\Phi95-2\Phi50}{2(\Phi95-\Phi5)}$ ....12. ** It measures the symmetry or preferential spread to one side of the average (Blott and Pye, 2001).

Scale for Sk_1,		
	Very fine skewed -	+0.3 to +1.0
	Fine skewed -	+0.1 to +0.3
	Symmetrical -	+0.1 to -0.1
	Coarse skewed -	-0.1 to -0.3
	Very coarse skewed -	-0.3 to -1.0

[10] Kurtosis, $K_G = \frac{\Phi95-\Phi5}{2.44(\Phi75-\Phi25)}$ ....13. **It measures the ratio of the sorting (degree of concentration) in the extremes of the distribution compared with the sorting in the central part (Folk and Ward, 1957).

Scale for K_G,		
	Very platykurtic -	<0.67
	Platykurtic -	0.67-0.90
	Mesokurtic -	0.90-1.11
	Leptokurtic -	1.11-1.50
	Very leptokurtic -	1.50-3.00
	Extremely leptokurtic -	>3.00

[*** Here the percentile values of Φ are used (Folk and Ward, 1957, p-1241] helps largely in determining the geotechnical properties of sediments, especially in subglacial condition, where the rheological properties determine the response to porewater pressure and normal effective stress provided by overlying ice, and dilation and subsequent deformation, lodgement etc. Over all, the simple grain size analysis proves to be much more relevant in the present context.

However, if the clasts in the sediments are homogeneous they are called *'monomict'*. A *'Polymictic'* diamictons include clasts of many different sizes, and '*oligomictic'* clasts generally include two major (bimodal) size dominant clasts (Nichols, 2009). According to Owen et al., (1989) and in Benn and Owen (2002) most of the supraglacial clasts in the Himalayan glacier system are polymictic due to heavy debris production and incorporation as till.

3.4.1.2. Mineralogical Analysis:

Provenance study is one of the key to determine pathways of glacier transport and distance from source regions (Doyle et al., 2001). Detail analysis of mineral composition does provide information regarding source region and compositional maturity[11] of the sediment. X-ray Diffraction (XRD) method in the laboratory environment and hand lenses use in the field helps in identifying mineralogical characteristics of sediment. Orientation of magnetic particles at the time of deposition also helps in determining pathways in palaeomagnetic studies. Since in glacigenic environment, upside-down and mass movement processes often leads to mixture of sediments and deformation under subglacial condition, detail mineralogical study is worth require to determine not only provenance but also to infer the relative role of tributary glaciers in

[11] More the share of Quartz followed by feldspar in the sample and less the clay mineral content—the sample is said to be more compositionally mature and vice-versa (Tucker, 2003).

ice advance or retreat scenarios (Doyle et al., 2001). Besides, the evidences of preweathered surfaces (clay-mineral concentration) within a deposition also reveals possibly the past deglaciation history of the region and helps in constructing the glacial chronology (Newman et al., 1989).

3.4.1.3. Contact Surface Analysis:

Surface contacts between different sets or cosets and beds or unconformities also comprise one of the very important parts in lithological analysis. Existence of scour surfaces and other irregular surfaces bear the imprint of erosional contacts which if filed later like, scour-fill structures, indicate redepositional regime after a period of erosion or net negative deposition. Similarly apparent stratification may takes place due to sorted grain size differences in a set and if contains coarser sediments and gradually transit to finer one, these indicate initial relatively higher energy regime (by currents) followed by low energy condition (Bogg,2006; Leeder, 1982; Lindholm, 1987). Similarly, loadcasts and other dewatering features also show distinct contact surfaces; these structures are also helpful in determining way-up structures (Tucker, 2003). Therefore, the changes in the mechanism, energy regime, and time-gap or halt, if any, in geologic processes across time can be determined from contact surface analysis. Change in base-level condition may be inferred as well. Correlation with palaeoclimatic indicators, however, also provides very useful knowledge in facies modeling (Brodzikowiski and Van Loon, 1991).

3.4.1.4. Analysis of the Size and Geometry of Unit:

Size and geometry of a unit sedimentary deposit is another very important lithological analysis in facies modeling and understanding palaeoenvironment. Changes in the vertical and lateral succession over time and space also reflect changes in environmental conditions and process intensity. However, in general extensive laterally distributed deposits have sheet like geometry (Tucker, 2003). Other common (classical) geometrical forms include tabular form, wedge-shaped, and/or lenticular form (Fig. 37). Irregular geometry is called lens or patch and cone-shaped geometry is called fan or cone (Tucker, 2003). The geometry of palaeochannels generally has either ribbon-shaped geometry or dendroid branching system (Tucker, 2003). Hence, the geometrical shapes and their distribution in a sedimentary unit (facies) have wide ranging positive implications to the understanding of palaeoenvironmental condition (Tucker, 2003).

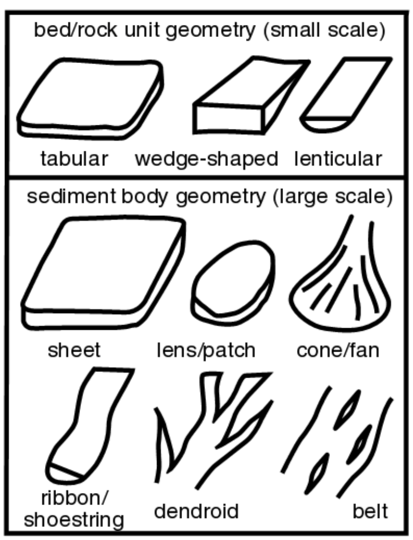


Fig. 37 The diagram showing common geometries of beds or rock units (on a scale of meters to tens of meters) and sediment bodies (on kilometer or regional scale). Adapted form Tucker (2003).

3.4.1.5. Structural Analysis:

Identification of structural fingerprints from the sedimentary deposits—unconsolidated sediments and/or consolidated hard sedimentary rocks, largely improve our understanding about the processes of formation, modus operandi and mechanism of formation and most importantly the energy condition in the system. Identification of few common structures from glacigenic sediments, like joints, faulting and slickensided surfaces, loadcasting, ripple cross-bedding, folding, boudins, rotations, galaxy structures, shear

Table 1. Size scale adopted in the GRADISTAT program, compared with those previously used by Udden (1914), Wentworth (1922) and Friedman and Sanders (1978)

Grain size phi program	Grain size mm/µm	Udden (1914) and Wentworth (1922)	Friedman and Sanders (1978)	GRADISTAT	
			Very large boulders		
- 11	2048 mm		Large boulders	Very large	Boulders
-10	1024		Medium boulders	Large	Boulders
-9	512	Cobbles	Small boulders	Medium	Boulders
-8	256		Large cobbles	Small	Boulders
-7	128		Small cobbles	Very small	Boulders
-6	64		Very coarse pebbles	Very coarse	Gravel
-5	32		Coarse pebbles	Coarse	Gravel
-4	16	Pebbles	Medium pebbles	Medium	Gravel
-3	8		Fine pebbles	Fine	Gravel
-2	4	Granules	Very fine pebbles	Very fine	Gravel
-1	2	Very coarse sand	Very coarse sand	Very coarse	Sand
0	1	Coarse sand	Coarse sand	Coarse	Sand
1	500 µm	Medium sand	Medium sand	Medium	Sand
2	250	Fine sand	Fine sand	Fine	Sand
3	125	Very fine sand	Very fine sand	Very fine	Sand
4	63		Very coarse silt	Very coarse	Silt
5	31		Coarse silt	Coarse	Silt
6	16	Silt	Medium silt	Medium	Silt
7	8		Fine silt	Fine	Silt
8	4		Very fine silt	Very fine	Silt
9	2	Clay	Clay	Clay	

lines and planes etc. helps largely in reconstructing palaeoenvironmental conditions (Brodzikowiski and Van Loon, 1991). However, a few of most common structures from glacial sedimentary records can be discussed through the following heads. It should be noted that few of the structures are found in non-glacigenic areas as well; hence multi criteria must be adopted, especially in the Himalayan condition, for the interpreting the genetic fingerprints.

3.4.1.5.1. Glacial Erosional Structures:

Striation, polish, and groove structures are essentially glacial erosional features (Flint, 1971). They also indicate the direction of flow of the glacier. According to Chamberlin (1988 cf. Flint, 1971) *"Fine –cut lines on the surface of the bedrock which were inscribed by the overriding ice is called striation".* However, it is not the ice-cut, rather the particles (clasts) incorporated in basal ice, which creates the striations. According to Flint (1971) relatively finer scratches made by sand and/or silt particles are grade into polished structures.

With increasing diameter and depth striations is graded into grooves. Among the other small scale structures of glacial abrasion, includes concentric gauges[12], crescentic fractures[13], lunate fraction[14] etc. These are also formed due to basal freeze on and sliding, rolling, plucking mechanism of ice in the ice-bed interface (Flint, 1971). These structures are generally reported from the surfaces of lodge clasts or lag boulder deposits (boulder platform) (Shaw, 2002) and also from pebble size clast surfaces during fabric analysis (Hicock, 1990).

[12] Concave up-ice direction (or may be some time down-ice direction (Flint, 1971).
[13] Concave down-ice direction (Flint, 1971).
[14] Set of fractures concave down-ice direction (Flint, 1971).

3.4.1.5.2. Palaeocurrent Structures and Stream Deposits:

Evidences of palaeocurrents may be found through structures like flute casts, groove casts, tool marks, and scour marks and scoured (and fill) surfaces (Tucker, 2003). Flute casts are bedding undersurface elongate or triangular, either rounded or pointed upstream end, and the flare in a downstream direction (Tucker, 2003). They indicate the direction of movement of palaeocurrents. Among other noticeable structures, climbing ripple-cross lamination, cross-bedding structures both trough and tabular cross-bedding, larger form of wave ripples, lenticular stratifications, imbricated structures etc. also are the common indicators of palaeocurrents (Tucker, 2003). In cross-bedded or cross-laminated structures often *'reactivation surfaces'* are found (Doyle et al., 2001). These are the indicative of changing energy regime (Tucker, 2003). Sometimes reverse flow ripples/cross-lamination in lacustrine deposits indicates the influence of bottom currents to the sediment deposition. Well sorted sandy parallel laminations are also formed glacio-fluvially in low energy regime (Brodzikowiski and Van Loon, 1991; Tucker, 2003).

3.4.1.5.3. Lacustrine Depositional Structures:

Thin graded and parallel laminated varves are the most common occurrence form of lacustrine deposits with occasional damp-stones and/or drape-stones (Brodzikowiski and Van Loon, 1991; Tucker, 2003). According to Brodzikowiski and Van Loon (1991) varve like structures are formed due to well recognized seasonal suspension deposition[15] and/or because of the influence of turbidity currents.

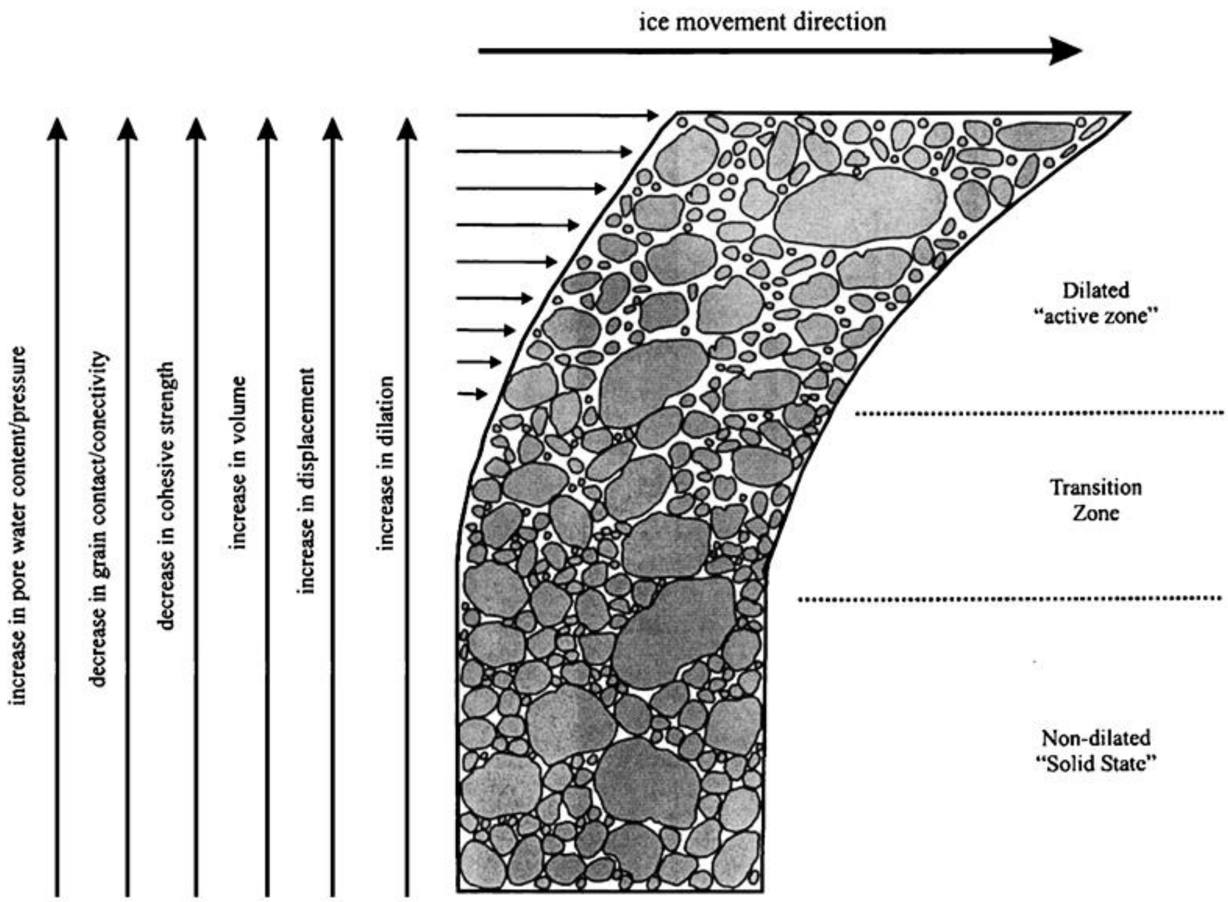


Fig. 38 Simplified diagram portraying the zonation of a relatively homogeneous subglacially deforming material and its relationship to dilation displacement, sediment volume, cohesive strength, connectivity, and porewater pressure. Adapted from Evans et al. (2006).

3.4.1.5.4. Mass movement Structures and Dead-ice Melting Evidences:

In glacial areas, often dead-ice leads to collapse of overlying deposits, after melting, which if more liquefied then lead to flow till formation (Brodzikowiski and Van Loon,

[15] Coarser material deposition in summer and finer particles in winter when icing of the lake surface water creates least disturbance condition and suspension takes place (Brodzikowiski and Van Loon, 1991).

1991) or fluidized flow structures. These kinds of structures are common in contemporary terminoglacial subenvironment (Brodzikowiski and Van Loon, 1991; Schomacker et al., 2006).

Other forms of massmovement structures, however, includes slump lobe, liquefied to moderately liquefied debris flow, slump scarps, flowage lobes in solifluction lobe etc. (Brodzikowiski and Van Loon, 1991).

3.4.1.5.5. Deformation Structures:

Deformation structures in the glaciated regions are mostly found preserve in the subglacial deposits, if not uncommon in other types of glacigenic sedimentary deposits. As discussed previously in section 1.3.2.2. (in Chapter 1) deformation within a region is combinedly dependent on the local geology, terrain conditions, ice-mass characteristics, temperature gradient, porewater content and dilation mechanism, rheological properties of subglacial materials, weathering history, syndepositional and/or post depositional mass movement processed and erosional-deformational-depositional history etc. There is little ambiguity now that dilation of subglacial sediments is largely responsible for different forms of deformation structures (Evans et al., 2006; Smalley, 1966; Smalley and Unwin, 1968; Menzies, 1979; Brodzikowiski and Van Loon, 1991). According Evans et al. (2006) when porewater content increases leading to more porewater pressure, the liquefaction may take place. This possibly causes decoupling at the ice-bed interface and lowering of effective normal stress. Hence, deformation is likely to be limited, but as the pore water pressure reduces, may be due to water dissipation, a critical level, the substrate materials may behave like plastic fluid and leading to deformation due to relatively more effective pressure of overlying ice-mass (Fig. 38). Different types of ductile deformations structures, such as recumbent folding (Hart, 1995, 1997; Menzies, 1979), isoclinal folding, over turned folding (Benn and Evans, 1998), recumbent isoclinal folding upright isoclinal folding, open folding (Stanford and Mickelson, 1985), sheath folding (Hart, 1995, 1997; Boulton, 1976), drag folding (Menzies et al, 2007; Shaw, 1980) etc. can be identifiable at macro and sometimes at micro scale as well. Besides, the massive homogenized appearance of diamicton is also attributed a product of extensive ductile deformation and higher strain rate, if at micro level they possess clast rotational structures and galaxy type structures, with smaller clast surrounding the larger clast etc. (Evans et al., 2006; Menzies et al., 1997; Hart, 1995; 1997). Other similar ductile deformation structures incorporates density stratification and consequent fluidization, density differences and formation of diapiric (Often folded) structures, stretching in softer bed due to basal ice sliding (advancing) and shearing often lead to formation of boudinage structures within glacial sediments (Hart, 1995) etc. Pressure dissolution structures in carbonate rocks or carbonate rich sediments have been mentioned by Tucker (2003) as largely due to over consolidation and fluid effects by overlying pressure as well. However, plastic (ductile) deformation and liquefaction structures have also been reported from the proglacial and marginal deltaic deposits, as a result of loading of bulk deposits and increasing pore-water content (Evans et al., 2006). Load casting, flame structures (indicating dewatering), dish and pillar structures etc. are the other forms of deformation structures related to plastic and/or viscous fluid materials (Tucker, 2003).

However, as the pore water pressure reduces drastically to have sufficient changes in the rheological properties of glacigenic materials and ice-bed coupling characteristics, different forms of brittle deformation structures are possibly formed (Evans et al., 2006). Subhorizontal foliation, fissilty, fracturing and jointing due to ice-loading and release (Hart, 1995; Menzies, 1979; Meehan et al., 1997; Stokes et al., 2011), faulting and movement along thrust plane (Evans et al., 2006), shear planes (Stokes et al., 2011; Zeles et al., 1997) and slickenside structures (Evans et al., 2006) etc. are different types of brittle deformation structures commonly encountered in the geologic sediments and indicate halt in the glacial processes or retreat of glaciers and lower energy regime (Brodzikowiski and Van Loon, 1991).

These structural fingerprints are of immense importance to develop facies model and reconstructing palaeoenvironmental and palaeogeographic conditions. However, apart from these lithological analysis the morphotextural analysis together prove to be very effective, especially the region in concern. They are discussed in the next section.

3.4.2. Morphotextural Analysis:

Particle morphological and textural analysis is also prove to be effective in the Himalayan conditions (Owen et al., 1989; Benn and Owen, 2002). Already a wealth of knowledge of the Himalayan glacigenic sediments are discussed effectively elsewhere, based on these methodological attributes. However, this part of the component includes the detail analysis of grain shape, sorting, grain surface, roundness, and clast fabric, both at the field level (macro scale) and at the laboratory condition (micro scale). According to Brodzikowiski and Van Loon (1991), ***"texture may give indications about the processes that the sedimentary particles have undergone."*** However, apart from identifying processes, the duration of transport and the medium before sedimentation or resedimentation, the energy regime, degree of post depositional weathering effects and shearing effects can also be derived from the detail textural studies (Brodzikowiski and Van Loon, 1991; Tucker, 1988; Owen et al., 1989).

3.4.2.1. Grain Shape Analysis:

Geometric shapes of grains have huge relevance to palaeo as well as present environmental conditions as they are believed to be shaped by prevalent processes if otherwise not greatly affected by geological and mineralogical composition. They are, however, most fruitful if combined with other lithological and textural analysis. Often fabric study includes particular geometrical shapes of grains because it is also believed that different particle shapes react in different ways, especially in the subglacial conditions where deformation and sliding processes are commonly reported (Carr and Rose, 2003). However, clast shapes are found to be largely affected by periglacial weathering (frost weathering) activities in the Himalayas giving birth to more of blade and rod shaped clasts. For example, the lateral moraines of the Batal Glacier, Himachal Pradesh, India, contains more of blade-shaped clasts due to phyllitic origin and also due to very high periglacial frost weathering and erosion rate in the adjacent valley walls and within the lateral moraines (Benn and Owen., 2002). Sometimes incorporation of different clast shapes of different origin and source rocks are found in geological deposits in glaciated areas. They also likely to provide essential insight of glacial-periglacial processes of the past if studied systematically. However, different types of clast shapes are reported in sedimentology based on their longitudinal (a-axis), intermediate (b-axis), and short (c-axis) axes lengths. They are viz. equant or sphere (c=b=a), rod or prolate (c=b<a), blade (c<b<a), and discoid or oblate (c<b=a) shapes according to Zingg's classification (Nichol, 2009). Sneed and Folk (1958 cf. Graham and Midgley, 2000), on the other hand, have identified three major shapes, viz. Blocky, slabs and rod shapes and represented them through the ternary diagram of clast shape.

3.4.2.2. Grain Sorting Analysis:

Another widely described morphotextural characteristics in literature is the grain sorting. Sorting, however, is defined as the process by which similar in size, shape, or specific gravity sedimentary particles are selected and separated from associated but dissimilar particles by the agent of transport[16]. Sorting analysis, hence, can be diagnostic to both processes, and mechanism of deposition involved as well as the energy condition during their deposition. Like normally graded grains mostly are reported from fluvial and lacustrine environments, whereas poorly graded (or sorted) grains are mostly recorded in glacial environment. Any permutation across different processes and environments including mass movement is possible, hence never reported solely in literature. However, textural maturity of a sedimentary unit can also be determined with the help of sorting coefficient (Owen et al., 1989) apart from process identification. This is generally done in the field with visual method (visual estimate) or using statistical tools of standard deviation (σ) (Fig. 39) (Tucker, 1988, 2003; Nichols, 2009). The normal sorting classification with corresponding σ values incorporate classes of *very well sorted* (σ = <0.35), *well sorted* (σ = 0.35-0.50), *moderately well sorted* (σ = 0.50-0.71), *moderately sorted* (σ = 0.71-1.00), *poorly sorted* (σ = 1.0-2.0), and *very poorly sorted* (σ = >2.0). (Nichols, 2009). However, the grading can occur in a sedimentary unit either as '*normally*' or *'inversely'*[17] (Tucker, 2003)—both is determined mainly by the energy regime of final deposition.

[16] Source: www.answers.com/topic/sorting-2

[17] Normal sorting indicates gradual transition from coarse grains at the bottom to larger grains at the top and inverse sorting is just reverse to the normal sorting.

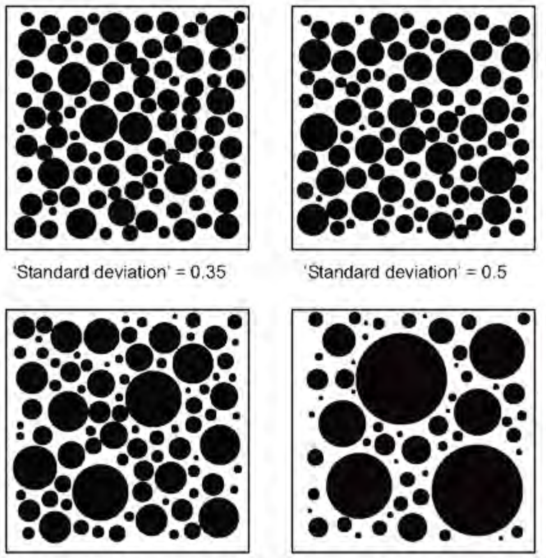


Fig. 39 Graphic illustration of sorting in clastic sediments. The sorting of a sediment can be determined precisely by granulometric analysis, but a visual estimate is more commonly carried out. Adapted from Tucker (2003).

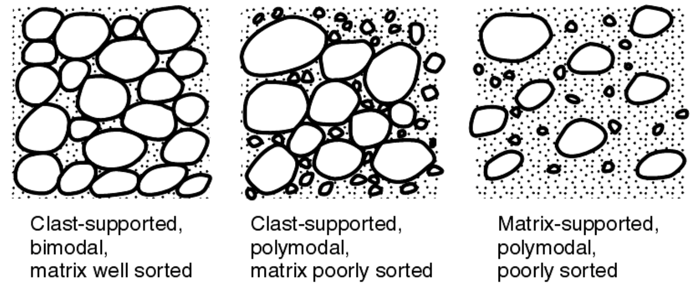


Fig. 40 Graphic illustration of grain fabric and sorting: clast-support with well-sorted and poorly sorted matrix, and matrix support. . Adapted from Tucker (2003).

Along with sorting, '*matrix characteristics'* are also applied to describe the textural characteristics to further support the mode of deposition and energy regime during final deposition. Three main types are mentioned by Tucker (2003) (Fig. 40). These are a) clast-supported bimodal and well sorted matrix (Fig. 40a), b) clast-supported polymodal and poorly sorted matrix (Fig. 40b), and c) matrix-supported polymodal and poorly sorted matrix (Fig. 40c). However, Nichols (2003) has used the term '*orthoconglomerate'* and 'paraconglomerate' for clast support and matrix supported sedimentary units, respectively.

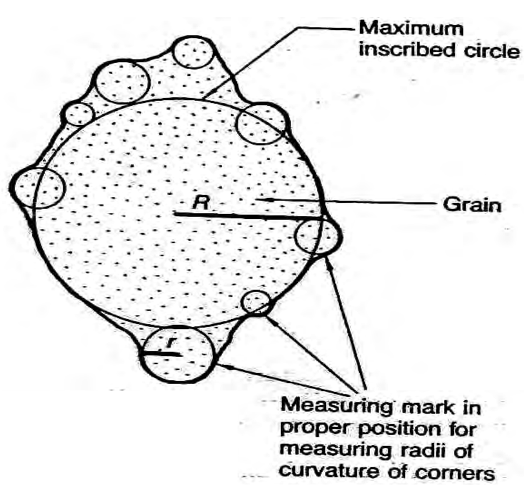


Fig. 41 Diagram of enlarged grain image illustrating the method of measuring the radius ® of the maximum inscribed circle and the radii of curvature (r) of the corners of the grain. Adapted from Bogg (2006).

3.4.2.3. Clast Roundness Analysis:

The roundness of clasts in a sedimentary unit is a function of medium of transport, grain composition, grain size, source material (type of rock) and duration and distance of transport etc. (Bogg, 2006). Like, clasts transported in glacier or solid-state medium are in general relatively more angular than those transported by fluvial processes (liquid-state medium). Clasts of softer rocks are also easily affected by abrasion, attrition and comminution processes when in a transported medium and possible become more rounded than grains of harder rocks. The same is true for minerals, like quartz grains are generally more resistance to change in shape. When quartz grains attain nearly spherical shape, they seldom undergo much change than any other mineral grains (Tucker, 2003; Lindholm, 1987). Owen et al. (1989), however, emphasized the duration and extent of transport medium in determining the degree of edge rounding. In their analysis of glacigenic clasts in Pasu and Ghulkin glaciers of Karakoram, Pakistan, they have come to the conclusion that because of the larger extent of Ghulkin glaciers their hard rock clasts are relatively more rounded than the softer clasts of Pasu glaciers which have experienced very short distance due to smaller extent of Later. So, roundness study could be a very good textural indicators providing all aspects are considered together. However, Wadell (1932) have given a mathematical formula for calculating roundness (Rw) (Bogg, 2006, Tucker, 1988, 2003). This can be written as—

$$\text{Rw} = \frac{\left(\frac{\Sigma r}{R}\right)}{N} \;/\; \frac{\Sigma r}{RN} \qquad \ldots\ldots\ldots\ldots\ldots\ldots..14.$$

where, r is radius of curvature of individual corners, R is the radius of maximum inscribed circle, and N is the number of corners (Fig. 41).

Dowdeswell (1982), contrary to this, analyzed roundness of Quartz sand grains using Scanning Electron Microscope (SEM) and applying Fourier shape analysis, that is— $Rn \cos (n\Theta - \Phi n)$ ……………15.

where Rn is the amplitude of the n^{th} harmonic, n is the harmonic order, Θ is the polar angle measured from an arbitrary reference line, and Φ represents phase angle.

However, because of the cumbersome nature of these methods and less practical applicability in the field, generally visual method of scaling roundness is favoured by most of the researchers. Power grain images for estimating roundness (Fig.42) visually and verbally (after Power, 1953 cf. Tucker, 2003) (and before him, Krumbein, 1941) is thus widely applied in this field. A comparison in class intervals between verbal Power scale and the corresponding Wadell's scale and modified rho (ρ) scale after Folk (1970), however, is presented below in table: 2 (Bogg, 2006). It is to be noted that effective study can be very limited only if visual scale is used.

Table:2	**Relation of Power's verbal rounding classes to Wadell roundness and Folk's rho (ρ) scale:** From: Bogg (2006), pp.128	
Power's verbal class	**Corresponding Wadell Class interval**	**Folk's rho (ρ) scale**
Very angular	0.12-0.17	0.00-1.00
Angular	0.17-0.25	1.00-2.00
Subangular	0.25-0.35	2.00-3.00
Subrounded	0.35-0.49	3.00-4.00
Rounded	0.49-0.70	4.00-5.00
Well rounded	0.70-1.0	5.00-6.00

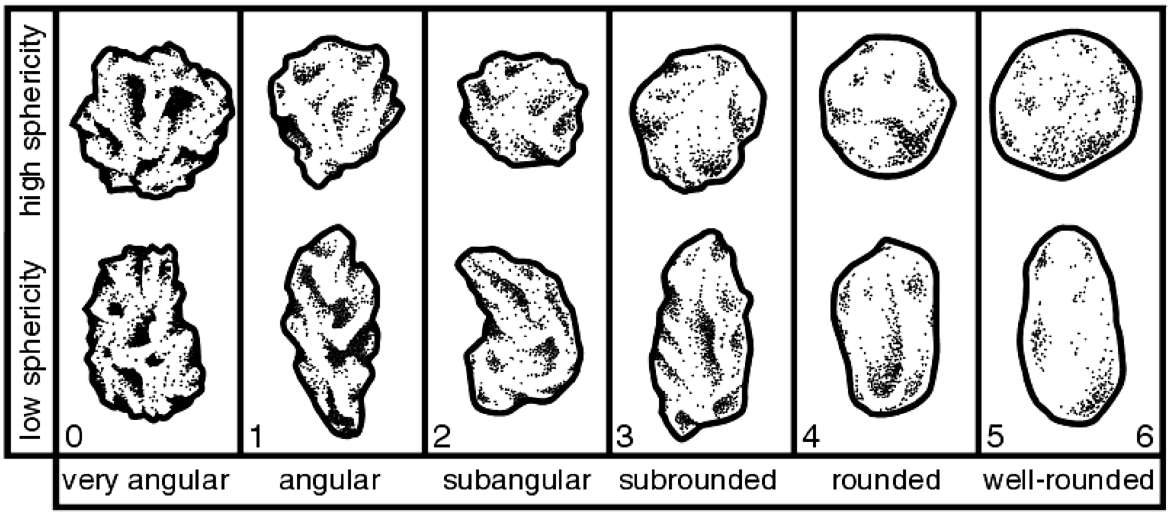


Fig. 42 Categories of roundness for sediment grains. For each category a grain of low and high sphericity is shown.

3.4.2.4. Grain Surface Textural Analysis:

Analysis of surface textures of mainly sand size grains may provide the textural signatures of different processes that the particle may have experienced during their denudational origin followed by entrainment in any transportation medium before final deposition. Hence, over printing and multiphase surface textures not only bear their denudational history and possible palaeoenvironmental condition but also their later stage transportation history. Since different sand grains of variable mineralogy property possess different capacity of preservation, hence Quartz sand grains are most favourable for studying superficial textural analysis using SEM in laboratory environment, because not only Quartz sand grains are abundant in natural environment but also they are one of the most hardest minerals (Benn and Owen., 2002; Lindholm, 1987; Brodzikowiski and Van Loon, 1991). However, SEM analysis of surface textures on Quartz sand grains shows many a different textures, viz. fractures faces, straight grooves, sharp angular fractures, low , medium, and high relief, crescentic gauges, arc-shaped steps, arcuate fractures, edge rounding, sharp edges, edge or corner abrasion, chipped edges, preweathered surfaces, weathered crushing surfaces, adhering particles, v-shaped percussion cracks, over printed structures, fresh and old fractures, upturned plates, effects of oxidation, solution etching and other (chemical) precipitation features (Tucker, 2003).

The presence of a suit of these textural signatures, thus, is the diagnostic of their environmental condition, transport medium and transport regime (i.e. duration of transport and also their energy condition) etc. (Table: 3). Like, Krinsley and Doornkamp (1973) have identified different combinations of surface textures on Quartz sand grains from different known environmental settings, such as glacial environments, loessic environment, diagenetic source material, subaqueous environments, glacial-subaqueous environment, purely aeolian environment, chemical environment etc. and attributed them as the diagnostic to each environment. Mahaney (1990) and Mahaney and Andres (1991) have identified over-printed signatures and of the view that they can be used to differentiate supraglacial and subglacial origin of Quartz sand gains (diagnostic signatures). Although, according to Whalley and Langway, Jr. (1980) such differentiation may not always possible from geological (older) deposits. Many of the studies also tried to infer the wet and/or warmer palaeoenvironmental condition (Mahaney et al., 1991), which indicates that before entrainment in glacial ice and subsequent crushing and grinding, they have undergone chemical weathering activities. Besides, presence of concoidal fractures and grooves etc. on subrounded to rounded grains indicate that they may have undergone glacial crushing before entrainment in fluvial or aeolian transportation (Whalley and Langway Jr., 1980; Mahaney, 1990; Mahaney and Andres, 1991; Mahaney and Kalm, 2000; Rose and Hart, 2008). There are, hence, a suit of textural signatures that can be easily identified and attributed to different environmental origin of sand grains from geological records. They are not full proof because different processes can create similar textures (like principle of equifinality), but when bringing together with other evidences, they are one of the strongest evidences to support with.

3.4.2.5. Clast Fabric Analysis:

Clast macro and micro fabric analysis has wide practical applicability in sedimentary research, especially in glacial geological records because former flow direction as well as many a unknown processes and mechanism can be identified using rigorous fabric analysis. Although their importance as a diagnostic signature is questioned by many researchers but when combined with other components of sedimentary research, they provide essential clues which otherwise may not be possible to identify.

Clast longitudinal axis or a-axis fabric generally found parallel and/or transverse to the flow medium direction i.e. the direction of principle stress, although oblique orientations are also reported elsewhere from deforming till deposits (Zelces et al., 1997; Stanford and Mickelson, 1985) and debris flow deposits (Brodzikowiski and Van Loon, 1991). According to Menzies (1979) clast fabric i.e. dip and trend analysis, not only signify principle stress direction imparted by flowing medium but also their mode of final deposition. Strength or weakness of fabric distribution is also reported along with dip and trend analysis, often as the diagnostic signatures, especially in different types of subglacial tills using statistical techniques. For example, Eigen values i.e. S_1,S_2, and S_3 and Eigen vectors i.e. V_1, V_2, and V_3 are generally calculated out of fabric data (see Chapter 6) (Benn and Evans, 1996, 1998; Menzies, 1979). The strong S_1 and weak S_3 value suggests mean orientation, whereas V_1 (Eigen vector) indicates the degree of clustering (Knight, 1997; Benn and Evans, 1996; Dowdeswell and Sharp, 1986; Hart, 1995). Benn (2002) further devised a triangular diagram for characterizing fabrics of different glacial origin. This triangle (Fig. 43) is generally devised to measure the *Isotropy Index* i.e. I= S_3:S_1, and *Elongation Index* i.e. E= 1- (S_2:S_1). The former measures the similarity of fabric to a uniform distribution while the later measures the preferred orientation of a fabric in the V_1/V_2 plane (Benn and Evans, 1996, 1998). Apart from this, traditionally fabric data are reported by two dimensional diagrams like rose diagrams for trend representation, histograms for frequency distribution of dip angles, and S_1 and S_2 bivariate plots etc., and by three dimensional Stereonet Equal area projection (Hubbard and Glasser, 2005). These methodologies are applied in the present dissertation as well and discussed briefly in the chapter 4, for identifying fabric pattern in drumlin genesis; that is possible glacial processes and mechanism and depositional condition.

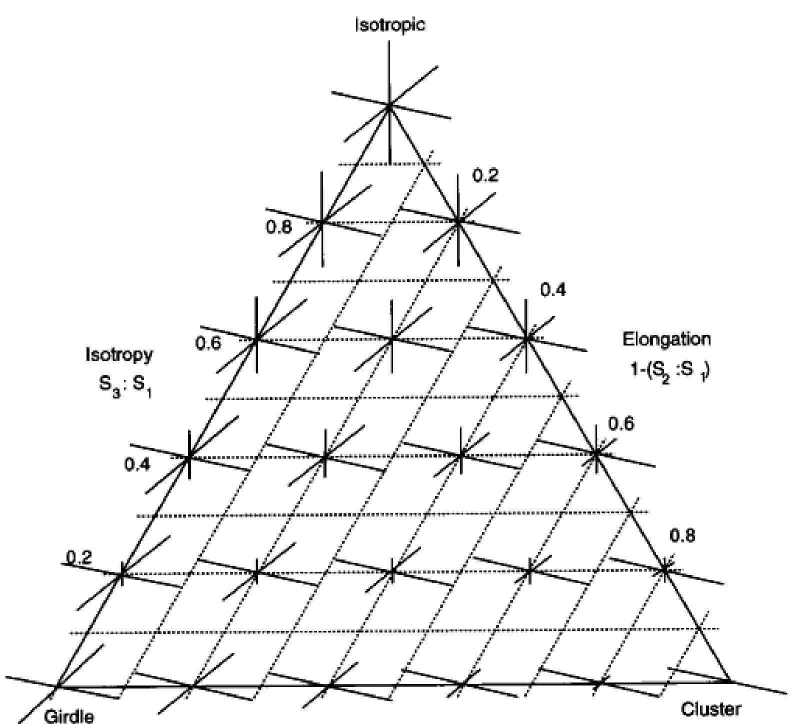


Fig. 43 Isotropic ternary diagram for determining Isotropy (I = S_3: S_1) and Elongation Index (E = 1- (S_2:S_1). Adapted from Benn and Evans (1998).

However, distribution and relative strength of fabric pattern is largely dependent upon various possible factors. Already some of them are discussed in chapter 1 (section 1.3.2.1). Like, according to Evans et al. (2006) parallel fabric may be the outcome of stronger currents (high energy regime) whereas normal fabric may be due to relatively moderate currents (relatively low energy regime). The parallel orientation of clasts is also attributed to extending flow regime (Piotrowski and Vahldiek, 1991) where the stress couple creates faster movement of fluid in the front of the particle than behind. This kind of flow thus, causes rotation along longitudinal axis, called *'Jeffery rotation'* (Fig. 99; in the section 6.2.2.4) (Stanford and Mickelson, 1985; Piotrowiski and Vahldiek, 1991; Carr and Rose, 2003). Similarly, the transverse orientation is attributed to compressive flow regime, where faster fluid motion is possibly occurred above and behind than below and in the front, hence log type rolling is more discernible (Fig. 99; in the section 6.2.2.4) (Stanford and Mickelson, 1985; Piotrowiski and Vahldiek, 1991; Rose and Letzer, 1977). This type of rotation is reported *'Taylor Rotation'* by Carr and Rose (2003). Besides, 'March Model' of deformation structures and fabric is also reported from thin deforming layer where brittle deformation is more likely. In these structures long axes of clasts rotate into parallelism with the plane of slip, towards more parallel orientation to the direction of flow and dragging (Benn and Evans, 1996). According to Wright, Jr. (1957) and Hill (1971) longitudinal orientation of clasts in glaciated condition is also largely due to sliding (dragging) and perpendicular orientations due to clast rotation. It is further stated that in clast rich medium the parallel longitudinal axes orientation is more preferable than transverse and vice-versa. 'Imbrication' of clasts, dipping up-stream, on the other hand, may be due to persistent lower flow regime (Brodzikowiski and Van Loon, 1991). Hence, different flow regime, density or viscosity of flowing medium, thickness of drift materials, density of clasts and any sort of perturbation in the flow etc. are responsible for different degree and orientation of clast fabric pattern, hence they must be taken with sufficient cautions and in combination with other litho-textural attributes. Emphasis solely on clast fabric, more than their satisfactory explanatory capacity, is often criticized in literature (Bennett et al., 1999). In the Himalayas clast micro fabrics are already explained successfully in differentiating process-mechanism, and thus, may prove more than helpful than any other morpho-textural analysis (Owen et al., 1989; Osborn, 1978). Clast micro fabric study also has demonstrated successfully in literature, in deciphering former flow direction and process-mechanism identification, especially from the massive homogeneous till deposits in glaciated environment (Piotrowiski and Vahldiek, 1991; Menzies at al., 1997). Therefore, the possibility of success for micro fabric analysis in the Himalayas may be more than ever appreciated before. However, since the Himalayan glaciers are mostly D-type where post depositional and mass movement processes often produce hybrid depositional structures, any fabric study in this area must take into account the locational as well as regional topographical and allied aspects in mind.

3.5. Glacigenic sedimentary characteristics:

General characteristics of glacigenic sediments may be discussed in the light of different glacial subenvironments as the scheme applied by Brodzikowiski and Van Loon (1991). However, here the glacigenic environment is broadly subdivided into four groups. They are:

1) *Supraglacial subenvironment,*
2) *Englacial subenvironment,*
3) *Subglacial subenvironment,* and
4) *Terminoglacial subenvironment*.

Besides, *Extraglacial subenvironment* is also discussed by Brodzikowiski and Van Loon (1991), but in the present context focus is only placed on the above four glacial subenvironments. A glimpse of extraglacial subenvironment of the study area, although, is already discussed in Chapter-2.

3.5.1. Sedimentary Characteristics of Supraglacial Subenvironment:

Brodzikowiski and Van Loon (1991) have provided five types of genetic facies, common in supraglacial subenvironment in the glaciarized areas. They are viz. supraglacial melting ice facies (includes, melt-out complexes, ablation till, and ice-raft deposits), supraglacial fluvial facies (includes, fluvial complex, tunnel-mouth deposits, stream deposits, stream and sheet-flood deposits), supraglacial deltaic facies (includes, deltaic complexes, deltaic topsets, foresets, and bottomsets), supraglacial lacustrine facies (includes, lacustrine complexes, lake-margin deposits, and lake-bottomset), supraglacial aeolian facies and supraglacial mass-transport facies (includes, subaerial, crevasse, and subaqueous deposits) (Brodzikowiski and Van Loon, 1991). These minor subdivisions of glacial genetic facies are generally observed from retreating glacial environments because of their limited preservational potentiality in the geological records (Brodzikowiski and Van Loon, 1991).

However, in the Himalaya identification of such genetic facies are rather obscured by the thick supraglacial debris cover which have sources through avalanche, debris flow and rock fall from adjacent valley sides and also contribution from tributary glaciers; and most likely, post depositional mass movement processes and glacio-fluvial reworking[18]. Owen et al. (1989) have, although, mentioned a few supraglacial features developed on the surface of the Ghulkin glacier, Karakoram, Pakistan. These are i) supraglacial stream (h), ice contact terraces (i), fines washed from supraglacial moraines (p), ice-cored supraglacial moraines (q), and supraglacial moraines (x) (Fig. 33). Although identification of the facies characteristics are difficult in geological records in the Himalayas due to very low preservational potentiality and obscuring processes, but they are relatively well recognizable from contemporary glacier surfaces.

In general, the sedimentological characteristics of supraglacial stream, deltaic, and lacustrine sediments can be identified; although reworking cannot be ruled out. Cross-bedding and lamination may also be found in well developed in glacio-fluvial facies. Deformation structures are frequent in supraglacial fluvial facies as well. Generally, sorted character may present. However, meltout facies may vary from massive to stratified facies and matrix supported clasts with relatively small average grain size are common characteristics (Brodzikowiski and Van Loon, 1991). Dropstone and clast-damp deposits are common from ice-raft facies. Terminoglacial facies may show coarser gravel rich facies without visible sorting due to high energy regime. Layer of stream flood (within palaeocurrent) and sheet flood (lateral facies distribution in the proglacial outwash) can also have gravel rich bed or beds due to higher energy followed by suspended fines due to reduction in energy (Brodzikowiski and Van Loon, 1991). Lateral facies transition may also be found in supraglacial deltaic facies which if large enough, have distinct topsets, foresets and bottomsets with coarser grain in proximal parts and gradual fining-up more in distal parts (Brodzikowiski and Van Loon, 1991). Deposition through

[18] Due to high rate of ablation and discharge of water in summer, these glaciers are highly active in nature and they are, thus, termed as D-Type and consists of thick debris cover of supraglacial environment (Owen et al., 1989).

suspension and turbidity currents may also help in producing varves in supraglacial lacustrine deposits.

In the Himalaya, however, these so called supraglacial genetic facies are difficult to identify with confidence if not impossible. Hence Owen et al. (1989) have suggested detail lithofacies study to differentiate broadly the supraglacial facies and subglacial and other forms of facies (see Section 3.2). The supraglacial sediments in the Himalaya are more of massive sandy-gravel rich (Fig.34, 35 and 36) matrix supported diamicton. They are mostly polymictic, positively skewed and poorly sorted. Lateral facies transitions are rather difficult to recognize and similarly is differentiating the glacial debris flow deposits from non-glacigenic debris flow deposits (Owen et al., 1989). However, the tills of lateral moraines, ablation valley (e) deposits, flow tills (Fig.33) etc. in glaciomarginal areas are also very important and very closely related to the supraglacial deposits (Owen et a., 1989). According to Benn and Owen. (2002), the debris-mantled Batal glacier, Himachal Pradesh, India, have *"much of ……coarse grained, and angular or very angular (A + AV = 94-98%, where A and AV are angular and very angular clasts, respectively), with mainly slabby*[19] *or elongate forms (C40 = 90-98%, where C40 is percentage of clasts with a c-axis:a-axis ratio ≤ 0.4) and no striated clasts, characteristics typical of passively transported rockfall or avalanche debris"*[20] (Fig. 44). Even extensive existence of glacier tables is reported as well from glacier surfaces. Besides, existence of longitudinal ridges of diamictic debris on glacial surfaces has also been mentioned (Fig. 33) (Benn and Owen., 2002). Analysis showed that these deposits not only contain supraglacial characteristic deposits but also some amount of subglacial deposits. According to Benn and Owen. (2002) these longitudinal ridges have 62-82% of A + Av clasts with C40 = 72-94% and 6-14% of subglacial

[19] Slabby clasts are extensively formed by periglacial processes.
[20] Benn and Ballantyne, 1994 cf. Benn and Owen. (2002).

striated clasts indicating the *"mixtures of rockfall/avalanche debris with basal origin, probably elevated along medium flowlines"* (Boulton, 1978 cf. Benn and Evans, 1998). Hence supraglacial sediments are vary chaotic in nature in the Himalayas and they are equally difficult and need care to use as signatures in geologic deposits, if not in contemporary supraglacial regime, unlike those which are generally discovered in higher latitudinal glaciated and glaciarized terrain[21].

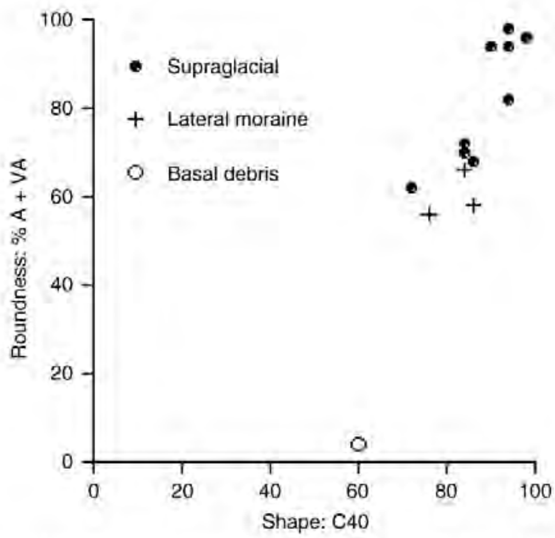


Fig. 44 Clast characteristics of debris from Batal Glacier, Lahul. C40 is the percentage of sample with a c-axis ratio ≤0.4 (slabby and elongate clast shapes); % A+VA is the percentage of angular and very angular clasts in the sample. Each point represents 50 clasts. Adapted from Benn and Owen (2002).

3.5.2. Sedimentary Characteristics of Englacial Subenvironment:

Benn and Owen. (2002) did talked about three major processes of incorporation of clasts and sediments as englacial deposits but the identification of these facies in geological record is not mentioned extensively in the Himalaya. The three main processes are – i) incorporation of debris in accumulation areas of glaciers, supplied by avalanching, rockfall etc., and latter embedded as englacial clasts with further snowfall over them submerge them followed by englacial transport, ii) incorporation of basal debris through thrust planes and iii) crevasse collapse of sediments to englacial caves or tunnels etc. (Benn and Owen, 2002). The crevasse deposits in the Himalaya contain variety of supraglacial deposits (Raina and Srivastava, 2008).

[21] The former glacial covered areas are indicated by the term glaciated areas and contemporary glacial covered areas are indicated by the term glaciarised areas (after Brodzicowiski and Van Loon, 1991).

However, details of different englacial genetic facies have been mentioned by Brodzikowiski and Van Loon (1991) but their preservation potentiality is very low. These includes englacial melting-ice facies which incorporates meltout complexes; and englacial fluvial facies which incorporates meltwater-tunnel deposits, and crevasse deposits. According to them the melt-out facies contains sandy/silty/clayey grain size materials with massive structures and ice-raft boulders (bullet-shaped clasts) in scattered manner, lenses and pockets of uniform grain size may generally found. The englacial fluvial facies generally lacks fines due to wasting effects by melt-out water in pressure. Cross bedding, stratification, and lenses structures are also commonly occurs. Clasts with fresh broken surfaces and striations are also can be easily identifiable. Edge rounding of clasts is also common in tunnel deposits. Lack of studies of englacial deposits due to inaccessibility makes their comparison difficult to other regions.

3.5.3. Sedimentary Characteristics of Terminoglacial Subenvironment:

The so called terminoglacial genetic facies, published so far in the literature, are extensively discussed by Brodzikowiski and Van Loon (1991). These include terminoglacial melting-ice facies (includes, till complexes, ice-raft deposits), terminoglacial fluvial facies (includes, fluvial complexes, tunnel mouth deposits, stream deposits, and sheet and stream flood deposits), terminoglacial deltaic facies, lacustrine facies, and mass-transport facies. However, terminoglacial aeolian facies has also been discussed. The melting-ice facies generally have variable matrix (clay to coarse sand) with occasional floating ice-raft deposits. Sveg till [22] coarse clast with horizontal bands are of common signature. Fluvial facies in terminoglacial

[22] Given by Lundquist, 1969 (Brodzikowiski and Van Loon, 1991)

subenvironment are more or less composed of matrix supported gravelly massive bed with poor sorting, reflecting the high energy condition predominant in this sub environment. Imbrications may occur dipping upstream. The esker formation is the most common glacial feature in the tunnel-mouth (Brodzikowiski and Van Loon, 1991). Clasts breccias are also common features. Evidences of sheet flood are more or less recognizable in distinct layers from glacigenic records. Different forms of deltas [23] and lacustrine varves are well recognized in the facies transition as they retains their basic characteristics but only recognizable if lateral facies transition is clear (Brodzikowiski and Van Loon, 1991). And because of the high energy condition the deltaic deposits lacks distinction between foresets and topsets. Post-depositional deformation is most likely process. Lenticular structures in terminoglacial deltas, however, often indicate the role of currents which frequently induced by glacio-fluvial streams / tidal currents (Brodzikowiski and Van Loon, 1991). The masstransport facies, on the other hand, lacks sorting and often slumps lobes may be found. Suspension and turbidity currents are mainly responsible for the varve formation in lacustrine deposits (Brodzikowiski and Van Loon, 1991).

However, the terminoglacial condition in the Himalayan glacial system is rather lacks such kind of clear distinction between different genetic facies mentioned above, mostly in ancient records. However, the contemporary glaciers like, Ghulkin, Pasu, Minapin, Ghulmit etc. in Karakoram, Pakistan, (Owen et al. 1989) have produced several distinct land features and related facies development, distinct to Himalayan conditions. These D-type glaciers with very high summer ablation often destroy or modify the terminal deposits. But since the input of debris is very high enough, land features like, ice-contact fans, ice-contact morainic fans (Fig. 33), galcio-fluvial outwash fans (4), slide moraines (5), slide-debris flow cones (6), slide modified

[23] Alluvium fan delta, braid plan or sandur delta etc.

lateral moraines (7), abandoned lateral outwash fan (8), meltwater channel (9), meltwater fan (11) (Owen et al., 1989), latero-frontal moraines (Benn and Owen, 2002) etc. are well developed. The descriptive names of the features do provide their characteristics geometry and processes operating on them. However, the ice-contact fans, according to Owen et al. (1989) are one of the most extensively and well recognized form in Ghulkin, Pasu, and Gulmit glaciers in Karakoram. They are cone shaped with predominant processes of slide and debris flow. Sometimes stratified till due to halt in masstransport mechanism (grain flow mechanism causes grain-size variation and pseudo stratification) and glacio-fluvial processes are the common structural characteristics. However, ice contact moraine fans generally flank the valley side with glacier present at the top whereas glacier toes have step scarp face (Owen et al., 1989). The slope is less for the latter than for the former. Ancient example of such features are commonly found in Hunza Valley (Karakoram, Pakistan) but lacking in the distal parts of Indus and Gilgit valley possibly because of modification and destruction which increases with distance (Owen et al., 1989). Formation of secondary ice-contact fans has also been mentioned by them within larger fan valleys due to downwasting of ice. Disconformities are generally found due to massive debris flows or such related processes (Owen et al., 1989). Flow slides in marginal areas and outwash fans with glacio-fluvial action often produce large fan facies distribution of such ice-contact fans, distinct from other glaciated areas (Owen et al., 1989). Extensive and sloppy lateral moraines (common in D-type glaciers) are also described by Benn and Owen (2002) as massive, large and thick (as much as 100m.) features with predominance of sliding processes in Ghulkin glacier.

Proglacial facies in the Himalaya usually contains proglacial lacustrine complexes, Hummocky moraines with pit intervals, dead ice cored end moraines or simply end moraines and often braided stream conditions. This subenvironment contains deposits which are generally polymictic, poorly sorted diamicton with diffuse fabric or parallel to the depositional surface due to sliding etc. However, those which are subglacially affected due to ice readvance (push effect) shows strong preferred orientation of clast a-b plane dipping up-valley. Hummocky or disintegration moraines are the result of the glacial retreat (ice-wasting) and contain irregular arrangement of pits and mounds. These morphological forms generally contain supraglacial meltout debris but may also have supraglacial lacustrine sediments (Owen et al., 1989). Large amount of annual debris supply, presently retreating evidences of glaciers and occurrence of debris-mantled dead ice bodies are the main reason of the occurrence of the hummocky moraines in the Himalaya (Owen et al., 1989). Pits in between hummocky moraines are generally shows the sign of dried out pool with silty lithology and planner bedded and planer laminated structures. Due to restricted origin the proglacial lakes are limited in spatial extent and lake margins bear the signature of mass transport processes. Deposition takes place through suspension and/ turbidity current. Ice-raft and clasts-damp deposits too are common occurrences (Brodzikowiski and Van Loon, 1991).

However, the extraglacial facies and periglacial processes also have more pronounced effect in the evolution and modification of former glacigenic deposits and landforms, especially in the Himalayas (see section 2.4.1). Hence they also need rigorous and careful investigation.

3.5.4. Sedimentary Characteristics of Subglacial Subenvironment:

Subglacial depositional environment shows variety of sedimentological characteristics and structural fingerprints. The major till types generally found in this subenvironment, incorporates deformation till, comminution till, lodgement till, glacitectonite, meltout till and sublimation till. Recently, Evans et al. (2006) have categorized them under three broad categories because of their overlapping and hybrid character. They are a) glacitectonites (both penetrative and non-penetrative subtypes), b) subglacial traction tills (includes deformation till, lodgement till, comminution till, sliding bed deposits, and lee-side cavity fills), and c) meltout tills (includes both meltout and sublimation till). The glacitectonites are rock or sediment units that have been deformed by subglacial shearing or deformation but retain some of the structural characteristics of the parent material (Evans et al., 2006). Subglacial traction tills are sediments deposited by glacier sole activities, either sliding over and/or deforming their beds, the sediments having been released directly from the ice by pressure melting and/or liberated from the substrate and then disaggregated and completely or largely homogenized by shearing (Evans et al., 2006). The subtypes i.e. deformation till, however, is applied to those which apparently shows homogenized, possibly due to glacier-induced shear of subglacial materials, whereas lodgement is defined by Evans et al. (2006) as, "… the plastering of glacial debris from the base of a sliding glacier on to a rigid or semi-rigid bed by pressure melting and/or other mechanical processes (pp- 118-119). Deformation till can further subdivided into two subtypes i.e. a) pervasive ductile deformation, and b) brittle shear. Meltout tills are more of theoretical construction because their direct field verification is still lacking. However, sediments released by the melting of stagnant or slowly moving debris-rich glacier ice, and directly deposited without subsequent transport or deformation, are interpretated as meltout till (Evans et al., 2006).

Apart from the variety of till types subglacial environment incorporates landforms like, drumlins, roches moutonee, fluted moraines, rogen moraines, crag and tails, eskers etc. Most of them are streamlined forms, distinct to subglacial (sub)environment. There is a very close relationship between subglacial sediment characteristics and these landforms—strong landform-facies association. Already in section 1.3.2.1 (Chapter -1), the complex relation of subglacial sediments with drumlin formation are discussed briefly. Benn and Evans (1998) have further review the relationship with other subglacial landforms. However, most of the studies concluded that deformation is the most prevalent and common process under subglacial condition (Menzies, 1979; Benn and Evans, 1998; Stokes et al., 2011). Deformation style and intensity, although, is influenced by a great many different sorts of subglacial conditions viz. over burden and stress imposed by glacier ice, content of water in the sediment unit, composition and thickness of the unit, as well as the temperature condition in the subenvironment (Evans et al., 2006). These factors often act together and lead to great variety of subglacial compositions and structural preservation. According to Evans et al., (2006), shear deformation, lodgement and ploughing—all processes are simultaneously taking place under subglacial condition over space and time and possibly *'Stick-slip type'* motion is responsible for the subglacial deformation, lodgement and other complex subglacial till sequences. According to them increase in shear stress either due to increase in overlying ice-pressure or increase in the effective pressure due to pore water pressure reduction, may cause lodging and ploughing of clasts in the substrate condition and thus develop *'prow-like'* structures (Fig. 45). This structure possibly arrests the forward movement of the clast and give rise to the final lodgement. Often it is stated that may be due to buoyancy and more shear strength the larger size clasts are more prone to ploughing and lodgement. The ploughing clasts may further augment deformation by two possible ways. Firstly, reducing the shear strength of underlying sediment through mechanical ploughing, and secondly increasing resistance may create more pressure melting and increase in porewater content and possibly more dilation of the sediment and subsequent deformation of the now plastically behaved sedimentary unit. They used the *Coulomb plasticity motion* equation (equation 17) to deal with this aspect. However, if the porewater pressure increase and critical stress exceeds a certain limit, slipping may take place instead of deformation, but when porewater dissipation takes place may be through underlying sediments or through overlying coarser materials, the effective stress further increase, leading to higher stress regime and deformation i.e. sticky motion[24]. It is the final form of deformation that is actually preserved in the few meters of sedimentary unit, according to them; and that may only take place when pore water pressure is low enough to generate liquefaction or flow but sufficient enough for deformation to occur. Further dissipation may lead to collapsing and brittle deformation of otherwise pervasive ductile deformation under relatively high porewater pressure, and subsequently again lodgement and ploughing may start. This *'stick-slip motion'* model of Evans et al (2006) effectively deals with many of the major complexities, experienced and reported in the geologic records, of subglacial subenvironment, although further support is required through more rigorous future field studies. Often rapid transition is recorded in the field from deforming to non-deforming tills (lodgement, ploughing etc.) or vice versa (Hart, 1995). The above model, thus, can effectively explain this form of till composition. Besides, the variable fabric patterns from subglacial deformation and lodgement tills are already discussed in the section 3.4.2.5 of clast fabric analysis. It is also suggested by Evans et al. (2006) that the subglacial sedimentary subenvironment generally consists of polyphase sequences i.e. polygenetic in origin rather than single phase of massive deposition. According to the model the repeated fluctuation in porewater pressure may result in the accretion of several layers of variably deform diamictons, separated by planer (detachment) or erosion surfaces, which when undergone later stage of pervasive ductile deformation, finally may appear as massive till sequence. Hence, wide range of dip values (anisotropic) and weak to moderate

[24] According to Evans et al. (2006) the plastically behaved till-matrix framework will begin to develop as dilation decreases, leading to a rise in intergranular contact and density and deformation. Their preservation within the till sequence is also dependent upon the degree of compaction.

preferred orientations of clast fabrics (low elongation) is the likely characteristics of such till composition. In terms of lithological and textural properties, the subglacial sedimentary deposits vary widely as well, as discussed in the section 1.3.2. The grain size ranges mostly from sandy grains to clay-silt in lacustrine and other deposits. While subglacial canal transport causes in most cases edge rounding of gravels, comminution causes fresh angular fracture faces and edges (Broadzikowiski and Van Loon, 1991). Apart from these, fissel clast arrangements, joints, and faults etc. brittle structures are also common in lodgement type till sequences (Brodzikowiski and Van Loon, 1991) . Imbrications are rare under meltwater stream deposits. It may be due to very high porewater pressure and high activity glaciers. Brodzikowiski and Van Loon (1991), however, have mentioned a number of genetic facies found in subglacial subenvironments. They are: a) subglacial melting-ice facies (includes, till complexes, lodgement till, basal till and ice-raft deposits), b) subglacial fluvial facies (includes, melt-water tunnel deposits), c) subglacial deltaic facies (includes, deltaic complexes), d) subglacial lacustrine facies, and e) subglacial mass transport facies. These variety of facies are not mentioned till now in the Himalayan glacial environment, possibly because of inaccessibility in the present glaciarized areas and chaotic and polygenetic nature of glacial deposits in the glaciated areas; although broadly subglacial and supraglacial deposits are differentiated by earlier workers (Fig. 34, and 35). According to Owen et al. (1989) and Benn and Owen (2002), the subglacial deposits are mostly consisting of gravelly-sandy grains with very high share of striated clasts (see section 3.2). They also mentioned that subglacial tills of basal origin are generally found in thin covers. At the base of Naktok glacier, Karakoram, Pakistan, they have reported 1m. thick striated debris-rock layer, possibly incorporated in the basal-ice zone by subglacial freeze-on process. Apart from that, lee side cavity filling roches moutonnees are also reported by Benn and Owen (2002), these scattered evidences in the literature, thus, indicate that that the subglacial environment is not explored extensively in the Himalayas and since drumlins are the diagnostic to marginal and subglacial streamlined bedforms, the present study holds the key to explore the process-mechanism in the Himalayan subglacial environmental setting, especially near the ice margins from the geologic record. Their interpretation, hence, must be based on detailed systematic observation and guided by sound theory.

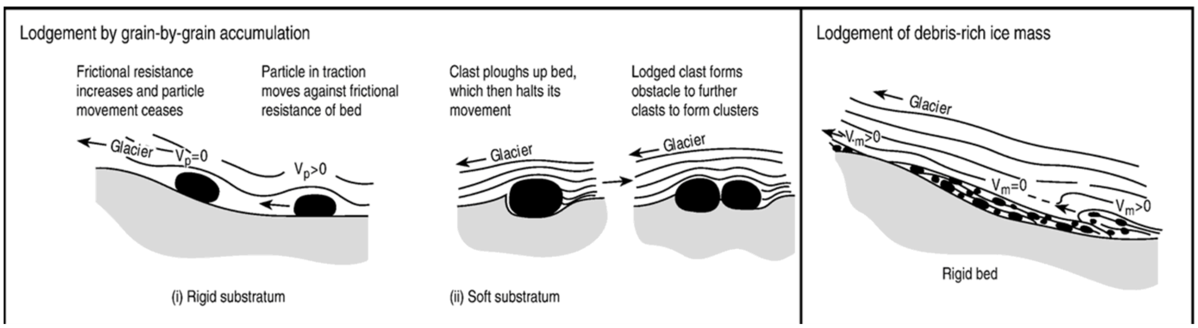


Fig. 45 Graphic description of the lodgement process under submarginal and subglacialsubenvironments (after Boulton, 1982). Note that deformation is inextricably linked to lodgement on a soft substratum. Adapted from Evans et al. (2006).

3.6. Nomenclature (or Codes) Used in Lithofacies Study (after Benn and Evans, 1998):

In lithofacies study of glacigenic sediments, often descriptive nomenclature or codes are used rather the genetic codes because of their chaotic nature and complex genesis. Assigning descriptive names/codes to the sedimentary unit, therefore, involves the inherent underestimation of some of the important lithological and textural descriptions, as well as the exclusion of the diagnostic or genetic properties to a certain extent (Benn and Evans, 1998). However, according to Benn and Evans (1998), *"….a comprehensive description of a sediment should include details of: (a) its properties, allowing aspects of its erosional, transportational, and depositional history to be reconstructed; (b) its geometry; and (c) its position with respect to the adjacent sediments and the land surface at a range of scale."* However, in practical the descriptive names/codes only includes some of the basic properties and far from comprehension and thus, it is necessary to consider the importance of the study of *'Sedimentary Graphic Logs'* and *'Mapping'* together (Benn and Evans, 1998). However, it is also very much important to apply such names/codes depending on the objectives of the study and properties which are, at least, required to retain. There are, however, range of lithological (such as, grain size, matrix-support, contact surface, structures, geometry etc.) and structural (such as, grain shape, grading, roundness, fabric etc.) properties which are applied while assigning descriptive names/codes. The first successful introduction of descriptive names (codes) using letters was given by Miall (1977, 1978 cf. Benn and Evans, 1998) for the deposits of a braided river system followed by the modification of Eyles et al. (1983 cf. Benn and Evans, 1998). However, these lithofacies nomenclature (codes) still lacks comprehension to describe the diversified nature of glacigenic environment (Benn and Evans, 1998). This research paper includes the modified scheme of descriptive lithofacies codes after Benn and Evans (1998)[25]. The lithofacies codes are given in the Table-4.

[25] Benn and Evans (1998) had modified the descriptive lithofacies codes after Miall (1978 cf. Benn and Evans, 1998) and Eyles et al. (1983).

Table: 3 Descriptive Lithofacies coding scheme, modified from Miall (1978) and Eyles (1983) and Other Sources (adapted from Benn and Evans, 1998)			
Code	**Description**	**Code**	**Description**
Diamictons	Very poorly sorted admixture of wide grain size range	**Granules**	Particles of 2-8 mm
Dmm	Matrix-supported, massive	GRcl	Massive with clay laminae
Dcm	Clast-supported, massive	GRch	Massive and infilling channels
Dcs	Clast-supported, stratified	GRh	Horizontally bedded
Dms	Matrix-supported, stratified	GRm	Massive and Homogeneous
Dml	Matrix-supported, laminated	GRmb	Massive and pseudo-bedded
_ _ _ (C)	Evidence of current reworking	GRmc	Massive with isolated outsize clasts
_ _ _ (r)	Evidence of resedimentation	GRmi	Massive with isolated, imbricated clasts
_ _ _ (s)	Sheared	GRmp	Massive with pebble stringers
_ _ _ (p)	Includes clast pavement(s)	GRo	Open-work structure
		GRruc	Repeating upward-coarsening cycles
Boulders	Particles > 256 mm (b-axis)	GRruf	Repeating upward-fining cycles
Bms	Matrix-supported, massive	GRt	Trough cross-bedded
Bmg	Matrix-supported, graded	GRcu	Upward coarsening
Bcm	Clast-supported, massive	GRfu	Upward fining
Bcg	Clast-supported, graded	GRp	Cross-bedded
Bfo	Deltaic foresets	GRfo	Deltaic foresets
BL	Boulder lag or pavement		
		Sands	Particles of 0.063-2 mm.
Gravels	Particles of 8-256 mm.	St	Medium to very coarse and trough cross-bedded
Gms	Matrix-supported, massive	Sp	Medium to very coarse and planar cross-bedded
Gm	Clast-supported, massive	Sr(A)	Ripple cross-laminated (type A)
Gsi	Matrix-supported, imbricated	Sr(B)	Ripple cross-laminated (type B)
Gmi	Clast-supported, massive (imbricated)	Sr(S)	Ripple cross-laminated (type S)
Gfo	Deltaic foresets	Scr	Climbing ripples
Gh	Horizontally bedded	Ssr	Starved ripples
Gt	Trough cross-bedded	Sh	Very fine to very coarse and horizontally/plane bedded or low angle cross-laminated
Gp	Planer cross-bedded	Sl	Horizontal and draped laminated
Gfu	Upward-fining (normal grading)	Sfo	Deltaic foresets
Gcu	Upward-coarsening (inverse grading)	Sfl	Flasar bedded
Go	Openwork gravels	Se	Erosional scours with intraclasts and crude cross-bedded
Gd	Deformed bedding	Su	Fine to coarse with broad shallow scours and cross-stratification
Glg	Palimpset (marine) or bedload lag	Sm	Massive

Code	Description	Code	Description
Sc	Steeply dipping planar cross-bedding (non-deltaic foresets)	**Silts and Clays**	Particles of <0.063 mm
Sd	Deformed bedding	Fl	Fine laminated often with minor fine sand and very small ripples
Suc	Upward-coarsening	Flv	Fine laminated with rhythmites or verves
Suf	Upward-fining	Fm	Massive
Srg	Graded cross-laminations	Frg	Graded and climbing ripple cross-laminations
SB	Bouma sequence	Fcpl	Cyclopels
Scps	Cyclopsams	Fp	Intraclast or lens
_ _ _ (d)	With dropstones	_ _ _ (d)	With dropstones
_ _ _ (w)	With dewatering structures	_ _ _ (w)	With dewatering structures

Chapter—4

METHODOLOGY AND LIMITATIONS OF THE STUDY

"... it is dangerous to be too precise with very little data to base judgments on ...".

——Ian. J. Smalley and J. Unwin (1968)

4.1. Introduction to the Basic Framework of the Study:

Methodological framework holds very fundamental and crucial part of any scientific study. Glaciology being interdisciplinary in nature has evolved quite dramatically especially over the last 150 years in general, whereas the study of Himalayan cryosphere has flourished over the last two decades. Quaternary glacial chronological study based on morphostratigraphy and dating methods (both relative and numerical), mass balance and meltwater discharge measurements etc. are now extensively applied in this high mountain realm. Detail and systematic analysis of subglacial materials form the geological records, however, still lacking in the Himalayan environment. Equally true is the study of drumlins—a streamlined form, which although reported sporadically elsewhere in the Himalayas on the basis of only their form analogy, detail study of their true existence, genesis, and evolutionary history are largely understated or not stated. This drumlin puzzle thus remains as a major research gap in the Himalayas. Already late Quaternary glacial chronology of the Lahul Himalaya (especially Chandra and Bhaga basin) is given based on the drumlins along with moraines and other morphological forms (Owen et al., 1995, 1996, 1997, 2001). This has sparked the debate regarding the very existence and development of such landform in the rugged high Himalayan terrain, because drumlin are mostly found in the former ice-sheet covered (glaciated) areas of the mid-latitudes, which is in sharp contrast to the high activity valley glaciers with the domination of thick supra glacial debris cover in the Himalayas (Owen et al., 1989). Owen et al. (1995,1996,1997) on the basis of the distribution of drumlins, moraines, striae, trimline and polished surfaces in the Chandra Tal, Batal, and other tributary valleys, have theorized the possibility of having once sufficiently thick valley glacier in the area but the very genesis and evolution of the drumlins, apart from their morphological form (on which the chronology is largely supported), still remains a major research gap. Hence, as discussed in chapter1 (see section 1.5.), the approach that is followed as a basic methodological framework in the present study, is the geomorphological mapping and compositional (sedimentary) analysis of the drumlins, followed by a theoretical reconstruction of their possible evolution in the Study Area. In terms of the sedimentological analysis, a brief description is already given in Chapter 3 (see section 3.2.) regarding the practicality of the use of lithofacies study in the Himalayas; hence the methodologies applied for studying the drumlin in detail, incorporates the above approach in general and litho-textural analysis in particular.

The current study, however, is entirely framed on fulfilling the basic objectives of the study (see section 1.11.). These objectives involve the identification of the landform (as drumlin), and their spatial distribution in the Himalayas, followed by their distinct morphological forms, genesis, and reconstructed evolutionary history in the study region. The basic data base (see section 1.12.) includes majority of primary field data (see section 1.12.1.1.) and laboratory data (see section 1.12.1.2.). Although secondary data set (see section 1.12.2.) is used too, but their use is limited in the current work. However, the rationally behind putting major emphasis on primary data may be discussed in the following section before explaining the detail methodologies applied so far.

4.2. Primary Data versus Secondary Data:

The current study of drumlins is based on the detail analysis of morphology and sedimentology in their selected sites (in Chapter 2, see section 2.2.), to be precise, in the Upper Chandra (site 1 of Fig. 14) and Yunan valley (site 2 of Fig. 14) and Kunzum La (site 3 of Fig. 14) area. The drumlins in these selected sites are generally found en echelon in a field (swarm), like basket of half buried eggs, as generally reported as the diagnostic to drumlin distribution elsewhere in the world (see section 1.8.), but their sizes (median length is ~58m. at the site 1 and width is also comparatively low) are small when compared with other drumlins in the mid-latitude glaciated (ice-sheet) regions (Fig.12). Due to this reason the presently available Advance Spaceborn Thermal Emission and Reflection Radiometer (ASTER) imageries with spatial resolution of ~30m. and even the Indian Remote Sensing series Cartosat-1 imageries with spatial resolution of ~2.5m. are unable to clearly detect the landforms and their precise distribution. In fact, in Yunan valley (site 2), the high resolution Google Earth satellite imageries, although are to some extent able to identify some of the larger drumlin forms at site 2, but may be due to strategic reasons, the area which is surveyed in particular possesses plates of very coarse (spatial) resolution; hence largely unsuitable for morphological and morphometric study of drumlins. Few studies also incorporate Resource Satellite imageries, for example, Saha (Article in Press) have used Landsat TM and ETM data also for studying drumlins, but even the Liss III data of IRS series with nearly ~23.5 meter of spatial resolution is largely unsuitable for such analysis. The topographical sheets are surveyed at the lowest scale of 1:50,000 (52 D/12 and 52 H/5) by the Survey of India (SOI) but they are also highly unsuitable for identifying and spatial mapping of drumlins. Strategic reasons is the another major cause that the aerial photographs are not sought because of time constraints. Hence the only option left with is the detail field surveying and mapping. Besides, the length, height, cross section etc. can only possibly be done at the very high resolution. Thus, only the primary survey is left with preferable option for studying them in detail.

Apart from that, the sedimentological analysis of the genesis of drumlins requires detail field evidences of the composition and structures of internal bed materials. Since, no other works have been done previously regarding this aspect, the reliability can only be placed on primarily recorded data base. Equally important is the fact that both macro and micro level analysis of glacial sediments have their own merits and limitations. It has already been discussed in section 3.5 of chapter 3, about the complexities related to the Himalayan glacigenic environment and their polygenetic nature. Hence while at macro level many of the deformational, erosional and depositional features are identifiable, these evidences may not prove suitable if the composition is more of massive in appearance or possess greater level of homogenization and complex clast rotation (fabric) patterns. Similarly if subglacial in origin, grain crushing and abrasion effects and clast striae are not always visible in necked eyes, hence micro level analysis is equally important to supplement the macro level limitations. Hence the present study being a preliminary attempt to study the drumlins in this environment, is taking more of a holistic approach, incorporating both macro level field mapping and sedimentological analysis to micro level analysis of surface textures of Quartz sand grains.

The primary data collected and recorded during the two field surveys and later in the laboratory, are mainly geomorphological maps, clast macro fabric analysis, surface exposure sketching, and sedimentary log preparation, grain size measurements, geomorphological cross sections and basic data of drumlin length, height etc., field notes and photographs, and Scanning Electron Microscopic (SEM) analysis of surface textures of Quartz sand grains. Contrary to this, limited secondary data are used either to support the primary data, such as geomorphological maps or deciphering the information of surroundings of the study area in terms of its physical settings. The secondary data used so far are topographical map at 1:250,000 scale (NI 43-16 by SOI), geological map, soil map, aspect map, slope map, relative relief and precipitation distribution map, and drainage density and stream texture maps, and other maps and diagrams from different sources of literature, Google Earth imageries, IRS Cartosat-1 imageries, LISS III imagery and IMD meteorological data at Keylong, Himachal Pradesh, India. They are briefly discussed in the following sections. But first the coding procedure of the samples of the present study, are required to mention in order to simplify further discussion.

4.3. Coding of Samples:

Samples are given codes on the basis of their location and/or type of source from where samples are collected. Since samples are collected during two field trips, there are some variations in the coding, and also for KG1/DPF drumlin, in site 1, the same sample site is later coded as DPF1 because during the 2nd phase, the study is conducted at depth from the surface of the drumlin. The location of the samples is given in Fig. 85. The sample coding procedure, however, is simplified in the Table: 4.

Table: 4 Coding Procedure Followed in the Present Study (For reference see the Figure 85)

Study Area	Sample Code	Location		Sample Collected from	Remark
		Latitude	Longitude		
Site 1	KG1/DPF	32.477	77.614	From the surface of the drumlin at the depth of 15 cm; this is the immediate lee face of the drumlin.	Samples are collected for SEM and grain size analyses, and clast fabric measurement is done on the field.
	DPF1	32.477	77.614	Sample is collected below 60 cm. depth from the drumlin surface.	Clast fabric measurement is done; both KG1/DPF and DPF1 are from same sample site (Fig. 85) but given different codes during different field visits.
Site 1	KG2/DPF	32.463	77.617	From the surface of the drumlin at the depth of 15 cm; this is at the ridge high of the drumlin.	Samples are collected for SEM and grain size analyses, and clast fabric measurement is done on the field.
Site 1	DPF2	32.468	77.617	From the surface of the drumlin at the depth of 15 cm; this is at the ridge high of the drumlin.	Samples are collected for SEM and grain size analyses, and clast fabric measurement is done on the field.
Site 2	DPF3	32.452	77.613	At the entire surface of the drumlin only; this is situated further south of Chandra Tal.	Lodged boulders are measured for trend analysis
Site 1	IDPF1	32.477	77.615	From the surface of the interdrumlin depressed area at depth of 15 cm; this is the depression between two drumlins.	Samples are collected for SEM and grain size analyses, and clast fabric measurement is done on the field.
Site 2	Sarchu 1 or Exposure 1	32.846	77.500	From the road cut exposure at the middle of the stoss side of the drumlin.	Samples are collected for grain size analyses, and clast fabric measurement and sediment log are prepared on the field.
Site 2	Sarchu 2 or Exposure 2	Do	Do	From the road cut exposure at the middle and upper portion of the lee side of the drumlin.	Only clast macro fabric measurement is done during field survey.
Site 3	KUN/07/50	32.409	77.638	Clast fabric measurement is done at 15 cm. depth below the drumlin surface at the ridge high, and boulder fabric measurement at the entire surface of the drumlin.	Samples are collected for SEM and grain size analyses, and clast and boulder (lodged at the surface) fabric measurements are done on the field.

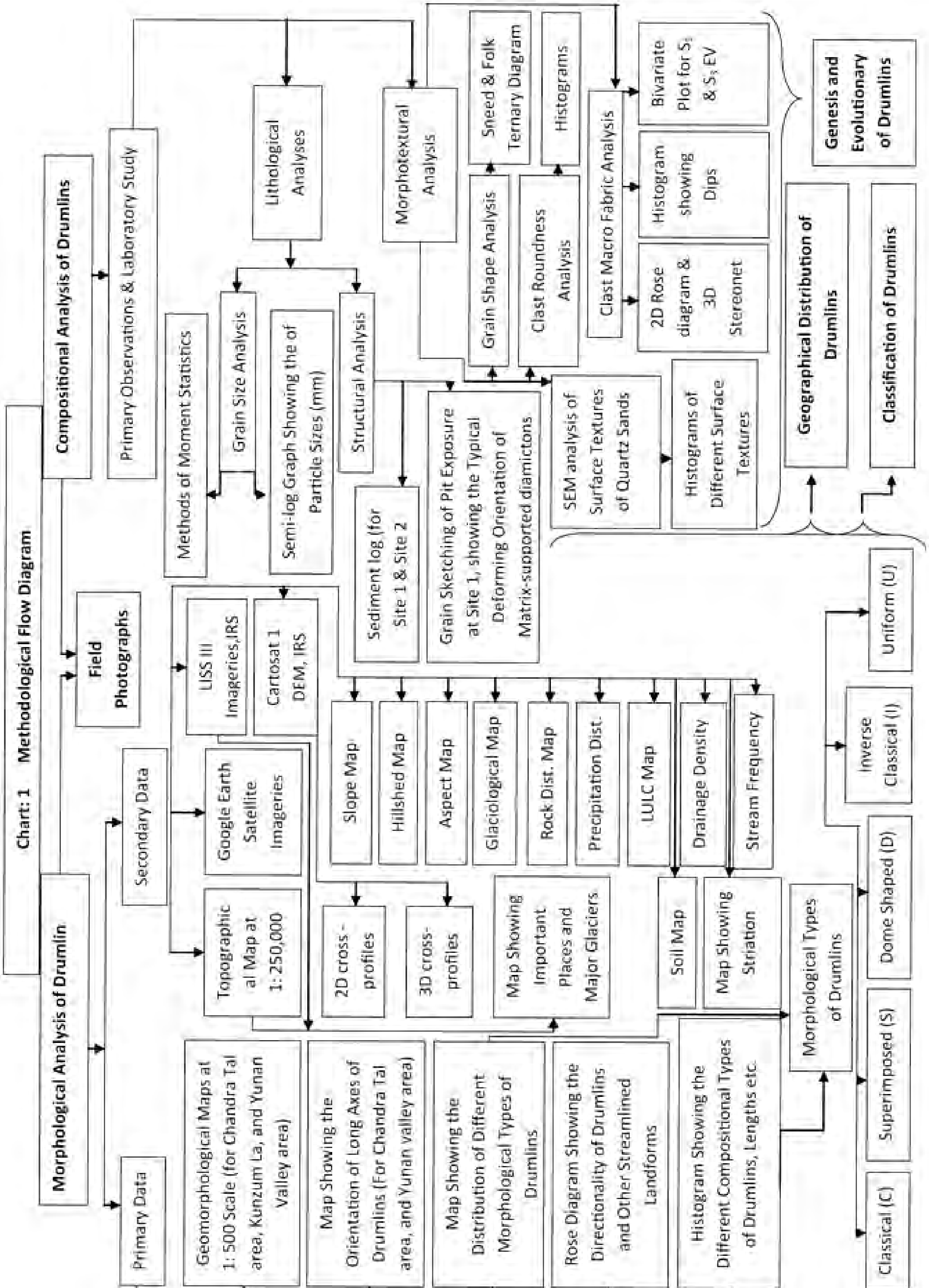


Chart: 1 Methodological Flow Diagram
Morphological Analysis of Drumlin
Compositional Analysis of Drumlins
Primary Data
Secondary Data
Field Photographs
Primary Observations & Laboratory Study
Geomorphological Maps at 1: 500 Scale (for Chandra Tal area, Kunzum La, and Yunan Valley area)
Map Showing the Orientation of Long Axes of Drumlins (For Chandra Tal area, and Yunan valley area)
Map Showing the Distribution of Different Morphological Types of Drumlins
Rose Diagram Showing the Directionality of Drumlins and Other Streamlined Landforms
Histogram Showing the Different Compositional Types of Drumlins, Lengths etc.
Topographic al Map at 1: 250,000
Google Earth Satellite Imageries
LISS III Imageries, IRS
Cartosat 1 DEM, IRS
2D cross-profiles
3D cross-profiles
Map Showing Important Places and Major Glaciers
Slope Map
Hillshed Map
Aspect Map
Glaciological Map
Rock Dist. Map
Precipitation Dist.
LULC Map
Drainage Density
Stream Frequency
Soil Map
Map Showing Striation
Morphological Types of Drumlins
Classical (C)
Superimposed (S)
Dome Shaped (D)
Inverse Classical (I)
Uniform (U)
Lithological Analyses
Morphotextural Analysis
Methods of Moment Statistics
Grain Size Analysis
Semi-log Graph Showing the of Particle Sizes (mm)
Structural Analysis
Sediment log (for Site 1 & Site 2
Grain Sketching of Pit Exposure at Site 1, showing the Typical Deforming Orientation of Matrix-supported diamictons
Grain Shape Analysis
Sneed & Folk Ternary Diagram
Clast Roundness Analysis
Histograms
Clast Macro Fabric Analysis
2D Rose diagram & 3D Stereonet
Histogram showing Dips
Bivariate Plot for S₁ & S₃ EV
SEM analysis of Surface Textures of Quartz Sands
Histograms of Different Surface Textures
Geographical Distribution of Drumlins
Classification of Drumlins
Genesis and Evolutionary of Drumlins

4.4. Methodology and Limitations of the Present Study:

A glimpse of the methodological framework applied so far in this analysis can be exhibited through a flow chart diagram in Chart 1, which incorporates two major sections of study i.e. morphological and compositional analysis input and are ultimately combined to postulate the genesis and evolution of the Himalayan drumlins with the special emphasis on the Lahul Himalaya, the Western Himalaya, India. The methodological selection, however, is different for each other, driven by the objectives of the study and are briefly discussed as follows.

4.4.1. Methodology for The Primary Data Input:

The primary data record and collected in the field, are based on the standard methods mentioned elsewhere in the books and articles of reputed journals. Several methodological limitations, although, are there while conducting field surveys and they are mentioned along with. But it is believed that they may not be large enough to influence the reliability of the results of the present study. It is also the preliminary study and further field experiences are required regarding several aspects. Many problems also came into the picture during processing of the data. However, they are discussed in the following points and is open for suggestion.

4.4.1.1. Preparation of the Geomorphological Maps:

Geomorphological maps are the first to survey and record during two field surveys; one was conducted in late June and early July, 2012 and another in early September in 2012. The purpose is to identify the geographical (spatial) distribution and general orientation of the longitudinal axis of the smooth elongated (streamlined) mounds in the three surveyed sites found en echelon. Since this basic objective requires the above aspects to fulfill the reconnaissance geomorphological maps are prepared for the present study site 1 (near Chandra Tal area, ~4,300 m asl.), site 2 (in the Yunan valley, ~4,450m asl.), and site 3 (at the Kunzum La, ~4, 430m asl.). The lack of precise base maps and coarseness of satellite imageries are substituted with these field geomorphological maps. Morphometric analysis is not suitable for the present study because of their limited distribution and smaller sizes. These filed geomorphological maps, however, are prepared using Suunto MC-2 compass and clinometer, Brunton Echo 440yard Leser Ranger Finder (LRF), Suunto clinometer PM5, Garmin GPSMAP 76 handheld GPS (Global Positioning System), Brunton ADC Summit (Automatic Data Centre) altimeter, centimeter size graph sheets, plastic ruler and protector, transparent plastic board, eraser, and pencils. The surveying is done following standard compass survey procedure mentioned in Basak (2007). Suitable triangulation points are first selected and their location is determined using GPS. The objects are sighted using compass and their distances are measured using LRF (analogous to EDM i.e. Electronic Distance Measurer). No magnetic declination adjustment is made in the compass. This kind of surveying, although, is a crude mapping technique in the context of the presently available precise instruments, like Total Station etc., but allows mapping for larger areas in quick time with single surveyor. For each drumlins the stoss side end point, ridge high and lee side end point, are recorded and for roches moutonnee the stoss ends and ridgh highs are recorded. They are also noted in the field note book along with their orientation and other characteristics. Mostly mapping is done in the field at 1:500 scales. Slope measurement, although not robust, is done using clinometer. That’s how the distribution and orientation of the drumlins in the study sites ate recorded. In Chandra Tal area, field mapping is further verified using GPS readings at the three parts of each drumlin, stated above, and roches moutonee. These readings when brought to the GIS environment thus provided a very good field map for further analysis. The extensive GPS readings, in fact, further allow the author to even accurately map the distinct features from Google imageries and overly them to have much better base map. The field map near Chandra Tal (site 1), hence, area highly robust and can be used for further analysis. The site 2 (Yunan valley) and site 3 maps (at Kunzum La) are modified wherever possible with Google earth imageries and may require further precision for other uses. However, the symbolization of all these maps is adopted from the available and recommended symbols in Arc GIS, v- 10 and also from the literature (Owen et al., 1995, 1996, 1997; Rose and Smith, 2008). The distribution of drumlins along with the distribution of several outline forms (morphological classification) of drumlins, are briefly discussed in chapter 5.

Limitation: The major limitation attached to the present geomorphological mapping techniques is that they, although, can be very useful for present morphological and other morphometric purposes, several other morphometric analysis which incorporates the width and proper outline shape of the drumlins, such as elongation ration, lemniscates loop, spacing etc. cannot be done through the present base maps. In the present survey although the lengths are recorded properly the drumlins widths are not always precisely recoded in the map keeping the present objectives in view. The general outline (morphological) shapes of each of the drumlins, although are recorded in the note books, but their quantification is difficult in the present context. Apart from this limitation the present maps are accurate enough to fulfill the present objectives.

4.4.1.2. Clast Macro Fabric and Shape and Roundness Analyses:

Clast macro fabric and shape and roundness analysis are the second widely applied methodology of this study because the landform in concern are mostly composed of matrix supported gravelly-sandy materials which are massive in appearance (Stokes et al., 2011). Identification of any structures from such homogenized composition is unequivocally difficult leaving only room for the clast fabric analysis as the most preferable option for studying the genesis of *'Drumlins in the Himalayas'*. Equally important is the fact that most of the drumlin studies till date indicate the importance of prolate clast fabric measurement in deciphering the principle stress direction (see section 1.3.2) as well as the mechanism of drumlin formation. It is also discussed in section 1.3.2 in detail that the surfaces of most of the drumlins generally have strong fabric distribution. It is for these reasons that the clast fabric measurements are done in extensively in the present study from some of the selected drumlins and an interdrumlin (depression) area.

For measuring clast macro fabric Suunto compass and clinometer MC-2 model is used and for cleaning the site folding shovel and trowel are used. In some cases digging is further aided by Estwing (Chisel edge) hammer and ice-axes. For high dipping clasts at depth, measurement is done using a flat plastic scale. This scale is inserted parallel to the surface of the clast for uninterrupted measurements. Clast sizes and shapes are measured using vernier caliper and in a very rare case by 3m. long pocket tape, and roundness of the clast by using *Power's visual images*.

However, for the clast fabric measurements, first the upper surface of more than 15 cm. depth is cleared by gently scraping (Schomacker et al., 2006) in order to reduce any effect of post depositional disturbances. Only the ridge highs are selected for preliminary study because of the same reason and/or to reduce the possible mass movement disturbances. Normally 0.5 m. X 0.5 m. area[26] (Hubbard and Glaser, 2005) is chosen for measurements. Generally, dip and orientation of 40 to 140 mm size clasts[27] with a-axis to b-axis ratio ≥3:2 (i.e. 1.5) [28] are recorded in the field. Number of clasts (N) studied so far, varies in different sample sites because in some cases either most of the clast studied shows nearly similar orientations or the accessibility of recording sufficient number of clasts is prohibited due to environmental constraints. However, at KG1/DPF (Fig. 85) 51 (N) clasts, KG2/DPF, DPF2, IDPF1, and sarchu 1—50 (N) clasts, KUN/07/50 and DPF1 25 (N) clasts, and at sarchu 2 41 (N) clasts are measured[29]. Similar fabric measurements, actually, is also conducted on small size (25-50 cm.) lodged boulders (N = 50) on drumlin surface, at the Kunzum La (4,430m asl.) and a number of (N= 121) similar size (25-50 cm.) boulders are also recorded at DPF3 (Fig. 85), south of the Chandra Tal area (4,300m asl.) for trend analysis.

The anisotropy or fabric data, however, are represented visually through the *rose diagrams* for general orientations (trend), and equal area (lower hemisphere) *Stereonet diagrams* with contours at 1% area method for both trend and dip analysis of clasts. Quantitative analysis is aided through the computation of *Eigen values* viz. S_1, S_2, and S_3, and *Eigen vectors* viz. V_1,

[26] Hubbard and Glasser (2005) talked about 0.5 m^2 of area as standard; Schomaker et al. (2006), although, used 25 cm X 25 cm area for studying clast macro fabric.
[27] Knight (1997) and Wright, Jr. (2006) have used clasts of more than 20 mm long (a) axis length; Schomacker et al. (2006) used 50-200 cm size clasts for macro fabric measurements; 30 to 125 mm. has used by Stanford and Mickelson (1985); 20 to 500 mm. size by Dowdeswell and Sharp (1986); and 50 to 150 mm. by Hart (2007).
[28] Generally clasts with a:b axes ratios more than equal to 3:2 is largely preferred by many workers (Hill, 1971; Stanford and Mickelson, 1985; Knight, 1997; Wright, Jr., 1957). Although reverse ratios are mentioned by Benn and Evans (1996) i.e.b:a ratios less than 0.67; both indicate the prolate shaped clasts. Dowdeswell and Sharp (1986), on the other hand, have used b/a <2/3: c/b >2/3 ratios for the selection of suitable clasts for macro fabric measurements.
[29] Hubbard and Glasser (2005) stated that minimum of 25 clasts and maximum of 100 clasts are generally sufficient for fabric analysis, with 50 clasts being the optimum. 25 clasts are also studied in many literature (Hart, 1995; Schomacker et al., 2006; Stanford and Mickelson, 1985; Dowdeswell and Sharp, 1986).

V_2, and V_3 [30] out of the fabric data recorded in the field as suggested by Dowdeswell and Sharp, 1986; Benn and Evans, 1998). They are shown through *Benn's Ternary diagram* for isotropy and elongation measurements. However, most of the diagrammatic representations and statistical analysis are performed in the *'Open Stereonet version 1.2'*; an open source software, and verified manually as well. Besides, S_1 and S_3 bivariate plot is used for further comparison and histograms are also used for showing the percentage of occurrence of clasts having similar dip (at 10° interval) amounts.

Clast shapes are measured in the field as well during the fabric analysis. All the three axes of a clast viz. a-axis (or longitudinal axis), b-axis (or intermediate acis), and c-axis (or short axis) are measured. Although not all the axis data that have recorded during fabric measurements, have used for clast shape measurement; the complex edged clasts are not recorded, and supplemented with additional clasts for only shape measurements. All the clast shape data is represented through the ternary diagram devised in excel under '*triplot'* version 1.4. (Fig. 46 a & b) by Graham and Midgley (2000). Percentages of each shape are also calculated in the same 'tri-pot' program. This shapes ternary diagram is basically based on the original Seed and Folk (1957 cf. Graham and Midgley, 2000) diagram. These shape measurements are also compared with Zingg's shape (Tucker, 1988) distribution for comparison and is briefly discussed in the section 6.2.

[30] For the statistical analysis out of fabric data collected in the field three dimensional (3D) vector analyses is used to extract the Eigen vectors and Eigen values of a 3x3 matrix. The matrix is constructed by summing the matrices which are the product of each measured axis and its transpose in Cartesian coordinates:

$$A = \sum_{i=1}^{n} \mathrm{Xi}\,\mathrm{Xi}^{\mathrm{T}}$$

………………………16 where, Xi is a unit vector paralleling the ith observation axis, Xi^T is the transpose of Xi and n is the number of observations (Dowdeswell and Sharp, 1986).

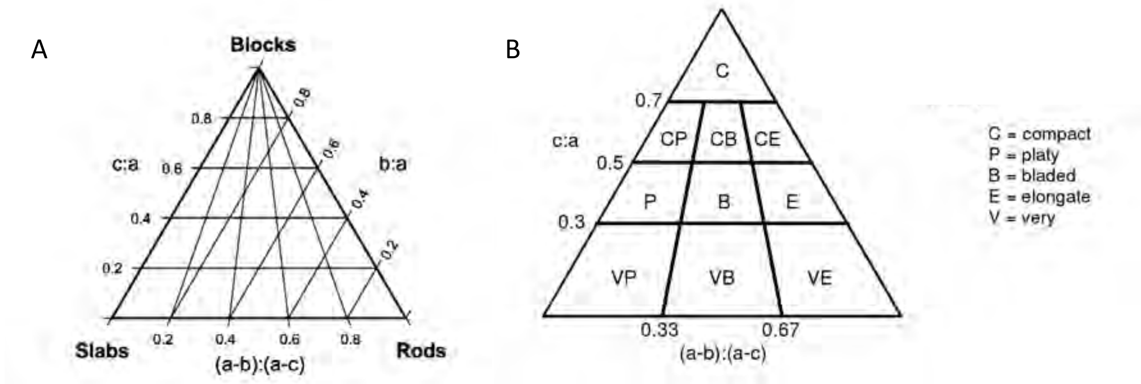


Fig. 46 Descriptive particle shape classes of Sneed and Folk (1958). (A) Shape ternary diagram showing the class sizes. (B) Shape ternary diagram showing the descriptive classes of clast shapes. Adapted from Graham and Midgley (2000).

For clast roundness as well as spherical analysis, Power's visual comparison chart (1982 cf. Tucker, 1988) is used in the field. This visual method has its own inherent draw backs and is thus, liable to author's understanding and interpretation. Although some filed photographs are provided aw well for further support any argument. They are shown through simple histograms.

Limitation: Clast macro fabric data are recorded only from few of the sample drumlin's surfaces and single interdrumlin area (IDPF1). These data are then extrapolated to the entire study area. However, it is believed that the general macro fabric pattern may be quite similar and the samples can be the representative to the population, but at the same time it is dangerous to be too sure and precise with little data to base judgment on (Smalley and Unwin, 1968). However, it to be noted that the present study is not given too much stress only on the fabric results and along with other lithological attributes fabric constitute just a part of the entire study; hence is considered here for determining the processes of evolution of the drumlins. However, the fabric data are also recorded from the ridge highs in the Chandra Tal (site 1) and Kunzum La area (site 3), and in the Yunan valley one is taken from the stoss end (sarchu1) and another from the lee end (sarchu2) of the drumlins respectively. No extensive fabric study of a single drumlin throughout (i.e. the stoss end, sideways, immediate lee face and distal lee face etc.), as like that under taken by Boultion, (1976) from a fluted moraine, is undertaken in the present study. The reason is to identify the general clast orientations and dip. Whether they are parallel to drumlin's long axes and principle ice-flow direction, or transverse, or just oblique type, as found in hummocky mounds, is the prime objective behind such isolated selection of fabric sites. Fabric measurements are done mostly from the surface, below 15 cm. depth. Much deeper fabric is found to be very difficult to retrieve manually. In the Chandra Tal area (site 1) at the sample site KG1, although a pit is dug up to more than 60 cm. deep, manually and form there only 25 clasts are able to record at sufficient depth (DPF1). In the Yunan valley (site 2), the road cuts provide exposures and in that case only the fabric data are recorded at nearly 1m. depth from the present drumlin surface (the middle section at the sarchu1and sarchu2). Apart from these few limitations, the methods applied here are believed to bring out some of the notable points required for further research, and the relative merit of each of the techniques in the landform evolution can be examined as well.

4.4.1.3. Field Exposures and Sedimentary Log Preparation:

The three sites (site 1, 2 and 3) studied so far, largely lack natural exposures to study the internal composition and structures of drumlins. Very few good road cut exposures are available along the road (NH 21) in the Yunan valley (site 2). Here two road cuts are selected (e.g. Exposure 1 and Exposure 2) during field surveying. Fabric measurements are undertaken for both and sediment logging is done for exposure1. Suitable photographs of the exposure1 are taken along with a sample collection for grain size analysis. Thick cover of loose materials possibly due to destabilization after road cutting, create burial of continuous exposures at many sites at the Yunan valley making it difficult for further study. The Chandra Tal area (site 1) and Kunzum La (site 2), on the other hand, do not have any of such road cuts for such study to conduct. That is why in Chandra Tal area (site 1), a pit is dug out by the author manually for up to 60 cm depth from the surface of the drumlin at KG1 (or DPF1, Fig. 85). This site is then carefully photographed and sketched. Clast general characteristics and orientation structures are also carefully recorded, and suitable sites are chosen for the collection of Quartz grains (sand size) for SEM analysis (at KG1/DPF). The internal composition, however, apparently looks homogenized in nature and micro thin section analysis may possibly reveal more important facts, which is lacking in the present study. Since the depth was limited, logging was not fruitful. However, fabric analysis is also under taken at the depth for 25 prolate clasts (DPF1). The author was unable dug deep (>60 cm. from the drumlin surface) due to heavy wind flow outside, and boulder content at the depth. An unsuccessful attempt was also made to dig the stoss face of the sample drumlin KG1/DPF (or DPF1), but the weathered bedrock knoll deter further advance. Hence future study, at both macro and micro level, is required form the suitable sites to strengthen present understanding (see section 6.2) of the evolution of drumlins in the Himalayan orogeny.

4.4.1.4. Grain Size Analysis:

Six sediment grain samples of ≤200μm. sizes are collected during field surveys in air locked plastic sample bags and coded with. They are later processed in the Geomorphological

Laboratory (Room No. 305) of the Centre for the Study of Regional Development (CSRD), JNU. For grain size analysis the samples are air dried in laboratory for 2 to 3 days and then dry sieved using motorized shaker (sieving machine) and suitable sieves. Gravel size grains are not recorded in the field except at KG1/DPF and also samples are collected keeping in mind the SEM analysis and hence for some, the gravel size grains are not collected. To maintain consistency, therefore, only grain sizes below 280µm. are dry sieved and recorded. The following sieves with mesh sizes, *2000 µm., 1400 µm., 1000 µm., 710 µm., 500 µm., 350 µm., 200 µm., 177 µm., 125 µm., 88 µm., 63 µm., 31 µm.,* and the *pan*, are used so far for the grain (or particle) size analysis. 180 grams of each sample is weighted and then they are sieved for 20 minutes. The sieves are then cleaned and repeatedly weighted after every sample processing to minimize the loss. For none of the samples, loss exceeds the limit of 2 grams (Tucker, 1988). The weight of each of the size class is then converted into percentage figure of the total weight. They are later on plotted using Gradistat version 8—an excel sheet program. The samples statistics are also calculated using the same software program (Blott and Pye, 2001), but their use is limited in the present study due to lack of entire stretch of grain size measurements (Annexure 1). The lack of grain size records of gravels and medium to fine silts and clay sizes (<31 µm), are believed to be the major limitation of the present study; although it is to be mentioned that except one case, the rest of the (5) samples shows very insignificant weight percentage of fine silt and clay content. Hence diagrammatic representation of grain sizes is made limited to phi (φ) line diagram only; ternary diagram, for comparison with other studies, is proved to be unsuitable here because of the absence of precise gravel measurements.

4.4.1.5. Surface Texture Analysis of Sand Quartz Grains Using Scanning Electron Microscope (SEM):

SEM study of Quartz sand grains are extensively reported in literature in the field of glaciology (Krinsley and Donahue, 1968; Krinsley and Doornkamp, 1973; Whalley and Langway, Jr., 1980; Mahaney, 1990; Mahaney et al., 1991; Mahaney and Andres, 1991; Mahaney et al., 1996; Helland and Holmes, 1997; Mahaney and Kallam, 2000; Rose and Hart, 2008). A number of surface textures are used to identify the process-environment relationship and often as the diagnostic tool. Since the present study intends to provide evidences for and against the subglacial origin of streamlined forms e.g. drumlins, and the active processes responsible for their evolution in the Himalayan terrain, SEM has proved to more than handy tool in supporting some of the key inferences which are tentatively inferred from the macro level field study.

The samples for SEM analysis are collected carefully along with the samples collected for the grain size analysis. These samples are then wet sieved later in the laboratory using standard methods (Tucker, 1988). The 100 grams of each sample are first weighted and then poured in a 1 lt. beaker with a mixture of distilled water and concentrated Hydro Cloric Acid (HCL). HCL is mixed as dispersant agent and the mixture along with the sample is stirred continuously for one hour. Proper care is maintained not to disturb the samples. Following stirring the samples are wet sieved and sand grains of 1,500-2,000 µm., 200-500 µm., and 63-200 µm. sizes are separated from the rest. They are then dried in drier at recommended 110°C until they are fully dried. Using binocular microscope the Quartz sand grains are then separated from the rest. When the first two samples of 500-2,000 µm., and 63-200 µm. sizes of DPF2 are coated and photographed using SEM, the problem of extensive adhering particles on the surfaces of the

Quartz sand grains are noticed. The 200-500 µm. size Quartz sand grains, therefore, are again boiled in a concentrated HCL for 10 minutes and then washed thoroughly with distilled water (Krinsley and Doornkamp, 1973). These are then prepared for SEM study.

Four samples viz. KG1/DPF, DPF2, KG2/DPF, and KUN of Chandra Tal (site 1) and Kunzum La (site 3) area, respectively are used in the present study for SEM analyses keeping in view the relative distances of the samples to each other (Fig. 85). However, samples are analyzed in the SEM/TM section of Advance Instrumentation Research Facility (AIRF), JNU, New Delhi. The model used is ***Car Zeiss EVO 40***. The 200-500 µm. size Quartz sand grains are air dried first after processing, followed by the arbitrary selection of 15 to 20 Quartz grains and their mounting on *metal stabs* with the help of *Carbon double stick tape*, and then sputter conductive coating of *gold* with *20-30 nm* thickness is performed with the help of *Polaron SC7640*. The coated stubs are then placed inside a vacuum chamber (-8 x $10^{-5 \text{ torr}}$) with accelerating voltage of 20 kv. The samples are generally tilted at 30° to 40° angle. At first *EDX (Energy Dispersive X-ray)* analyzer is used to verify whether the selected sand grains are truly Quartz grains or else. The EDX results are shown in annexure 2. EDX is done at first for randomly selected single quartz grain and also for the whole in the stab (annexure 2). The very high proportion of *O_2 (oxygen)* and *Si (silicon)* are the major chemical signatures of *Quartz (SiO_2).* The *gold (Au)* and *carbon (C)* content of the background, due to conductive gold coating and Carbon sticky tape, are eliminated from the EDX chemical analysis to reduce misinterpretation. However, it is the *secondary electron mode* under which all the photographs are taken. In total 52 Quartz sand grains are analyzed and photographed. A number of textures are identified from these photographs using SEM and they are already mentioned in the section 3.4.2.4. Representation of these textural signatures is mostly done using histograms.

Limitation: In this study no oxidizing solution is used and it is also not required due to very low organic content in the samples. Only 200 to 500µm. size Quartz grains are used for comparison, although other smaller (63-200 µm.) and larger (500-2,000 µm.) sand grains are studied at least for one sample (DPF2), but more is always preferred to identify the pattern of textural variation across different grain sizes; in the present study, although, no as such discernible changes in textural pattern is found in DPF2 sample and hence believed to be insignificant.

However, it is required to mention here that boiling of Quartz sand grains in HCL reduces the amount of adhering particles, allowing better identification of some of the surface textures which otherwise may be very difficult to identify. Similarly, it also must be kept in mind that SEM analysis as a diagnostic tool for identifying processes and environment of deposition, from geological records, can be tricky if not supported by other evidences.

4.4.1.6. Other Primary Data:

During field surveying observations are extensively recorded in the note books. In Chandra Tal area (site 1) each drumlins are visited and their characteristics are recorded' which includes the general outline shapes, their predominant composition, and ridge type at the crest of the drumlins (bedrock or entirely diamictic) etc. They are coded with Dx_1, where x is the respective numbering of drumlins. Field photographs are also extensively taken as evidences. GPS further allows quick measurements of the lengths and heights of the drumlins. Besides, sketches of clast deformation patterns are also prepared from different photographs.

4.4.2. Methodology for Secondary Data:

In the present study secondary data are used partially and only to provide back ground information; hence basic mapping is actually undertaken. Such as IRS Liss III data is used for mapping using simple digitization technique under Arc GIS ver. 10 platform. Similar technique is also applied while mapping is undertaken using Google Earth Imageries. They are then 'append' to merge together with the field maps. IRS Cartosat 1 DEM imageries are also used for cross profile creation and three dimensional terrain diagram preparation. Besides, watershed, slope, aspect, and hillshed maps are also prepared using hydrology tool under Arc GIS platform ver. 10 from the same Cartosat 1 DEM. Some of the very important maps and diagrams are also adapted from the literature with modification or without modification. However, there are not much attention paid on generating more secondary data and hence may not require further discussion.

In summery it can be stressed that although there are some limitations in the present study, but they have made very insignificant mark and can be ignored. The inference,s that have been derived so far, are encouraging, and if not fully satisfactory but sufficient enough to improve the present understanding of the Himalayan drumlins and also in directing the future areas of research. The present thrust is largely placed on the primary data generation and secondary data are only used for support and background knowledge. Extensive use of secondary data is found in map preparation and generating cross profiles. The general methodologies, thus, mostly chosen in such a way that the primary data can be best utilized and displayed. The morphological techniques, however, applied so far in the present study are geomorphological mapping and recording of the general characteristics of drumlins e.g. their superficial composition, outline shape and size etc. along with GCPs. The sedimentological *(compositional) study, however, incorporates clast macro fabric analysis, grain size determination, roundness and sphericity analysis, clast shape and size analysis, SEM analysis of surface textures of quartz sand grains, sedimentary log preparation etc. and photographs are also supplied with for further support.*

Chapter—5

GEOGRAPHICAL DISTRIBUTION AND MORPHOLOGICAL CLASSES OF THE DRUMLINS IN THE STUDY AREA

"The identification of drumlins is based mainly on the superficial streamlined morphology of the features rather than on internal composition and structure."

——Hill (1973)

5.1. Introduction:

Drumlins, at first sight, are identified in the field on the basis of their outline streamlined morphology and also on the basis of some of its landscape characteristics, which is common in most of the drumlin fields of the world. Drumlins are defined by Menzies (1979) as, *"... typically smooth, oval shaped hills or hillocks of glacial drift resembling in morphology an inverted spoon or an egg half-buried along its long-axis. Generally the steep-blunter end point in the up-ice direction and the gentler sloping, pointed end faces in the down-ice direction, these two ends being respectively known as the stoss and lee side"* (p- 315) (see the section 1.2). This definition certainly covers most of the characteristics to identify drumlins in situ. These may be listed as follows—

a) A drumlin has typical streamlined form with generally steep stoss face in the up-ice direction and smooth and gentle lee face in the down-ice direction (Fig. 1.b),

b) Drumlins are formed en echelon in a filled i.e. parallel oriented sufficient number of landforms characteristics in the entire field. Often they are regarded as resembling to *'basket of egg'* topography,

c) Longitudinal axes of drumlins are not only found parallel to each other, but also they indicate the direction of the former ice movement. Couple with striation marks and other streamlined landforms, drumlins are effectively used in many ice-sheet covered areas to reconstruct the ice-sheet moving direction,

d) Drumlins are essentially subglacial to submarginal landforms, and hence many of their characteristics incorporates typical subglacial and submarginal characteristics,

e) Classical drumlins are 'tear-drop' in shape but within a swarm or drumlin filed, a number of wide ranging morphological types of drumlins can be identified (Spagnolo et al., 2010) and this seems to be ubiquitous characteristics rather than unique etc.

These diagnostic signatures are followed in the present study as well in order to identify the drumlins and record their spatial (geographical) distribution in the Lahul Himalaya, and Zanskar region. Apart from these aforementioned general characteristics of drumlins, the topographical configuration of the area is also required greater attention, especially in the present context because drumlins are relatively rare in the Himalayas and Transhimalaya. The present study is the first study dedicated entirely to the detail study of the *'drumlins in the Himalayas'*. Several favourable factors, thus, are identified subsequently in this work to answer many the questions. This study also provides the criteria to identify drumlins in the Himalayas which may reduce the misinterpretation of these geomorphological landforms elsewhere.

5.2. Identification of Drumlins in the Field:

Drumlins are identified in the field on the basis of their superficial morphology and verified on the basis of aforementioned general characteristics at the Chandra Tal area (site 1), Kunzum La (Site 3) of the Lahul Himalaya, and Yunan valley (site 2) which is ~11 km. before the Sarchu Plain, in the Zanskar range (Fig. 14). In the Chandra Tal area (site 1) small parallel oriented inverted spoon like hillocks are found on a low ridge section (~4,300 m asl.), left of the Chandra Tal (Fig. 49) (~4, 280 m asl.), which is ~200m above the present Chandra river bed at upstream reach. Plate: 14 exhibit some of these parallel oriented hillocks at site 1. These are typical streamlined forms oriented in southeasterly direction and show no sign of post depositional modification by other geomorphological agents. The classical tear-drop shapes are well developed (Plate: 15 & 16) in this region and nearly 56 percent of these hillocks are truly classical drumlins in shape with steep up-ice and gentle down-ice faces; excluding the other superimposed classical forms. These (Plate: 15 & 16) hillocks also posses typical lodged boulders at their surfaces, which according to Owen et al. (1997) are englacial and subglacial in origin. Besides, similar southeasterly oriented typical complex streamlined morphological types (superimposed) are also identified (Plate: 17) in the site 1. These hillocks, thus, possess the typical morphology, common to drumlins in a field as mentioned in the literature (see chapter 1) (Menzies, 1979; Benn and Evans, 1998). Their longitudinal axes are also parallel to each other (en echelon) with southeastward trend along with the lodged boulders at their surfaces which are mostly subglacial and/or englacial in origin and/or also contain some supraglacial boulders. Hence, the morphological characteristics together support that they are drumlins and mostly in the Chandra Tal area they are subglacially to submarginally formed; except the bedrock drumlins which might entirely subglacially formed. It also corroborates the observation of Owen et al

(1997, 2001). Other streamlined forms are found in the form of roches moutonee (Plate: 18 & 19) with gentler stoss section and steep lee section in this area. These are oriented ~120° from the north i.e. southeasterly. According to Owen et al. (1997) they may be older in age as the well developed rock varnishes indicate. Apart from that striation marks (Plate: 20) are also identified in this low ridge area (~4, 300m asl.) with ~140° (from the north) general orientation (i.e. SE). Hence not only the long axes of the drumlins in the Chandra Tal area, but other streamlined form (e.g. roches moutonee) and other glacial scour marks (striae) as well, define the possible southeasterly flow direction of the main valley glacier in the late Pleistocene time; this is in sharp contrast to the present north-south course of the main Chandra valley at the upstream reach and is briefly discussed in the subsequent sections. Multiple evidences not only firmly support that these hillocks are drumlins and not hummocks or any other geomorphological forms interms of the outline shape is concerned, but also helps in generating a number of valuable inferences of former glacial characteristics and palaeoenvironmental condition, which otherwise may be difficult to generate. The sedimentary evidences of the origin of drumlins are discussed in chapter: 6 for further support.

Similar streamlined hillocks are also preserved at the Kunzum La (~4,600m asl.) and has already been reported by Owen et al. (1997) (Fig. 52). The study site 3 is situated near Kunzum La (~4,550m asl.) into the upper Spiti valley (~4,430m asl.). It is ~9 km. southeast from the Chandra Tal area (site 1) and one has to cross the north-south trending Kunzum range to reach to the study site 3. This area represents few of the drumlinized mounds (plate: 21). These hillocks possess smooth outline form with classical tear-drop shape i.e. relatively steeper and blunter stoss end and gentle and pointed lee end (Plate: 22 & 23). They are also en echelon in the field with parallel longitudinal axes orientation of 100°-110° from the north i.e. southeasterly orientation. These streamlined forms also possess similar lodged boulders at their surfaces. These boulders are smoothly polished and mini Roche moutonnee type, typical to subglacial and englacial origin. These boulders (a-axes) also have general trend (Fig. 53) which is parallel to the long axes of drumlins. Later it can be further shown that micro scale analysis (see the section 6.2.2.3) also supports the glacial origin of the (quartz) sand grains. These evidences together, thus, support that these hillocks are possibly drumlins, although the author is cautious about the use of the term 'drumlins' to these streamlined forms and rather '*drumlinized mounds'* are retained for further analysis in site 3. The site 3 hence waits for further evidences to confirm. However, the present evidences do support that these are possibly submarginally formed and have southeasterly flow direction. This, along with Figure: 52 after Owen et al. (1997), supports that the main valley glacier of the Chandra Basin possibly overtopped the Kunzum range at Kunzum La (4,550m asl.) and spread, at least, in the upper Spiti valley. This is later discussed in the section 5.4.

Drumlins like hillocks also common north of Baralacha La (4,900m asl.) in the Zanskar range adjacent to Lahul Himalaya (Fig. 14). Baralacha La, as discussed previously in chapter: 2, is the origin of three main rivers of this region. They are Chandra River and Bhaga River of the Lahul Himalaya, and Yunan River of Zanskar valley. The study site 2 (~4,450m asl.) at the Yunan valley is situated northeast of the Chandra Tal area (site 1) (Fig. 14) and possess similar well developed streamlined hillocks (Plate: 24). The hillocks in site2 are highly variable interms of their heights (Plate: 25) and sizes (Plate: 26) and further in terms of their longitudinal axial orientations. Although they possess typical smooth classical drumlin shapes (Plate 27) and found together in a vast field (Plate 28), at times during filed survey they apparently appeared as chaotically organized hummocky mounds. But when the field mapping is finished (Fig. 55) and compared with the topography of the region, two possible long axes orientations of these hillocks i.e. parallel, oblique and transverse flow directions, are well detected. But given the geomorphology of the site 2 it also seems largely possible that the smaller transverse drumlins may have been largely modified by the debris flow activities, prevalent in this section, and achieved typical oblique to transverse main valley directionality or orientation. Later on in the chapter: 6 (section 6.2.2.4) it can be further shown that the pebble fabric data (Fig. 96) from one sample drumlin found somewhat analogous to the long axes orientation of drumlins. The fabric data are very limited in number to firmly conclude anything, although, together with form analogy, it helps in recognizing these hillocks as drumlins in the field (site 2). These long-axes data of the drumlin in study site 2, thus, in turn further assist in deciphering the typical ice flow directions of the entire region during their formation.

Therefore, while form analogy is the key to identify and record drumlins in the field, it must be kept in mind that several common form characteristics or properties must be served carefully before admitting them as drumlins. And also wherever it is possible, form analogy must also be backed with detail sedimentological (compositional) evidences to evade any misinterpretation. In the present study drumlins at site 1 (Chandra Tal area) is supported both with form analogy and sedimentary evidences, and at site 2 form analogy is only considered as a major evidence in support with until now, and only clast macro fabric data is given for additional assistance, whereas at site 3 (Kunzum La area) the form analogy and sedimentary evidences do support the submarginal origin of the streamlined landforms but more detail evidences are required before firmly concluding them as drumlins. Till then they are discussed as ‘drumlinized mounds’ in the present study. However, the criteria prescribed in the section 5.1. for identification drumlins thus,

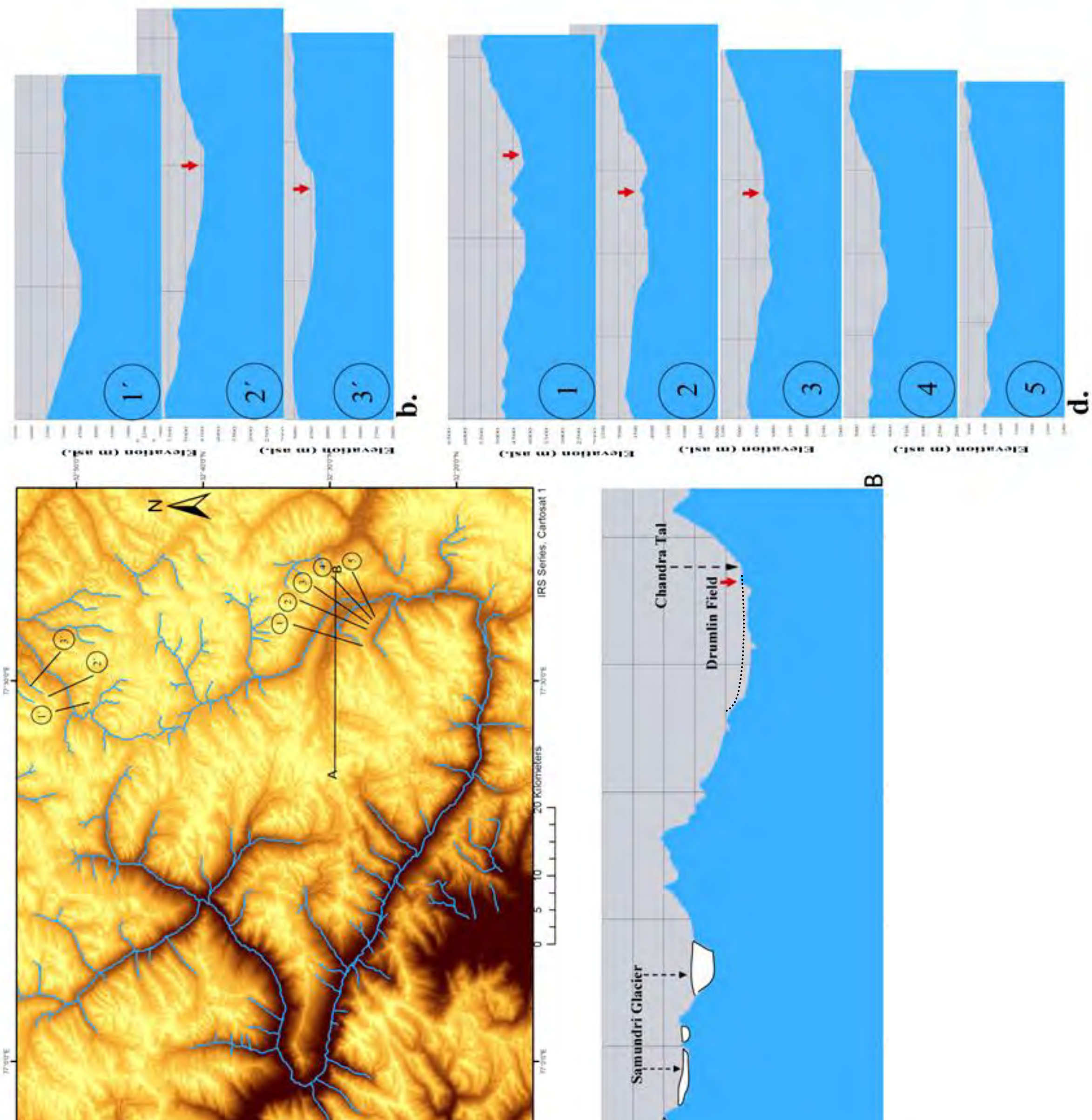


Fig. 47 Sequence of cross-profiles drawn in the Chandra valley (site 1) and Yunan valley (site 2). (a) DEM map showing the location of the transects, from where cross-profiles are generated; (b) sequence of cross-profiles (1',2', & 3') in the Yunan valley displaying the gradual valley widening; (c) cross-profile along the line AB in site 1, showing valley profile and location of the drumlin field (red arrow). This profile clearly indicates the hypothesized broad and flat funnel valley (black dashed line) in site 1 before post glacial fluvial incision and development of narrow incised valley (mini-gorge type); (d) sequence of cross-profiles (1,2,3,4, & 5) in the Chandra Tal area exhibiting the valley widening. This broad and wide valley (>100m) possibly allow the glacier-ice to spread. Arrow indicates the low ridge area containing most of the drumlins.

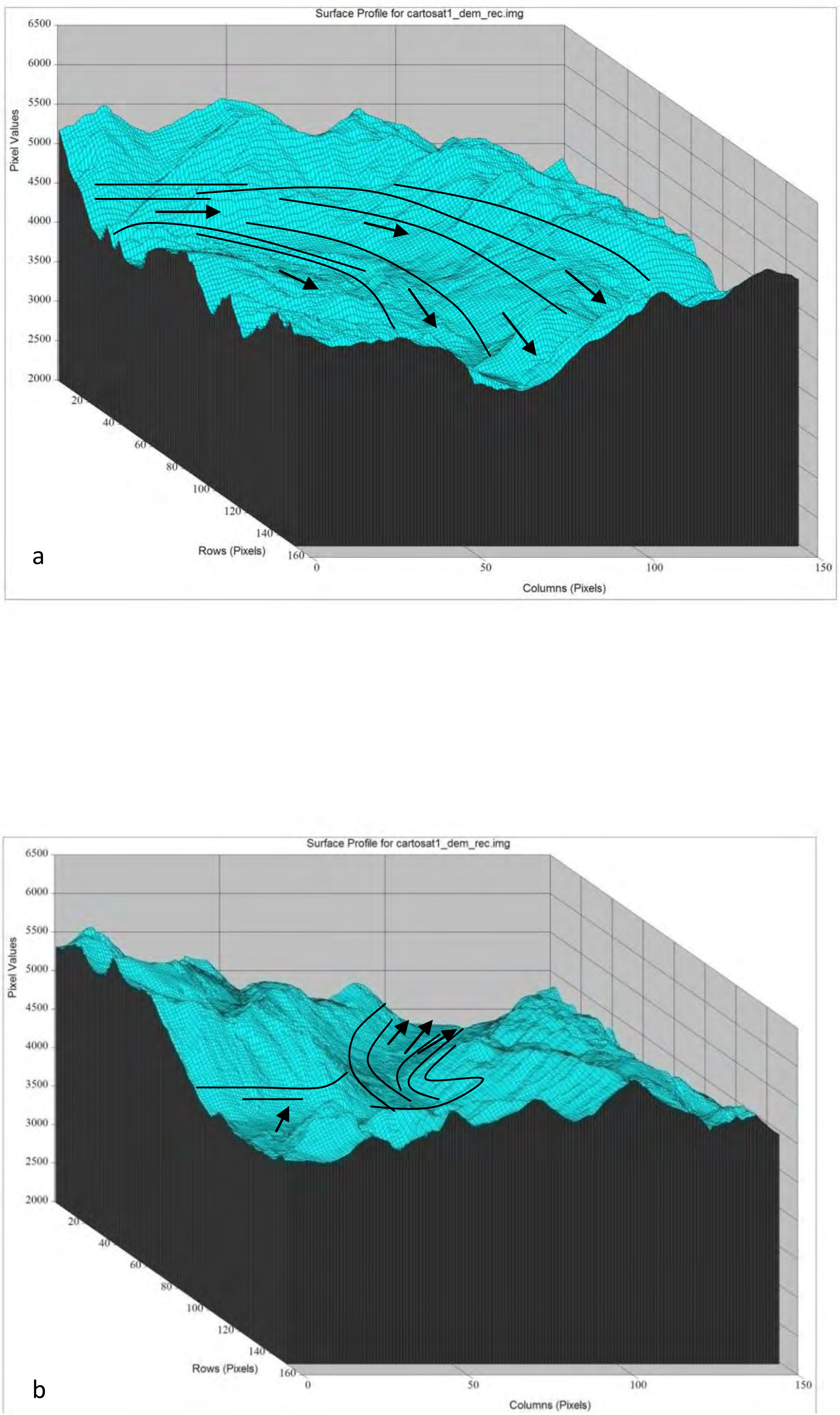


Fig. 48 Broad and wide 3D valley profiles of the Chandra and Yunan valleys.(a) showing the 3D terrain configuration in the site1. The valley gradually widens developing funnel shaped valley. The main valley glacier accumulates in this funnel valley and spread southeast to overtopped Kunzum range to upper Spiti valley (site 3); (b) the similar valley profile configuration is also found in Site 2 and allows for spread of glacier during extensive valley glaciation.

5.3. Typical Configuration of Valley Topography:

The study area constitutes one of the very high and rugged topography of the earth. Bounded by the Pir Panjal range in the south, Greater Himalaya in the Middle, and Zanskar range in the north –all of them have summit levels more than 6,000 m asl. Across the entire reach the river Chandra shows spatially variable aggradation and incision history. This is also true for Bhaga river. Spatially variable braided river systems are naturally replaced by narrow gorges and vice-versa within short distances. Although drainage systems are best developed at the down-stream section, the up-stream section exhibits typical drainage characteristics in this arid zone. Widening into broad valley is the most typical in the Chandra valley at the upstream reach. That is unlike the Bhaga valley and many other parts of the Himalayas and Transhimalaya, the upper Chandra and Yunan valleys are broad, flat and have gentle gradient in the upstream section (Fig. 26) making it favourable for the spreading of ice and creating conducive conditions for the formation of impressive subglacial landform like drumlins. In order to validate the above argument several transacts are drawn both across the Chandra valley (site 1) and Yunan valley (site 2) in the present study (Fig. 47.a). The high resolution IRS Cartosat Digital Elevation Model (DEM) helps largely in creating precise cross profiles at that scale in the study sites. However, these cross profiles clearly demonstrate the 'broad opening' of the valleys in both the study sites. The cross section along the line AB in the Chandra Tal area (Fig. 47.c) broadly displays the broad valley characteristics (> 100 m. in width). The drumlin filed is represented here by red arrow. If the post glacial fluvial incision history of the valley is ignored and the present low ridge area, containing the drumlins, are extrapolated (the dashed line in Fig. 47.c) then the broad as well as shallow valley topography hypothesis of Owen et al. (1996, 1997) can be further corroborated. A series of cross profiles when drawn along the Chandra valley (Fig. 47.d) the valley profiles become gradually more wide and flat (gentle) in width in the drown-stream direction. This kind of picture is similar in the Yunan valley (Fig. 47.b). A series of transacts also display similar flat valley and their gradual widening (Fig. 47.b). Apart from two dimensional (2D) visualization, when three dimensional (3D) DEM of the topography is created using ERDAS ver. 9, this fact becomes more clear (Fig. 48.a). Several inferences tentatively discussed in previous section (5.2), can further verified here. In the Chandra Tal area (site 1), the low ridge topography (site 1) is situated in a funnel like basin (Fig. 48.a). The valley during extensive glaciation i.e. Batal stage glacial advance[31] (Owen et al., 1997, 2001) was shallow as well wide, making the accumulation and spreading of ice hypothesis realistic. The main valley glacier-ice possibly accumulates more in this part of the basin rather than elsewhere. It is also possible the up-valley parts have rather less thick glacier-ice than this funnel like basin part at the site 1. Thicker ice also most probably spread along this broad valley opening and because of greater thickness and spreading effect——the most conducive condition for the drumlin formation (Fig. 49), development of drumlins took place in this area. These topographical factors are rarely common in most of the other regions of the Himalayas. The down-valley part beyond site 1 is also relatively narrower making it difficult for the formation of drumlins further downstream. The funnel basin hypothesis also makes it realistic that the thicker ice possibly overtops the Kunzum range at Kunzum La and spread into the Upper Spiti valley (site 3). During extensive (Batal Stage) valley glaciation the ice possibly reached a greater thickness than the then Chandra Valley (funnel basin) can contain and thus spread into upper Spiti valley (site 3). This inference is further verified later in subsequent chapter (Chapter 6) with more evidences. In the Yunan

[31] The detail study of the geomorphological landforms, especially lateral moraines and drumlins (Owen et al., 1997) and extensive CRN dates (Owen et al., 2001) already verified that the drumlins are formed during the late glacial extensive (12-15.5 ka) valley glacial advance in the Lahul Himalaya (see the section 2.5), named as Batal stage glacial advance.

basin (site 2) as well, it can be found that the valley opens up gradually beyond Baralacha La (~4,900 m asl.) and extensive (> 100m. in width) and gentle flat valley is found at the study aite (Fig. 48.b; Plate: 29). In the previous section (section: 5.2) two sets of orientations of drumlin's long axes are mentioned at site 2 (~4,450m asl.). In Figure: 55. it would be clear that the one set of drumlins are parallel to the valley profile, whereas another set indicates oblique to transverse orientations due to post depositional modifications of debris flow activities (Plate: 30). More elaborative discussion is given in the subsequent chapter.

Plate:14 Drumlin field or swarm in the Chandra Tal area (site 1). This plate consists of dome shaped and small to medium length classical drumlins. Flat depressions often developed in the inter drumlin areas possibly during glacial recession. In the back is the Samundri glacier snout with proglacial lake. Arrow indicate the direction of ice flow which is parallel to the long axes of the drumlins.

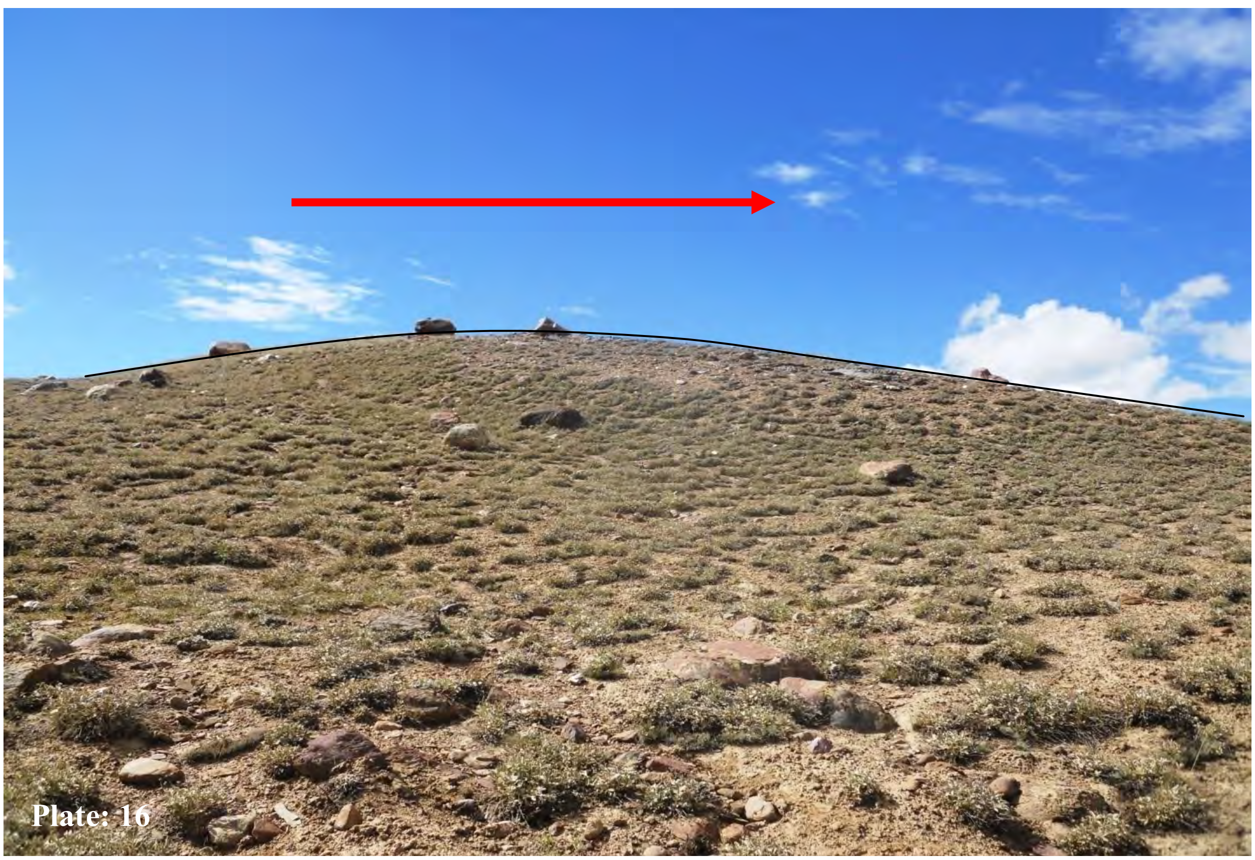


Plate: 15 Typical classical form of drumlin in site 1 with lodged boulders at the surface. This is the sample drumlin DPF3. Arrow indicates the ice flow direction.

Plate: 16 A very well developed classical streamlind drumlin in site 1. Lodge boulders at the surface of the drumlin are also aligned parallel to the long axes of the drumlin and ice flow direction (arrow).

Plate: 17 Superimposed drumlin in the site 1. Two bedrock ridges are found protruding on the drumlin surface with one drumlin superimposed on another. Arrow indicates the ice flow direction.

Plate: 18 A large rochemoutonnee in the site 1. Ice polished surface is well developed. Arrow indicates the direction of ice flow.

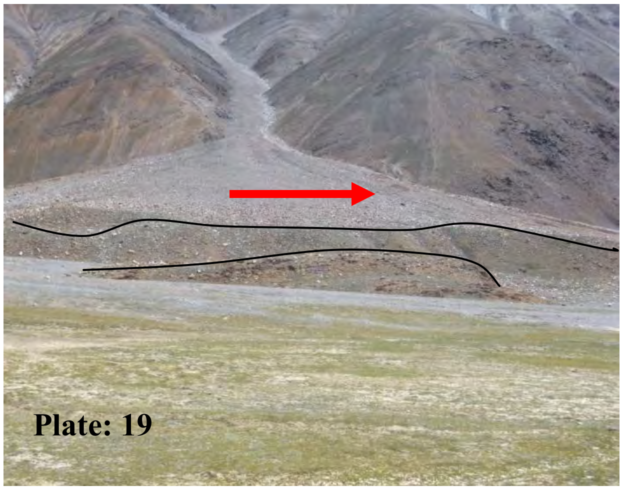


Plate: 19 Another rochemoutonnee developed north of the Chandra Tal. Behind this landform is possibly the Batal stage moraines buried under the debris flow deposits.

Plate: 20 Well developed striations on the bedrocks in site 1. Bands of well-polished rocks also developed. The scale is 15 cm. in length and pointing the ice-flow direction.

Plate: 21 Thedrumlinizedmoraininc (arrows) filed in the Kunzum La area (site 3). These are classical in form and eroded by the stream at the lee faces. The general direction of the long axes of the drumlins is 100° to 110° (shown by the red arrow).

Plate: 22 The enlarge portion of the Plate: 21 3. The classical drumlinized moraines are shown in this plate. The long axes possibly indicates the ice flow direction which is southeast as well.

Plate: 23 One of the typical classical (asymmetrical) drumlinized moraines in the site 3. The outline forms do not signify that these are any form of mass movement deposits rather possibly ice marginally formed and may be drumlinized.

Plate: 24 The basket of egg topography (drumlin filed) in the Yunan valley area (site 2). View is looking along the valley from the downstream section. The small drumlins in the back ground are generally parallel (in the distal section) and oblique (in the proximal section) to the main valley orientation which is northeast. The oblique orientation is because of the post depositional modification of the drumlins by the debris flow deposits. As the deposits indicate, these are actually predominantly ice marginally formed.


Plate: 26


Plate: 27


Plate: 28


Plate: 29


Plate: 30

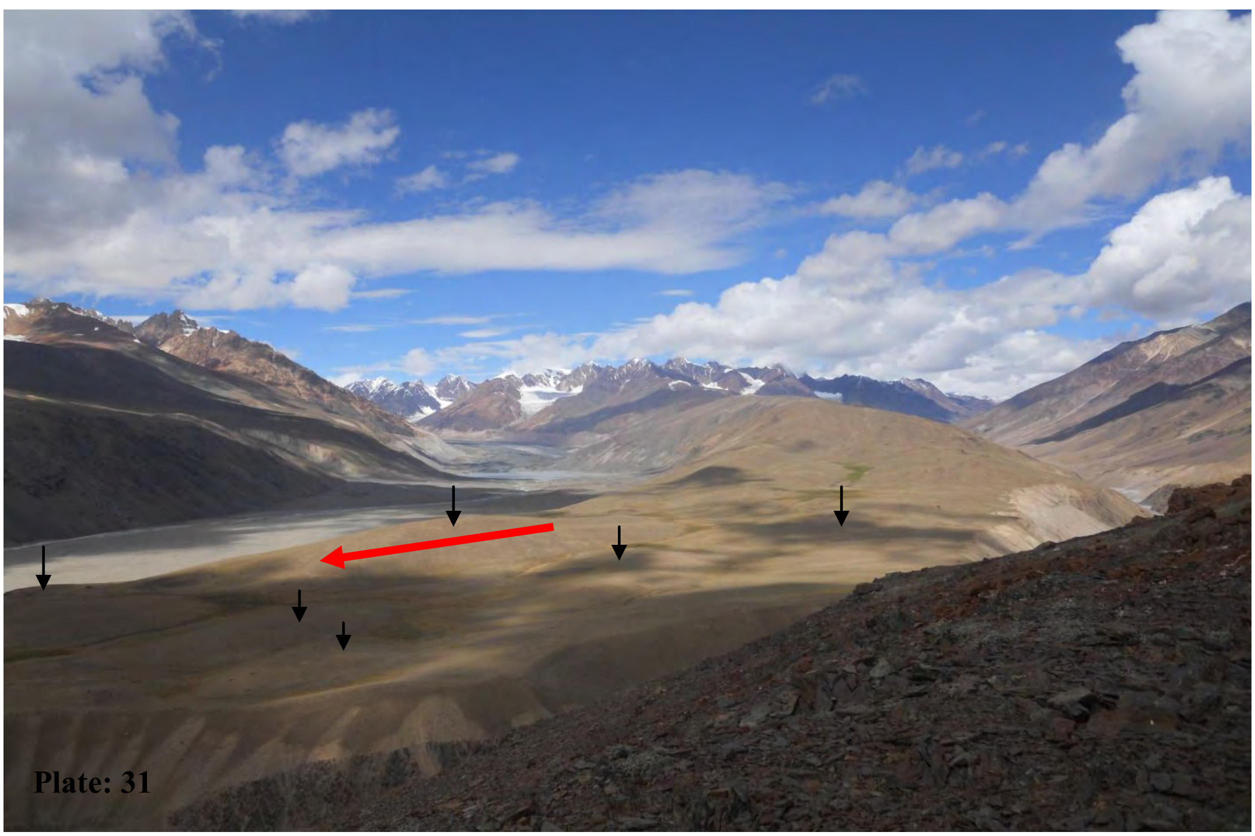


Plate: 31

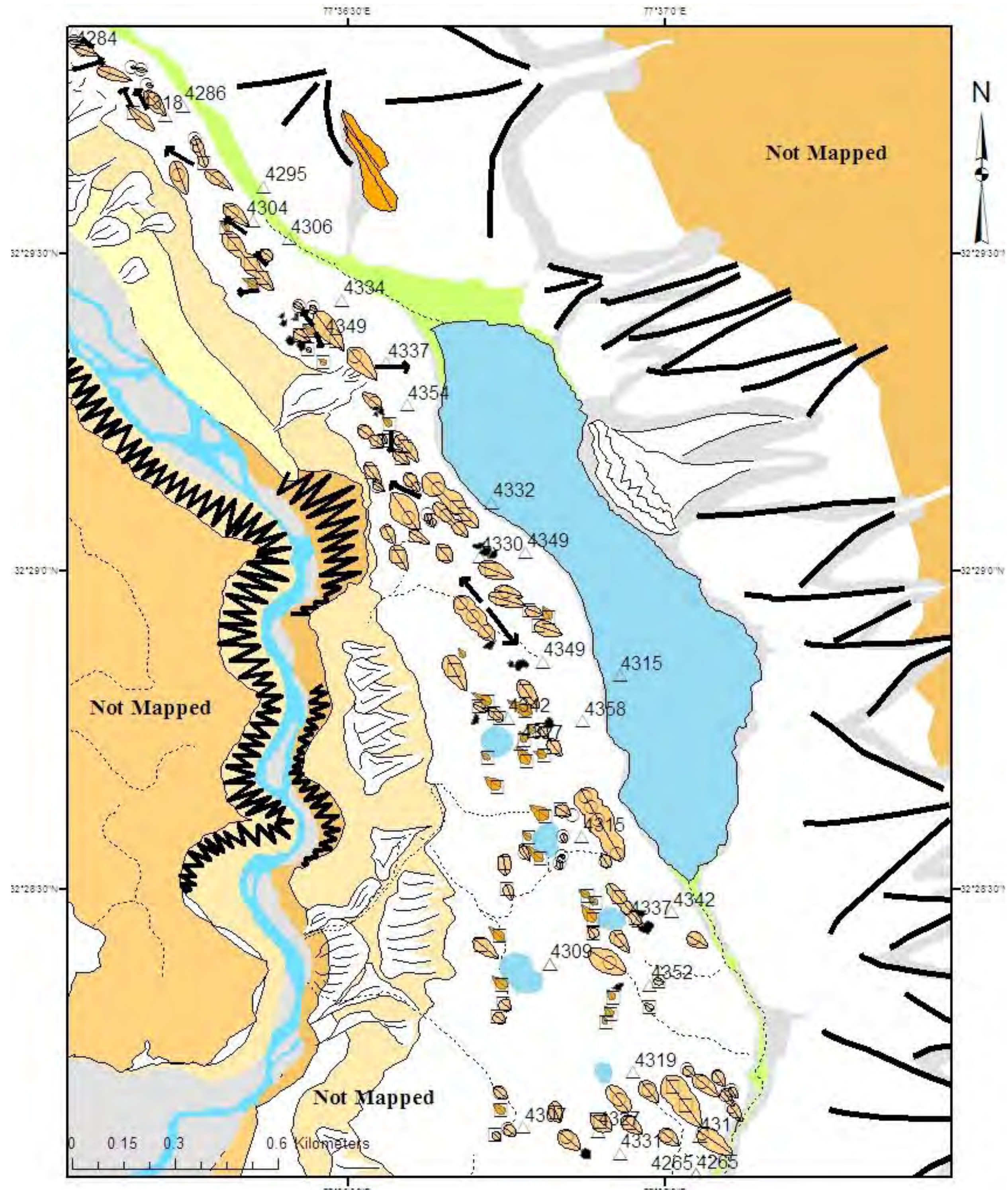


Fig. 49 Geomorphological map showing distribution of drumlins in the Chandra Tal area (site 1).

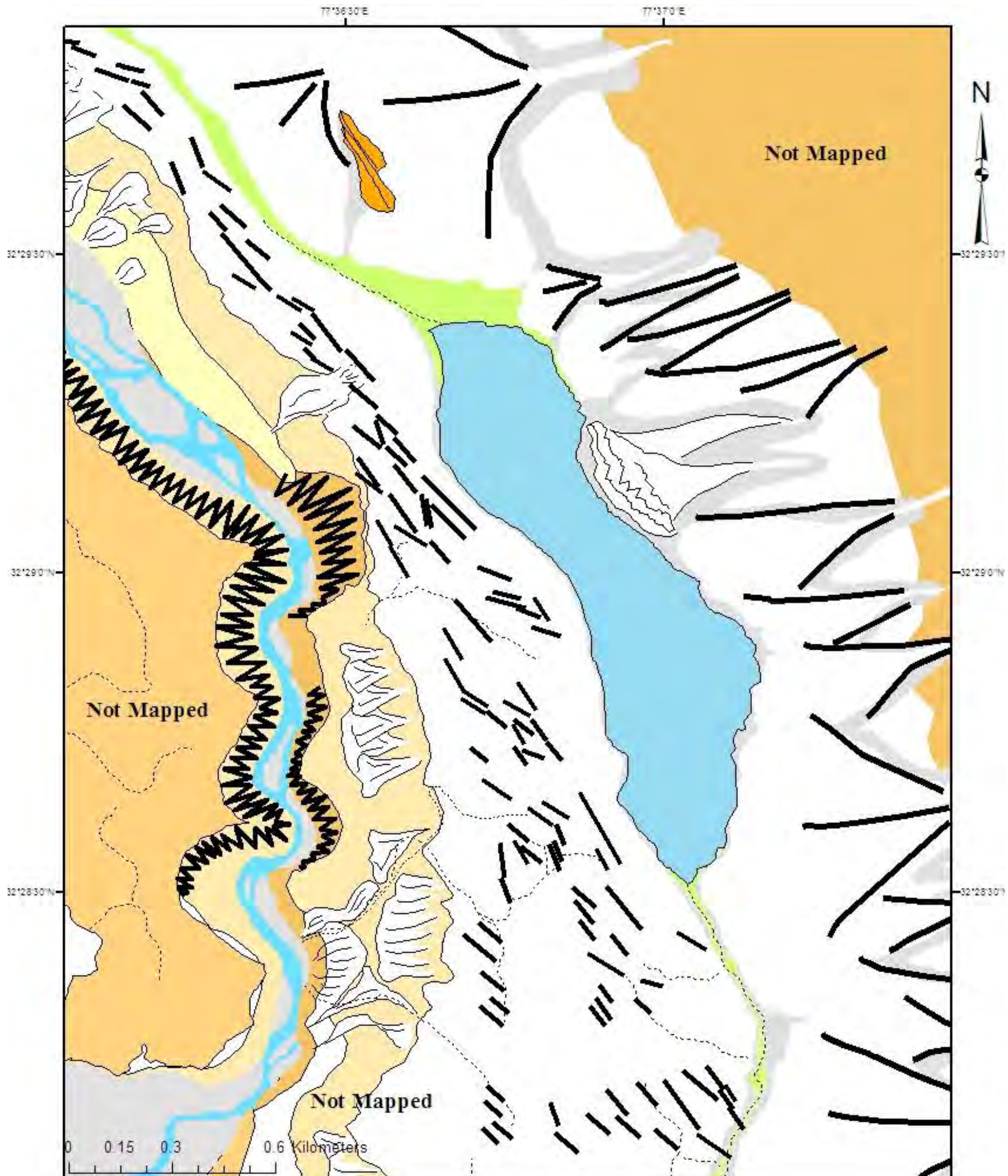


Fig. 50 General trend of longitudinal axes of drumlins in the Chandra Tal area (site 1).

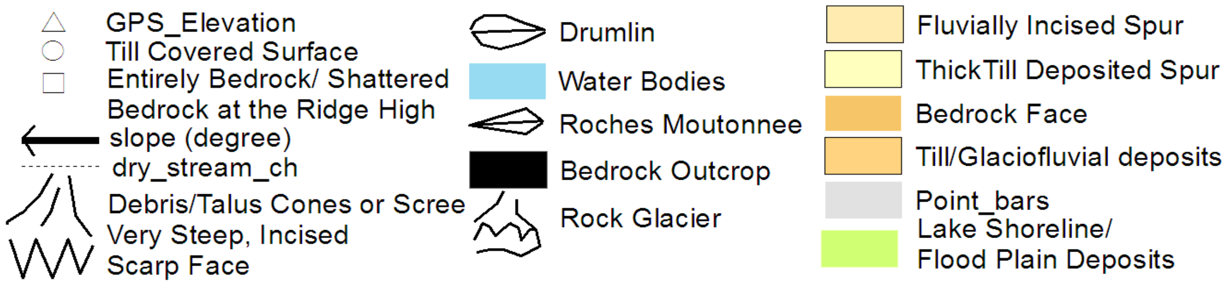


Plate: 25 The drumlin field in the site 2. Photograph has taken from the road. The large variation in the drumlin sizes and heights are clear in the plate. Except the road side deposits (disturbed during road preparation), even some of the drumlins contains supraglacial deposits at their surfaces, possibly emplaced at the ice-marginal condition. The loose (unconsolidated) composition further suggests that these are predominantly ice-marginally formed drumlins.

Plate: 26 Typical dome and classical shape drumlins 2. The drumlins contain supraglacial deposits at their surfaces, possibly emplaced at the ice-marginal condition. The arrow indicates the ice-flow direction and long-axis of the drumlins.

Plate: 27 More of symmetric form of drumlin. The present drumlin long axis is modified by the debris flow deposits. Two persons are given for scale.

Plate: 28 Classical form of drumlins parallel to the ice-flow direction (arrow) at the site 2.

Plate: 29 Broad, flat and wide valley of the site 2. View is looking down stream. This wide valley allows ice to spread and possibly augment the formation of drumlins in the area.

Plate: 30 The large debris fan near camp site in the Yunanvalley. Such paraglacial activities, predominant in the valley, largely modified the drumlins in the area; hence oblique orientation of some of these drumlins is found parallel to these large debris fans.

Plate: 31 Some of the classical drumlins are also found distributed in other site of the low ridge area. This ridge portion is found in between the Chandra river and Samundrinala. This is at the west of the surveyed low ridge area in site 1. Arrow indicate the samundri glacier in the back.

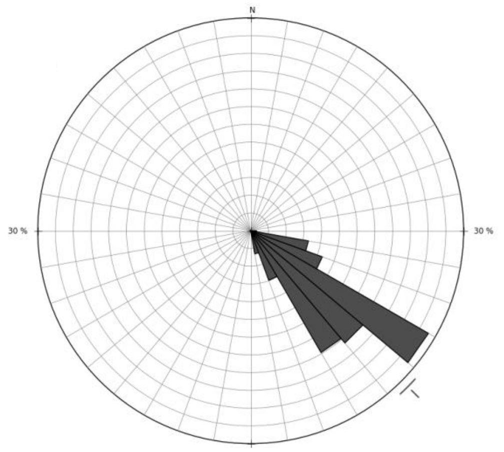


Fig. 51 Rose diagram showing the general orientation of drumlins and rochesmoutonne in the Chandra Tal area (site 1).

Several key points, however, can be inferred, from this analysis. The above analysis is very important in the light of subsequent interpretations of the geographical distribution of drumlins in the study area and their hypothetical explanation of evolution (see chapter: 6). This also explains why drumlins are uncommon in other parts of the Himalayas and Transhimalaya and why topography matters a great deal in regional glacial history and landscape evolution, apart from the climatic factors, in this Central Asian high mountain realm, especially during the Late Pleistocene and Holocene times.

5.4. Geographical Distribution of Drumlins in the Himalayas: A case study of Lahul Himal and Zanskar region.

It has already been discussed that drumlins are spatially distributed at the Chandra valley, at the Kunzum La area (site 3) of Upper Spiti valley, and at the Yunan valley (site 2) of Zanskar range. This section actually intends to discuss about the geographical distribution of drumlins at each study sites and their longitudinal axes orientations to decipher the former ice-flow direction in the region. Unlike the vast drumlin fields of the mid-latitude countries, formerly glaciated, the Himalayan drumlin fields are small and hence any systematic discernable changes in the size and shape is rare. This also limits the use of different morphometric techniques to these drumlins to identify any possible changes in the subglacial condition over time and space. Hence only the general interpretation of the spatial distribution of the drumlins is given in this section with the use of geomorphological maps as follows.

In the ***Chandra Tal area (Site 1)*** drumlins are found distributed on a low ridge area (~4,300m asl.) between Chandra Tal in the right and Samundri glacier in the left. This low ridge is dissected in the middle by the Chandra River. While the mapping is conducted in the right hand side of the ridge i.e. between the Chandra Tal and Chandra river, the other portion of the ridge is difficult to access easily (Plate: 31). The drumlin like ridges in this portion are variously defined as *'drumlinised moraines'* by Owen et al. (1997) (Plate: 31). Since no detail study is conducted on this ridge in the present work, they are not discussed here further.

In the site 1, drumlins are mostly found well distributed along the ridge (Fig. 49.a). Few of the similar oriented drumlins can also be identified (Fig. 49.b) in the south (32.442°-32.452°N/77.61°-77.614°E) on the vast outwash plain (Plate: 32); plate: 32 displays one of such drumlin which is also the sample site DPF3 (Fig. 85). Huge whale back structures composed of bedrock and having scree deposits at its flank, also can be found here in this outwash plain (Plate: 33). This whale back is possibly older in age and may be belong to older Chandra stage glaciation (Owen et al., 1996. 1997). However, in the north of the drumlin filed the deposits are heavily dissected by the ephemeral gullies emanating from the debris fans (Plate: 34) and no trace of drumlins whatsoever is preserved there. Hence field mapping is undertaken from the low ridge portion in which no dissection is taken place and the landforms are preserved well (Fig. 49). During field mapping, although the classical forms of drumlins overwhelm, wide ranging morphological forms have also been identified. They are discussed in the section 5.6. However, apart from morphological variation a distinct fact is recorded during field mapping; that the drumlins north of 32.479° north latitude i.e. more than first half of the low ridge section in the upstream reach, are generally larger in sizes but lesser in height and south of this, the relatively thicker but smaller drumlins replace the previous less thicker drumlins. This may possibly be related to the characteristics of glacier ice during their formation. May be higher stress in the upstream (or up-ice) section results in relatively larger sizes drumlins but with smaller heights and in the down-stream (down-ice) section the stress reduces (and/or supply of glacial materials increases) to form relatively thicker drumlins with small sizes in general. This generalize pattern requires further verification and quantification in future studies. However, bedrock ridges are also found along with drumlins in this area and some are found aligned in the same direction as drumlins (Fig. 35). These rock ridges and outcrops consist of deep red-brown rock varnishes. Besides ice molded rocks are also common in this area (Fig. 36). The important outcrops are also mapped (Fig. 49.a) along with Roche moutonnee and drumlins. These rock ridges and outcrops are found very important because few of them developed bedrock drumlins (Plate: 37). Besides they also act as bedrock core for some drumlin formation (Plate: 17) and also sometimes drumlins are tend to develop at the lee of the high rock outcrops (e.g. DFP3 in Fig. 85). They are well discernible at the surface of ridge highs of some of the drumlins (Plate: 38) (see section 5.6. for brief analysis) in Chandra Tal area (site 1). No discernible gully erosion or any sort of fluvial activities are found in the area to modify he drumlins (Plate: 39). Field evidences clearly indicate from the outset that these are impressive glacial landforms. The mini roches moutonnee like boulders, firmly lodged at the surfaces of the drumlins (Plate: 40), further strengthen the subglacial and submarginal origin of drumlins at the superficial level. Already, striations i.e. glacial scour marks (Plate: 20) are mentioned previously from this area, which have similar trend as the drumlins. These evidences strengthen the distribution and orientation of drumlins in the site 1 (Fig. 50). Some of the drumlin like hillocks are not mapped in the southwestern corner of the map but the photograph of them is given here in support (Plate: 41). These drumlin like hillocks are not so sharp compared to those mapped in the present study. However, a small drumlin (KG2 location in Fig. 85) which is mostly covered by debris fan deposits is also chosen for studying clast macro fabrics (Fig. 91). Previously it may be mistaken as moraines of Batal Stage glacial advance by previous workers, but the fabric data along with its long axes orientation disagree with their interpretation and place the landform as one of the drumlins (Plate: 42). However, several discontinuous morainic features of possibly Batal stage are clrealy identified during the field survey as well. One is found north of the Chandra Tal (Fig. 49.a; Plate: 43) and another south of it (Plate: 44) flanking the western slope of Kunzum range. Among the other interesting features, impressive debris cones (Plate: 17, 19, 34), rock fall deposits (Plate: 45), small rock glacier like features (Plate: 46), erratic boulders[32] (Plate: 47) with extensive rock varnish, lake shoreline deposits (Plate: 45), and braided course of the river (Plate: 41) are identified and mapped (Fig. 49). The ridge area west of the present mapped area (Fig. 49) at the Chandra Tal contains not only 'drumlinized moraines' (Owen et al., 1997) but also extensively distributed thick diamictons overlying the bedrocks at the bottom (Plate: 48). Recent rapid fluvial incision[33] in this part of the basin, also leads to the deposition of fluvio-glacial deposits along both the banks of the present Chandra River. However, along with the distribution of drumlins in site 1, the longitudinal axes data of the drumlins and roches moutonnee when mapped (Fig. 50), indicates the southeasterly flow direction of the glacier ice during extensive glaciation, especially during Batal stage (Owen et al., 1996, 1997, 2001). The average flow direction is ~135° from the north (Fig. 51) with maximum clustering between 120° to 150°. This is dissimilar to the present north-south trending main Chandra valleys, hence supports the view of the Owen et al. (1997,

[32] The erratic boulders are mostly granitic.

[33] According to Adams et al. (2009) the rate of fluvial incision in the Chandra valley is rapid but highly spatially variable, with a minimum of 5mm a^{-1} to as high as 12mm a^{-1}.

2001) that the ice flow was southeasterly and possibly involved overtopping of the Kunzum range at the Kunzum La and its spread into the upper Spiti valley. The glacially polished and ice molded bedrock at Kunzum La (Plate: 49) (4,7000m asl.) and striation marks on them (Fig. 52), in addition to the CRN numerical dates from these polished surfaces (Owen et al., 2001), are also now strongly support the above inference. The striation data provided by Owen et al. (1997) (Fig. 52) of this area, demonstrate the same directional pattern—with the mean trend of striae is ~138° from the north (Fig. 53). Several minor variations in the distribution of striations are there (Fig. 52) but the general pattern remains intact in all these data. It is also noted that some of the striae may be the signatures of older age glacier advance but such possibly is very limited because the data is collected from those areas and altitudes which is believed to be overridden by the Batal stage extensive valley glaciers during late glacial interstadial period (Owen et al., 2001). Another fact also requires attention here. The flow direction of the main valley glacier (Fig. 52) during this extensive glacial advance also found to be largely affected by the tributary Samundri glacier coming from northwest (Fig. 51; Plate: 35). It may be possible that the glacier ice coming from the Baralacha la (4,900m asl.) in the valley head, when joined by the Samundri glacier downstream (~4,300m asl.), deflected in the southeast direction and followed a rather dissimilar flow pattern compared to the main Chandra valley in the upstream reach at the present. Some of the drumlins south of the area (Fig. 49.b) also possess similar southeasterly trend which seems to be nearly similar to the present course of the Samundri glacier if projected downstream. Hence in addition to the spreading effect in the 'funnel valley' at the Chandra Tal area (site 1), the glacier ice also may be deflected by the tributary Samundri glacier to further augment the spreading of ice and overtopping of the Samundri glacier (Fig. 51). Existence of some of the drumlins north of the Samundri glacier, also negate any speculation that drumlins are also

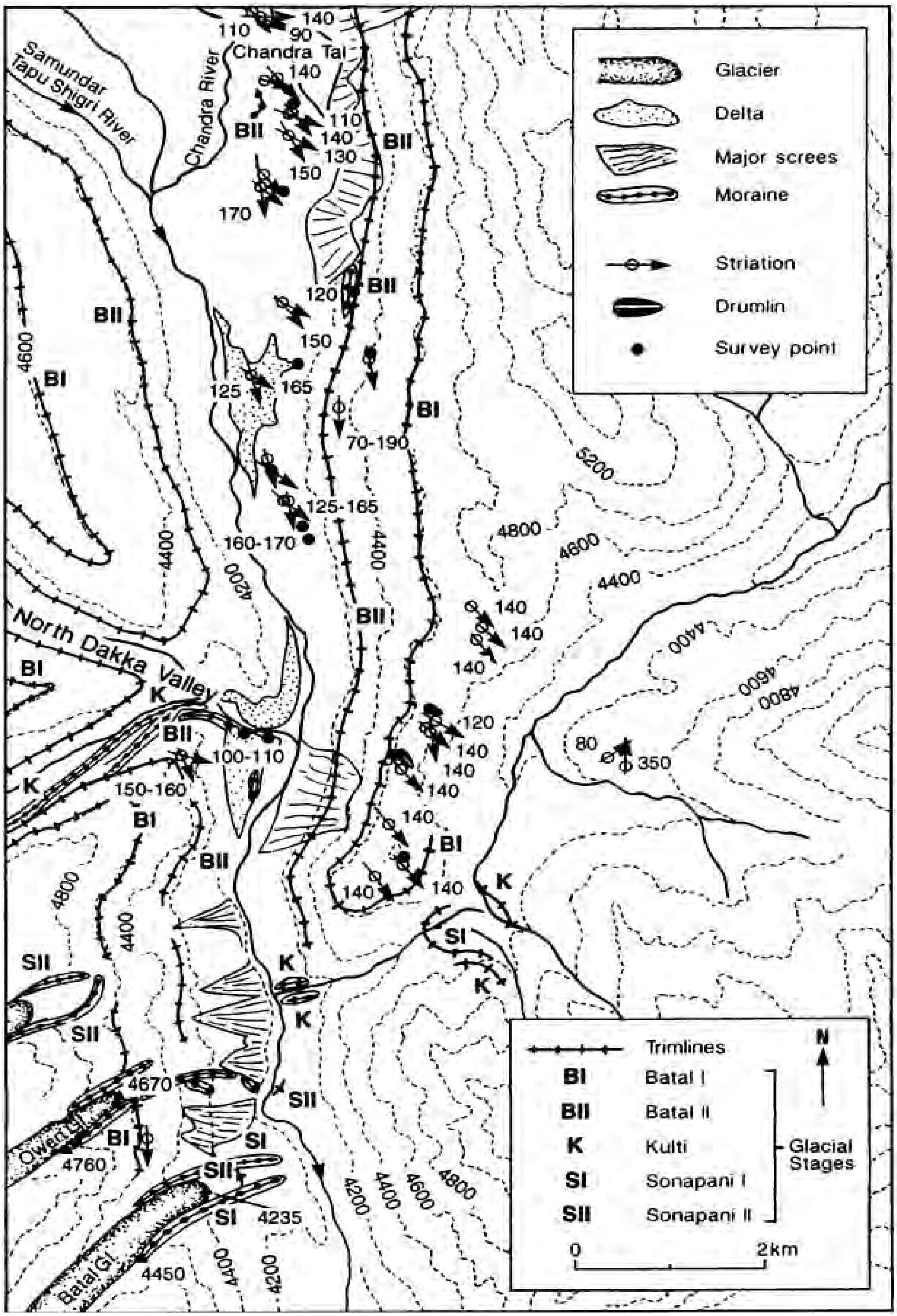


Fig. 52 Map showing the striations in the Chandra Valley and at the upper Spiti valley and drumlins at the Kunzum La. Adapted from Owen et al. (1997).

formed by the ice coming from Samundri glacier only (see section 5.5). Also other evidences clearly pointed that the landforms is drumlin and not any morainic deposits.

However, when the geomorphological map is prepared for the **Kunzum La area** (site 3), it is also found that the drumlinized mounds have long-axes orientation between 100° and 110° from the north, agreeing with the general flow directional pattern (Fig. 52). Although several moraine like features are identified during short field survey (Plate: 50, Fig. 54) but more rigorous study is required in this area to confirm them firmly because extensive dissection by the streams occurs in this area. The drumlinized mounds are similar in sizes and found within a small area flanking the eastern slope of Kunzum range (Plate: 21). They are mostly classical in shape (Plate: 23) and posses extensive lodged boulders at their surfaces, typical to subglacial lodgement (Plate: 51). Later fabric data is supported along with their morphological types (see section 6.2.2.4). Often these landforms are found dissected by gullies in their depressions and modified at the lee side by the stream. However, other drumlinized mounds/drumlins in this area is already mapped (Fig. 52) by Owen et al. (1997) at the Kunzum La ~4,600 m altitude.

Yunan valley (site 2, at ~4,450 m asl.) incorporates the second most extensive distributed drumlin fields in the Himalayas next to Chandra valley near Chandra Tal (site 1). The drumlins are found to be spatially distributed parallel along the valley (Fig. 55) and also they are diagonally to valley from the southwest due to post depositional modification. Such a geographical distribution of the long-axes of the drumlins (Fig. 56) suggests that glacier ice possibly flown through the Yunan valley following the main valley gradient and spread out along the broad opening of the valley. Some of the oblique to transverse drumlins in the Yunan basin are now extensively covered with debris fan deposits and show. This may be accounted for large scale post depositional modifications (Fig. 55). Drumlins, however, are extensively observed in this valley and such hillocks are absent beyond the outlet point of the Yunan basin. This may be due to the limited deposits glaciation in the main valley (also discontinuous evidences of glaciation in the tributary valleys), especially during late glacial interstadial period or Historical time (Taylor and Mitchell, 2000; Hedrick et al., 2011). More extensive study is required and there is an urgent need to date the drumlins of Yunan valley (site 2) and also to compare them with the drumlins of the Chandra Tal area (site 1). This may unlock many of the research gaps and answer many of the questions related to past glaciation and palaeoclimatic condition in the region.

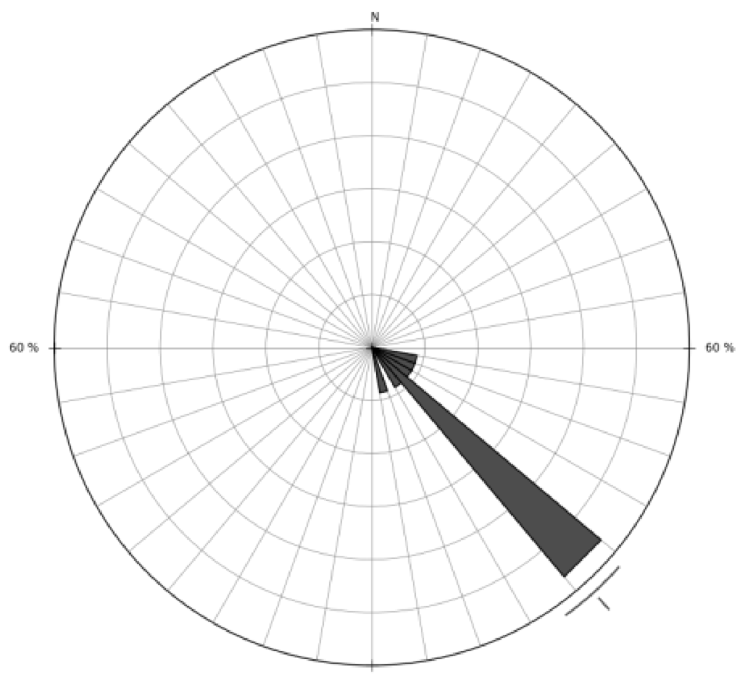


Fig. 53 Rose diagram showing the general orientation of drumlins in the upper Spiti valley at Kunzum La (site2).

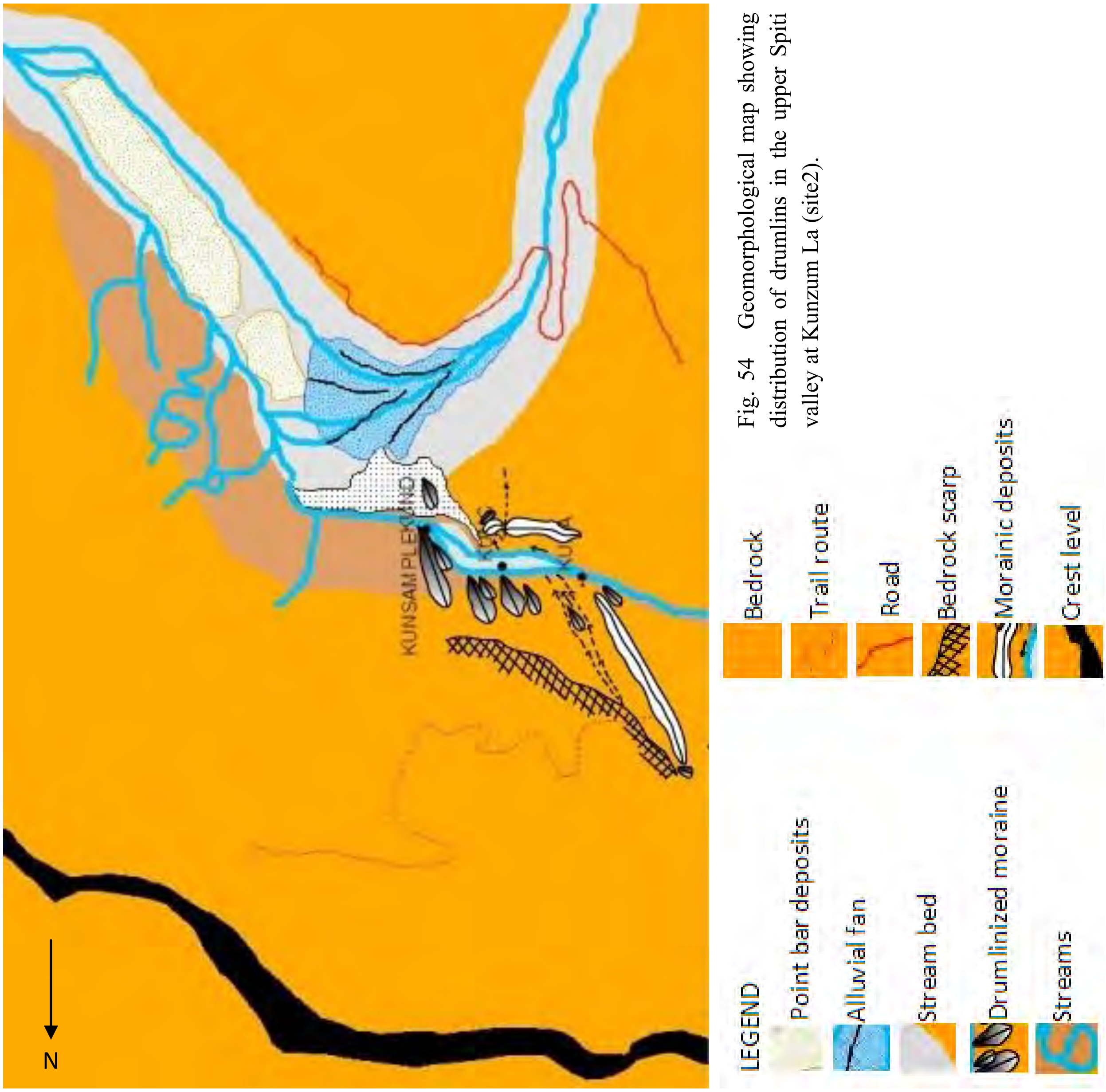


Fig. 54 Geomorphological map showing distribution of drumlins in the upper Spiti valley at Kunzum La (site2).

However, the drumlins which are parallel to valley, are mostly oriented northeastward in the main valley and those which are diagonal to transverse to the main valley, are mostly trending north to north-northeast (NNE). Hence two sets of orientations of the drumlins are clear in the valley (site 2), although the later requires to be excluded due to their remodification by other processes than glacial. Different geomorphological types of drumlins are observed but not recorded for the Yunan valley. It has been also observed that the valley shows great spatial variations in the sizes and thickness of the drumlins within short distances (Plate: 25 & 26). Some mounds also look like hummocky moraines in the field (Plate: 53 & 54), and few of them do possess loose glacial boulders of possibly supraglacial origin at their surfaces (Plate:54), unlike them found in the Chandra Tal area (site 1), suggesting their evolution in the ice marginal condition. However, the drumlins in the valley have parallel long-axes orientations in general (Fig. 56), and other drumlin properties as well (section: 5.1). However, classical drumlins overwhelm (Plate: 24 & 55) in this basket of egg topography. In the upstream section drumlins are relatively huge in thickness and size (Plate: 56) with low elongation ratio and hummocky in appearance (Plate: 57), compare to the downstream drumlins, which are relatively less thick, more elongated and relatively smaller in size (Plate: 53). The reason behind this is unknown, although they may be related to the ice marginal condition and/or the supply of diamictons. Some of the road-cuts in the recent years, however, exposes the internal composition of the drumlins in the valley (Plate: 59) creating more scope for future research on their internal sedimentology. These may serve many of the questions raised till now. Among the other features, erratic (Plate: 60) are found extensively in the valley (possibly belong to older age glaciation); debris and talus cones (Plate: 26, 30, 55; Fig. 56) are also very extensive all along the flanks of the valley walls. Extensive debris flows often found covering the smaller drumlins leaving their ridge-highs visible at the surface (Plate: 61). A rock glacier is also mapped (Fig. 55) in the upstream section. These evidences and their geographic distribution denote that during glacial advance thick ice covered the area and spread all along the main valley. Presently paraglacial processes dominate in the valley and often lead to modification of the exiting landforms. However, more rigorous analyses are required in this area (site 2) to unrevealed many of the mysteries pointed out by this preliminary study. Putting together all these evidences may complete the puzzle to a considerable extent.

Plate: 32 Medium size typical classical form of drumlin (DPF3) in the site 1. Lodged boulders are extensively lodged at the drumlin surface. This is the sample drumlin on which the trend data for the mini-rochemoutonnee type lodged boulders are recorded (see Fig. 93).

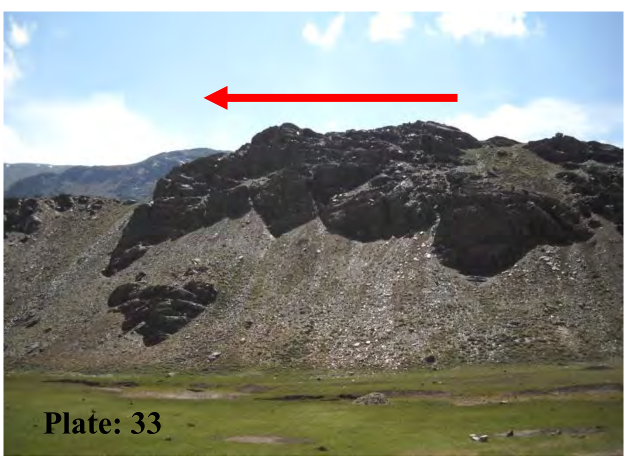
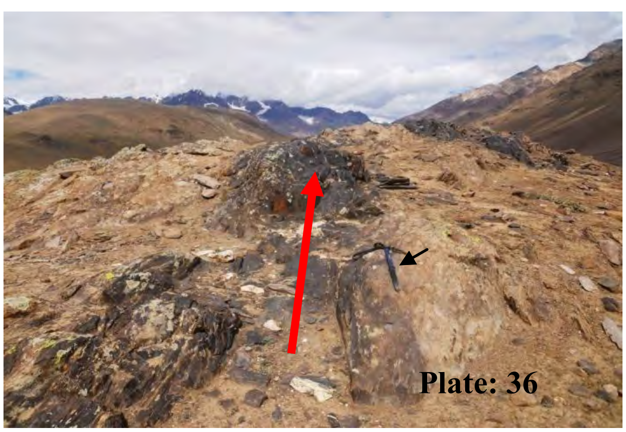
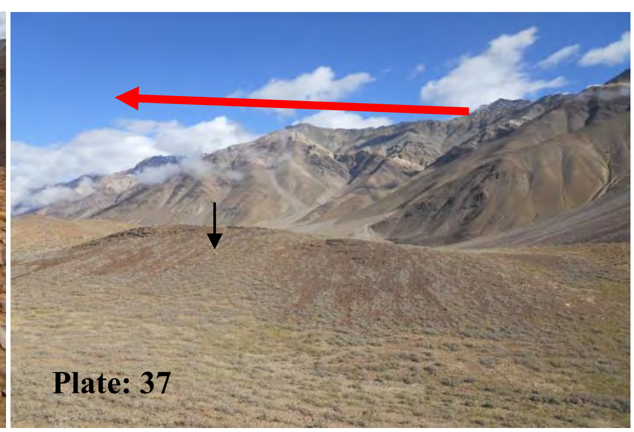


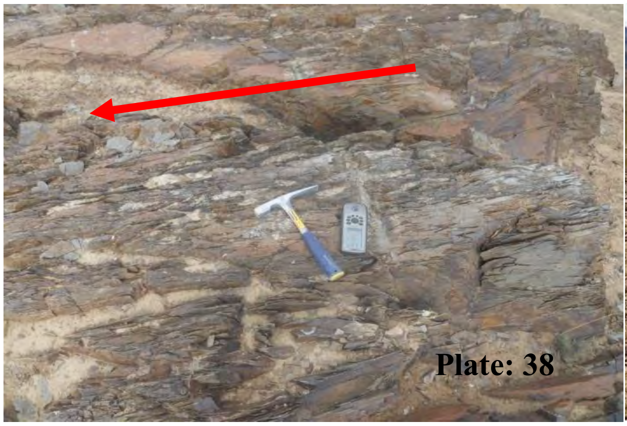
Plate: 33 The bedrock bench or large whale back landform in the site 1. According to Owen et al. (1997) this large erosional landform is formed during the extensive Chandra stage valley glaciation.

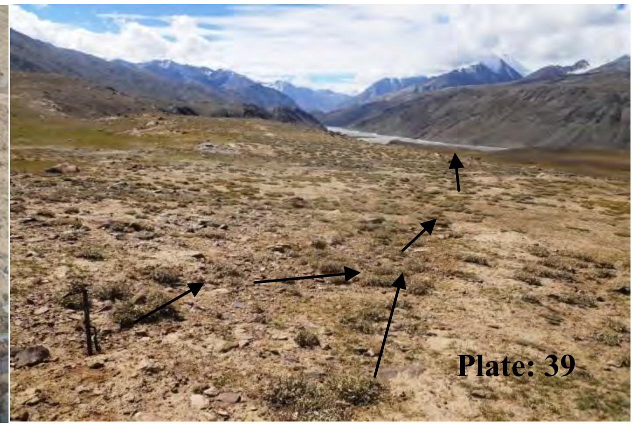
Plate: 34 This is the extensively eroded low ridge portion in the upstream side (north). This survey portion does not preserve any history of drumlin formation and hence mapping is done basically south of this eroded part in site 1.

Plate: 35 The bedrock outcrops are also found aligned in southeast direction and shows the same alignment as the Samundri glacier if ectended further downstream. This along with the drumlins also support that the tributary glacier might have some role in deflecting the main valley glacier to have southeasterly course. The outcrops are entirely covered with deep red-brown rock varnishes.









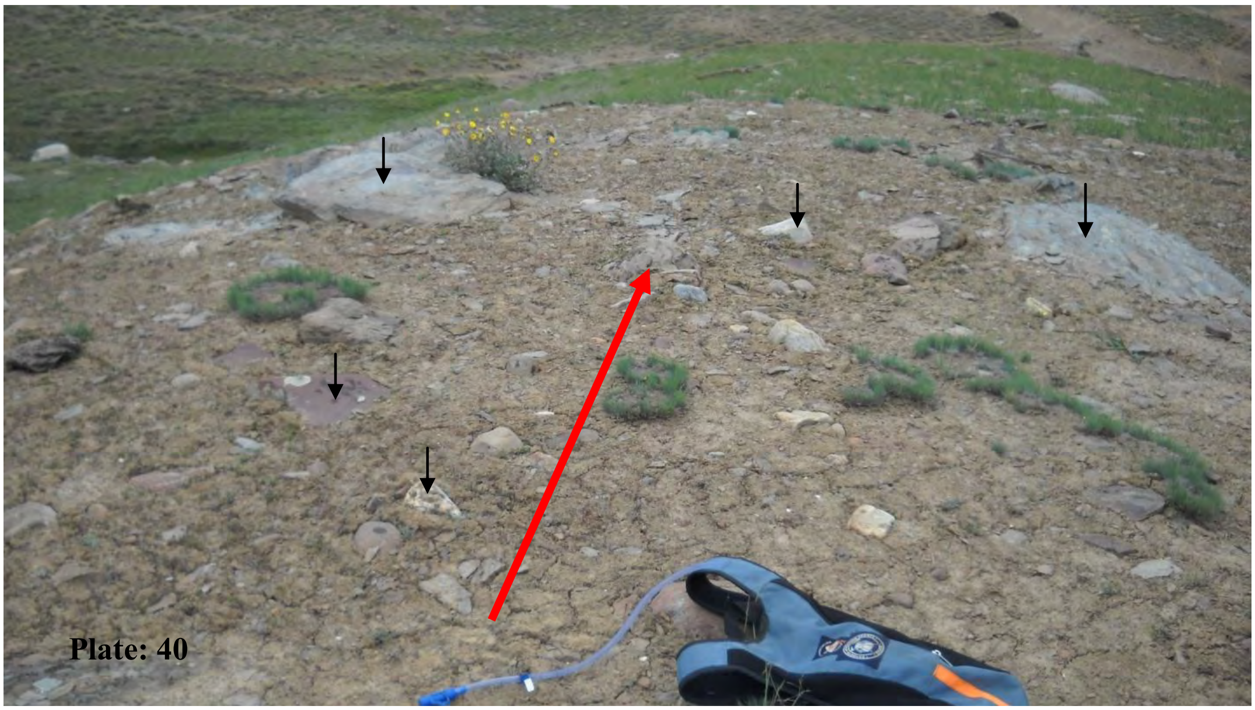


Plate: 36 The ice-molded roks are also found oriented parallel to the long axes of the drumlins and often protrude at the surfaces of the drumlins at the site 1.

Plate: 37 Entirely classical bedrock drumlins with very thin till carapace, possibly deposited at the ice-marginal subenvironment in the site 1.

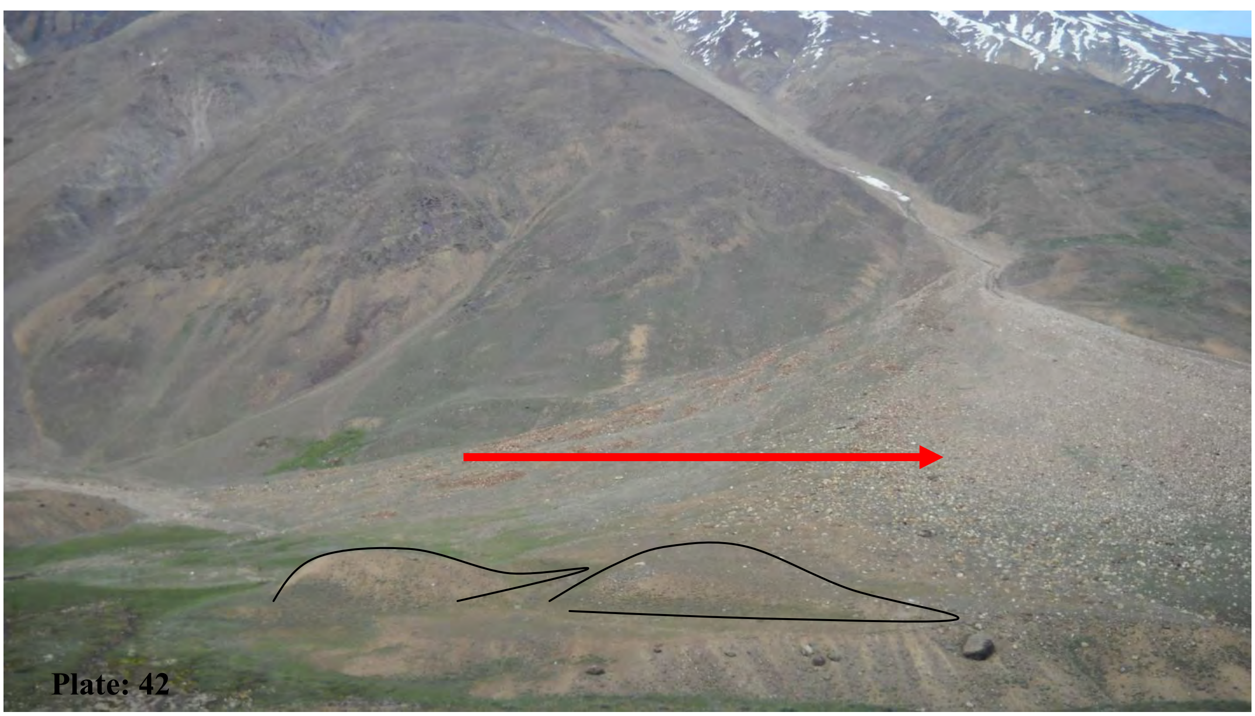


Plate: 38 The glacially eroded and periglacially weathered shale/slate bedrock outcrop at the drumlin surface at the site 1. Such kind of bedrock not only acts as obstacle to the flow and allows the formation of drumlins, but also supply locally available blade shaped clasts. The GPS and hammer is given for scale.

Plate: 39 The very small gullies develop at low ridge are of the site 1, on which survey is mainly conducted. Besides these insignificant features no other fluvial effect is discernible in the valley and thus the streamlined forms are extensively glacially developed rather than any other geomorphological agent. The ice-axe (for scale) is showing one of such gullies.

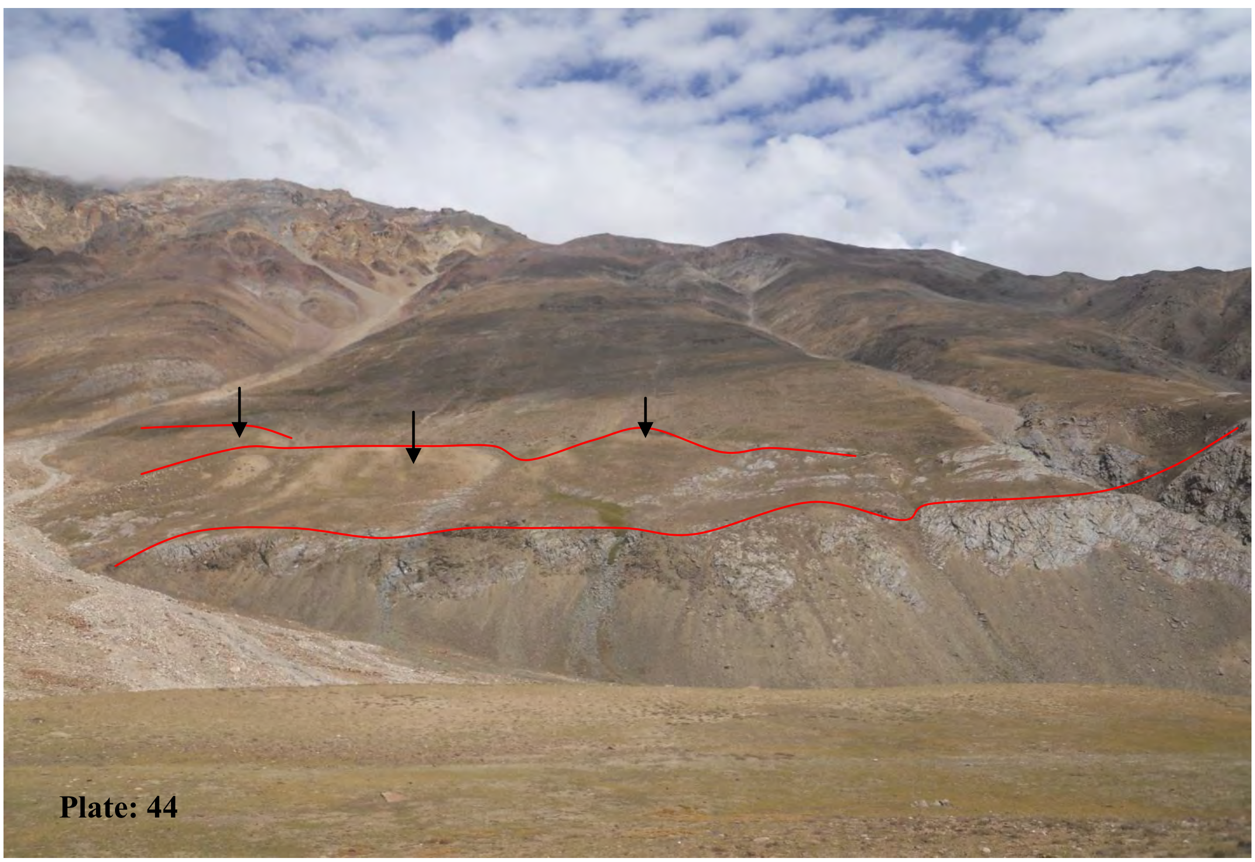
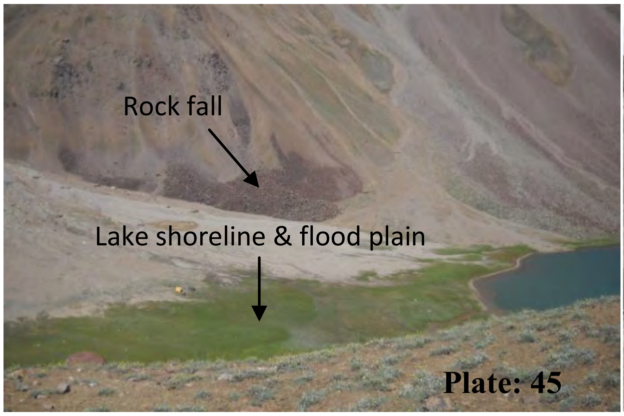
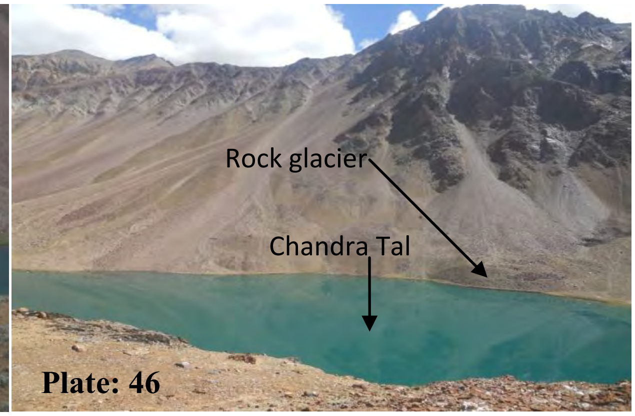
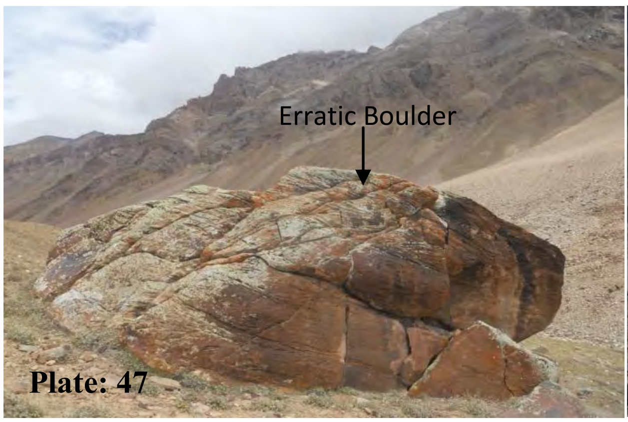


Plate: 40 The typical mini-rochemoutonnee type lodge boulders at the surface of the drumlin DFP3 at the site 1. These are believed to be englacially or subglacially supplied. The arrow indicates the ice-flow direction in the valley. The bag is given for scale.

Plate: 41 Inthe extreme west of the low ridge area at the site 1, few drumlins are later identified but they are not mapped in the Map (Fig. 49).







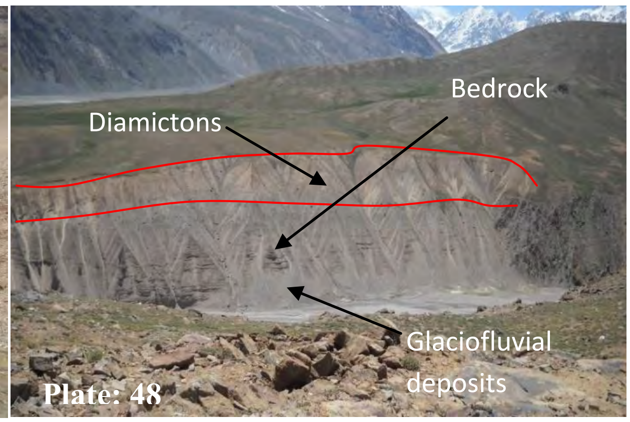


Plate: 49

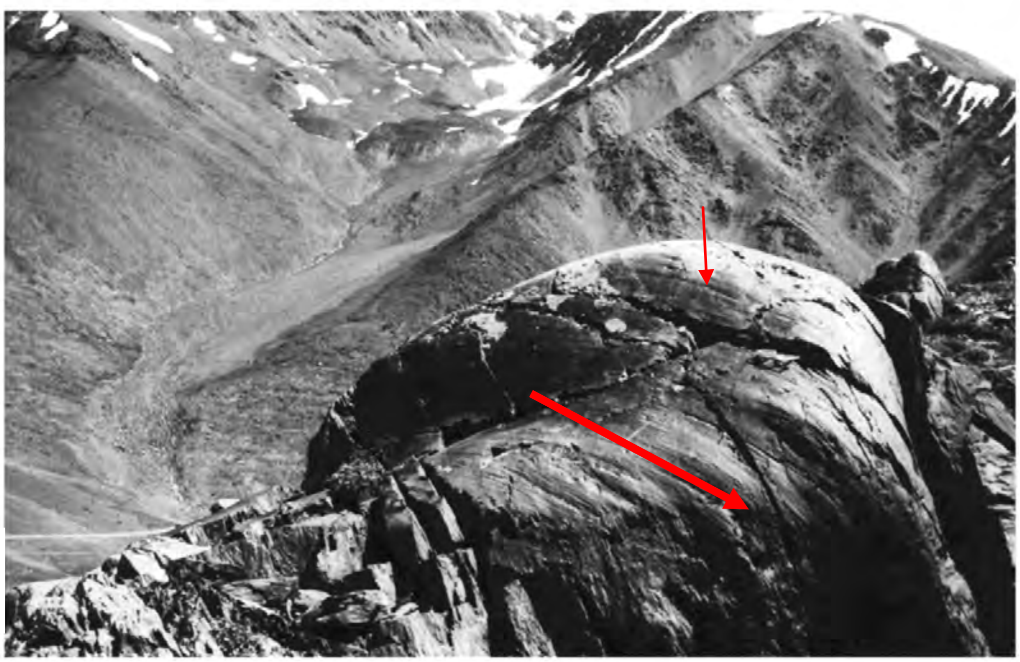


Plate: 42 The KG2/DPF drumlin (arrow) at the site 1. This drumlin is surrounded by the debris fan flank the western slope of the Kunzum range. Clast macro fabric analysis is done from this drumlin.

Plate: 43 Batal stage lateral moraine (red line) at the site 1. This moraine is extensively covered with debris fan. It is located north of the Chandra Tal.

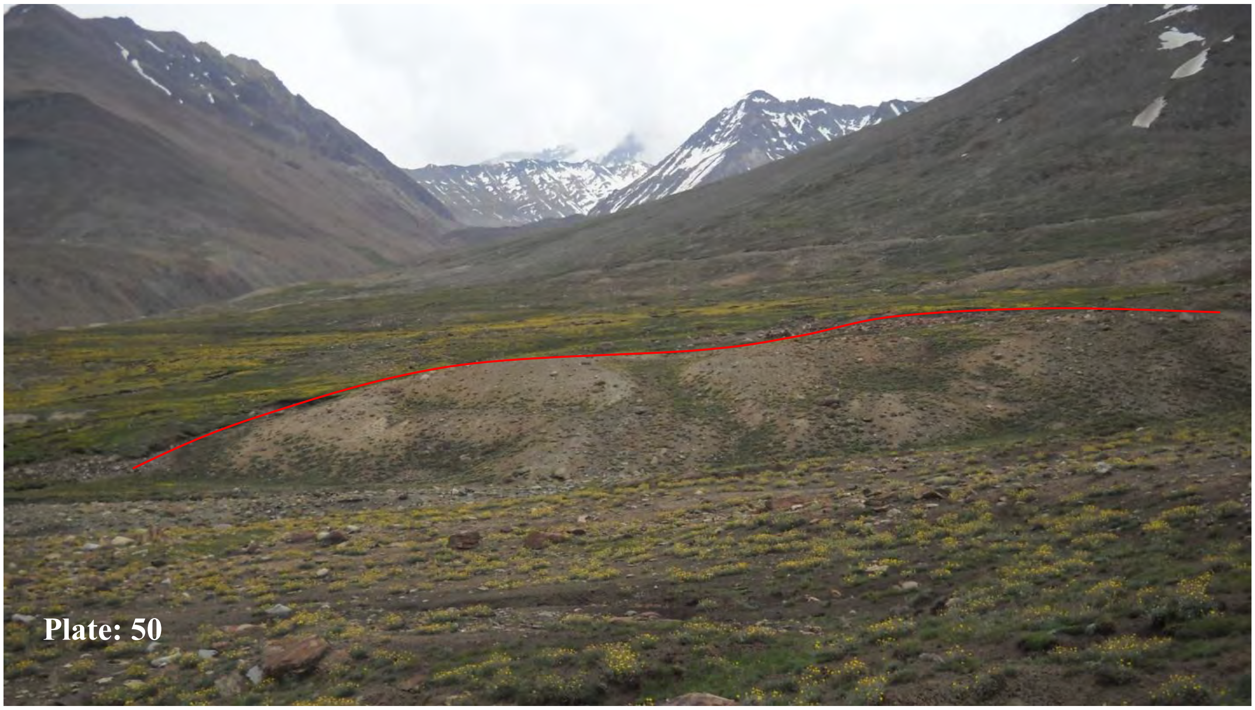
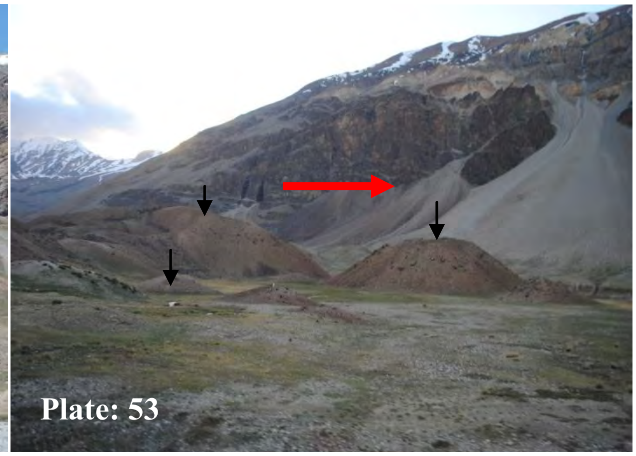


Plate: 44 The Batal stage moraine above and the trimline and glacially polished surface below at the south of the Chandra Tal. The discontinuous moraine is located at the western flank of the Kunzum range.

Plate: 45 The lake shoreline deposits (grassy cover) and rock fall deposits (arrow) in the Chandra Tal area.

Plate: 46 Thesmall lobate type of rock glacier (arrow) right side of the Chandra Tal (site 1). The Tal is located at the front of the picture.

Plate: 47 The erratic boulder at the low ridge area. Possibly deposited during Batal stage glacial advance.



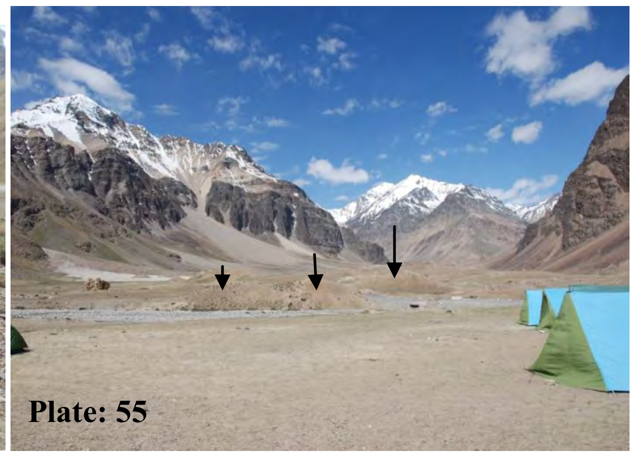


Plate: 48 The ridge area west of the Chandra Tal consists of thick deposits of diamictons above, and is underlying by the bedrocks. Spatially variable but rapid fluvial incision causes recent deposition of fluvial and mass movement deposits along the banks of the Chandra river.

Plate: 49 The ice-molded rocks at the Kunzum range near Kunzum La (site 3). This molded rock is also overridden by the glacier during the Batal stage extensive valley glaciation in the Lahul Himalaya. Adapted from Owen et al. (1997).

Plate: 50 Themoarinic landform in the upper Spiti valley. This is extensively eroded by the stream in the right leaving more confusion regarding this landform.

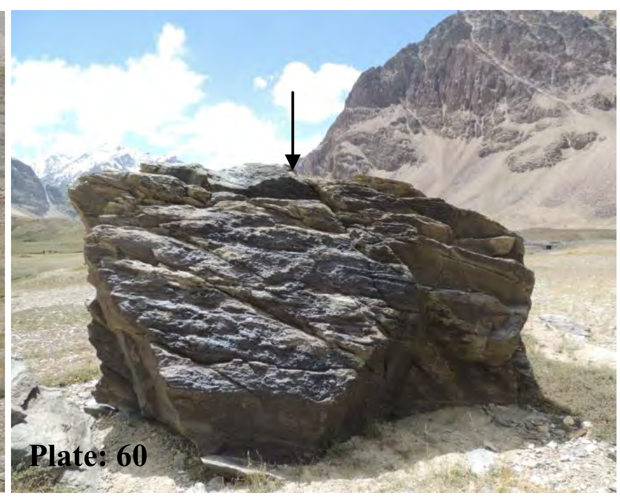


Plate: 51 The typical mini-rochemoutonnee like small boulders lodge extensively at the surface of the drumlin (KUN/07/50) in the site 3. These boulders are subglacially or englacially sourced and lodge at the surface. They also indicate strong fabric (Fig. 94a,b) parallel to the long axis of the drumlin. The walking stick is given for scale.

Plate: 52 The typical ice-marginal drumlin at the site 2, orientation of which is extensively modified by the debris fans behind. The trimline(red line) behind, also indicates the extensive valley glaciation in the valley; although their age is not determined yet or referred anywhere. Two persons are given for scale. (Supplied by M.C. Sharma).

Plate: 53 The ice-marginally formed drumlins at the site 2 show large scale size and height variations.

Plate: 54 The unconsolidated (loose) composition of these drumlins and supraglacial boulder deposits at their surfaces at the site 2, strongly supports that these are ice-marginally formed. The CSRD (JNU) MA.Geography students for scale.

Plate: 55 The obliquely oriented drumlins at the site 2, near base camp. The long axes of them are modified by the debris fans and ephemeral streams. Tents are given for scale.

Plate: 56 Very large size and thick drumlins are mostly developed in the upstream section rather than the downstream at the site 2. These are also largely eroded due to post depositional fluvial activities in the main valley.

Plate: 57 This also indicates more larger forms of drumlins in the up-valley section than the down-valley at the site 1.

Plate: 58 More smaller forms of drumlins in the downstream section of the site 2.

Plate: 59 Recentroadcuts at the Yunan valley provide the scope for studying the internal composition of these mostly classical drumlins more effectively. The temple is given for scale.

Plate: 60 Largeaugen gneissic erratic boulder at the Yunan valley. These kinds of boulders are extensively reported in the literature.

Plate: 61 The large debris fan deposits buried the smaller drumlins near the valley slope at the distal part of the site 2.

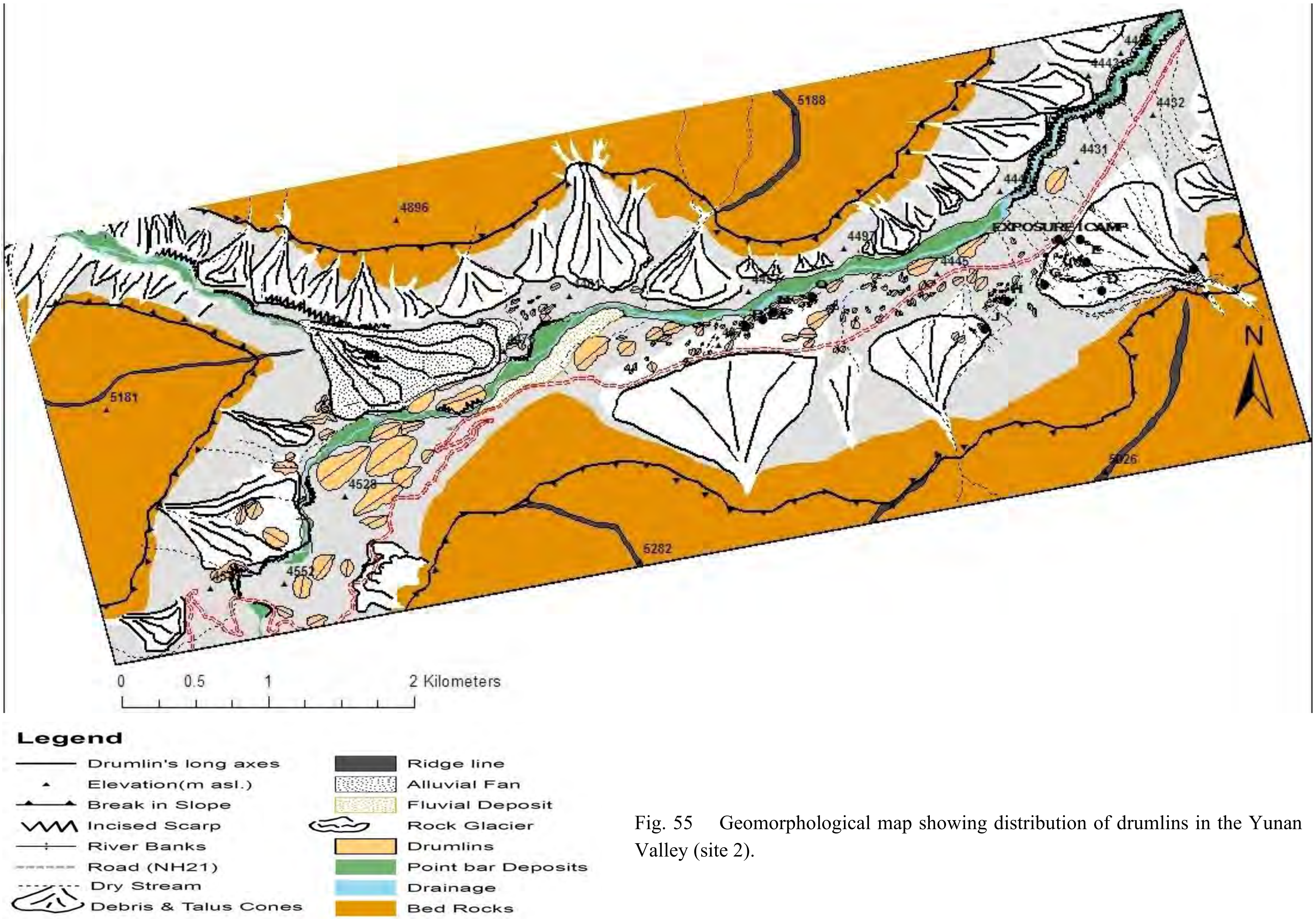


Fig. 55 Geomorphological map showing distribution of drumlins in the Yunan Valley (site 2).

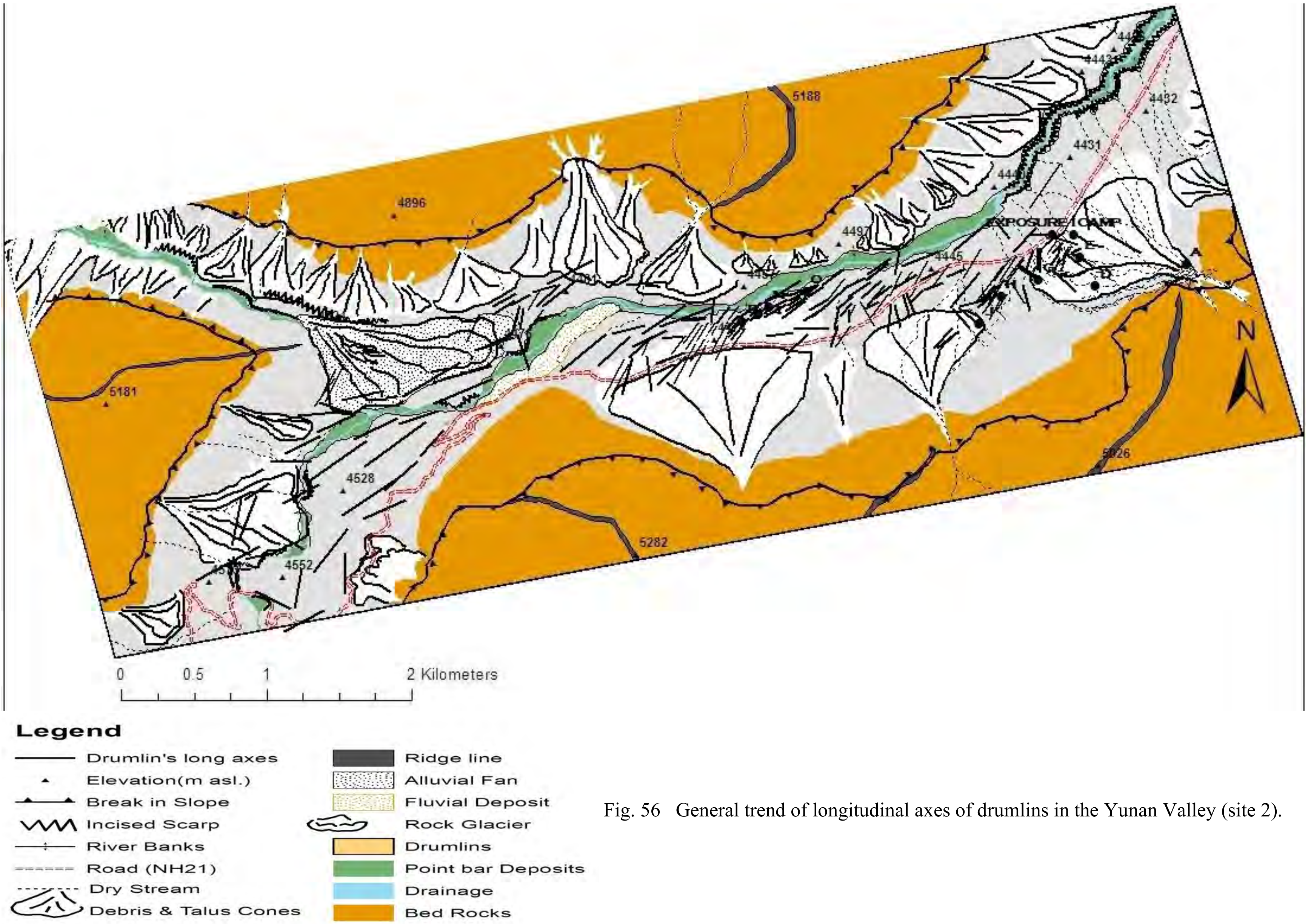


Fig. 56 General trend of longitudinal axes of drumlins in the Yunan Valley (site 2).

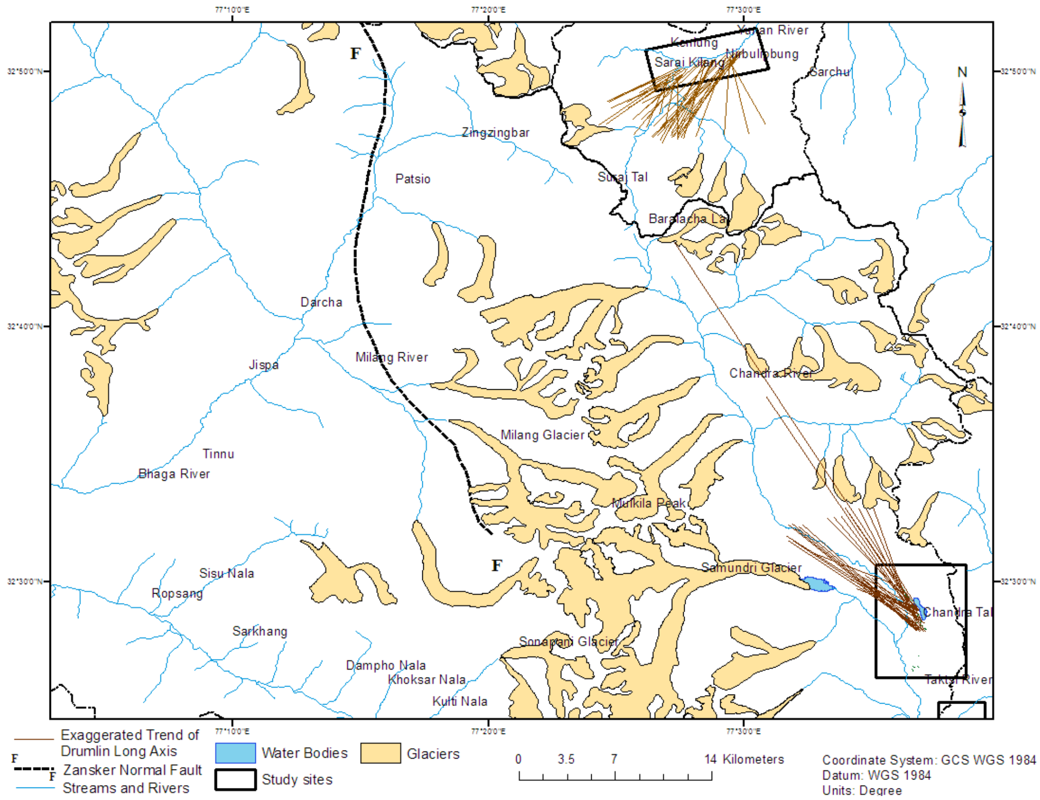


Fig. 57 Location of ice-divide in the Lahul Himalaya and Zanskarvalley, based on the extrapolated drumlin long axes data from both the adjacent valleys. They may be or may not be of similar age, but whatever it is the location of the ice-divide was well in the Baralacha La rather than near Darcha in the Bhaga valley.

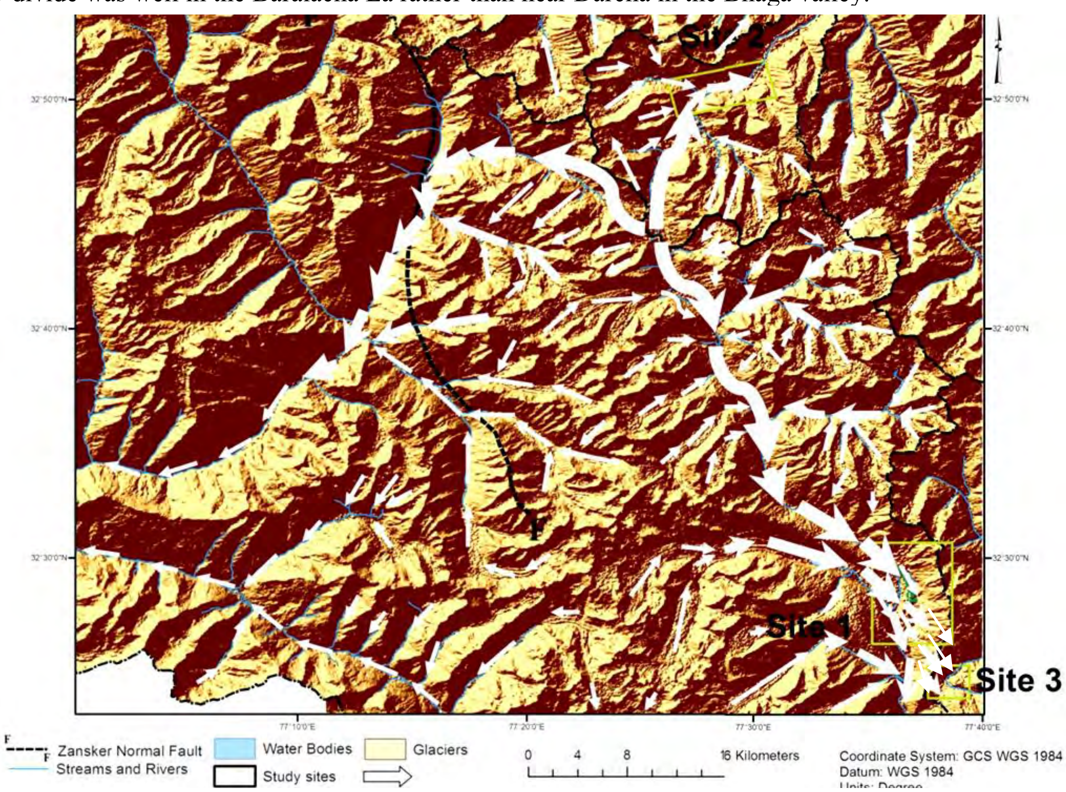


Fig. 58 Reconstructed ice-flow directions in the Chandra and Bhaga valleys of LahulHimal, based on the available evidences of the drumlin's long axes, trimlines, and striations and moraine deposits of extensive Batal stage. In the Yunan valley ice flow along the valley only. Note that the main ice flow direction was southeasterly at the Chandra Tal area and likely to overtopped the Kunzum range to flow into the upper Spiti valley.

5.5. Location of Ice-divide at Baralacha La during extensive valley glaciation:

During extensive valley glaciation in the study area, i.e. during Batal stage glaciation (12-15.5 ka, Owen et al., 2001), the possible location of the ice-divide, according to Owen et al. (1997), was at the Baralacha La. they provided the evidences of an indurated tillite at Baralacha la (at the head of the Bhaga valley), which displays ice-flow towards Yunan valley of Zanskar range, and also towards the southeast down the Chandra valley, i.e. towards the Lahul valley. This suggests that the ice-divide is right at the Baralacha La. although Porter (cf. Owen et al., 1997) interpretated them as belong to Chandra Stage glaciation (in the Lahul Himalaya) due to their induration, but Owen et al. (1997) cautions such inference by saying that age not always determine induration. However, Taylor and Mitchell (2000), on the contrary, believed that during Chandra Stage (Zanskar 1) *'ice-cap type'* broad glaciation in the Zanskar valley , the ice-divide was possibly located at a significant distance from the Baralacha La (4,900m asl.), south into the Bhaga valley of Lahul Himalaya. According to them, the distribution of erratics of gneissic rock indicates that they could only come from the Lahul Himalaya; ~100 km. up-valley to the south of Zanskar Normal Fault (ZNF) near Dracha. This area, according to them, consists of huge grade metamorphic outcrops and also the nearest possible provenance of these (gneissic) erratics boulders. Thus, they came into the conclusion that the ice-shed (or ice-divide) was to the south of ZNF, and moreover, according to them, former drainage divide was also possibly further to the south than at present. Owen et al. (2002), however, criticized this inference of Taylor and Mitchell (2002) and provided satisfactory evidences against their hypothesis. The present study, however, based on the long-axes data of drumlins, tries to identify the possible location of the ice-divide during extensive Batal stage glaciation in the Lahul region. Previously it has been stressed that in the Chandra Tal area the main Chandra valley ice was possibly deflected by the

Samundri glacier (Fig. 50) to have rather southeasterly course. The long-axes data of drumlins seem to be representative of this former ice-flow direction and also supported by the striation data (Fig. 52).

However, when the long-axes of drumlins in both the site 1 and site 2, is extrapolated (Fig. 57) it becomes clear that the ice possibly flow from the Baralacha La area (4,900m asl.) and not from the south of the ZNF near Darcha, Himachal Pradesh, as suggested by Taylor and Mitchell (2000). The extrapolation of the long-axes of drumlins in both the regions meets roughly at Baralacha La (Fig. 57) and thus, the present study corroborates the conclusion made by Owen et al. (1997), and place the location of the ice-divide during extensive Batal stage glacial advance or younger in the Zanskar valley at the Baralacha La. Evidence of three well developed roche moutonnee trending down to Chandra valley (SE orientation) at the pass also can be used as supportive evidence. From the Fig. 57, the spreading of ice becomes further clear (See section 5.4) at the site 1. In the Yunan valley (site 2) as well spreading might took place along the valley (Fig. 57). Previously Mitchell et al. (1999) have mentioned that in the Zanskar, the main source of ice in all glaciations was at the northern slope of the Main (great) Himalaya and ice then flowed generally northwards into the Zanskar valley and its tributary valley leaving between them a landscape supporting only a few and scattered minor local glaciers. This view also supports that the ice-divide was possibly located at the Baralacha La (4,900m asl.) during the last extensive valley glaciation in the Lahul Himalaya and Zanskar respectively. Figure: 58, is showing the reconstructed ice flow directions and spreading effects in this region during Batal Stage glacial advance. This figure (Fig. 58) may not be perfectly accurate for the entire region but the general pattern possibly remains same as per the present understanding. The ice flow pattern reconstructed in the site 1, is more accurate and verified by the number of evidences which incorporates long-axes trends of drumlins and roches moutonnee, and striation marks, glacially polished surfaces, whale back structures, ice-molded rocks etc. Therefore, it is now clear from the aforesaid discussion that the landforms are drumlins and their geographical distribution well preserved the former flow direction of glacier ice in the region; it fulfills the first objective of the present study satisfactorily.

Two major points that needs greater assistance in future study are: a) numerically date the drumlins of both the Chandra Tal area and Yunan valley to compare them whether they belong to the same age or different, and b) more accurate mapping of the other glacial landforms and features (e.g. trimlines, striations, moraines etc.) are required too from this area to further strengthen the understanding of late Quaternary glacial history of this region. However, while the numerical dates for the minimum age of the drumlins are already available for the Lahul Himalaya (Owen et al., 2001), which is around 12-15.5 ka i.e. during Batal stage, for the Yunan valley of the Zanskar, no such dates are available for the drumlins till now. Although according to Taylor and Mitchell (2000), glaciation did take place mainly in the Yunan and Markha valleys during 12.2to 16.2 ka[34] (Zanskar 3 or Kulti stage) which may be analogous to the Batal stage glaciation proposed by Owen et al. (2000) (see section 2.6.), but more controlled date are required from these areas for accurate comparison; because similar drumlins in the Miyar basin of Lahul Himalaya formed during ~4 ka. (as suggested by M.C. Sharma) which is much younger than the Batal stage drumlins in the same area, and if the drumlins in the Yunan basin formed during the same period, then these drumlins needs to discuss in different environmental context.

[34] According to Taylor and Mitchell (2000) except Yunan valley the evidences of Kulti stage (Zanskar 3) glaciation are very sporadic and rare in the other tributary valleys of the Zanskar range (see section 2.5.2).

5.6. Morphological Classification of Drumlins:

Previous sections deals with the geographical distribution of drumlins in the Chandra Tal area (site 1), Kunzum La (site 3) and Yunan Valley area (site 2). Although their morphological diversity is appreciated, different morphological types (classes) are not talked over in detail. In the Chandra Tal area (site 1) a variety of different shapes are identified and although pure classical tear-drop shape of the drumlins dominate (56 % of the total drumlins surveyed, excluding the classical superimposed forms), other morphological types also require attention. Systematic analysis of them reveals key insight of the subglacial dynamics and other glacial characteristics. Hence in order to fulfill the second objective of the present study drumlins are subdivided into different dominant morphological forms. They are as follows.

a) **Classical drumlins (C):** Classical drumlins are tear-drop in shape with blunter steep stoss end and gentle pointed lee end (Fig. 59.a). They are elongated but elogantion is not very high, and have asymmetrical profile in general. In the site 1 such kind of drumlins are extensively recorded (Plate: 16 & 32) and assigned a sigh 'C'. They are further subdivided on the basis of outline form.

   i) **Normal classical forms** are those which have typical tear-drop shape with no distortion in superficial profile (Fig. 59.a.i. Plate: 16 & 32). They have not assigned with any sign.

   ii) **Classical superimposed forms** have overall classical form in appearance but actually consists of smaller drumlins on their surfaces (Fig. 59.a.ii), but not so distinctly identifiable. They are assigned with the sigh 'CS'. These are likely to be formed by different phases of glaciation.

iii) **Classical spindle forms** are those highly elongated drumlins which have very high length but low width. They are hair-pin like in shape and overall possess classical drumlin morphology (Fig. 59.a.iii; Plate: 62). They are denoted as 'CSp'.

b) **Superimposed drumlins (S)** possess two or more drumlins, one overriding the others at their surfaces (Fig. 59.b). They are denoted as 'S'. Superimposed drumlins as far rule mainly indicate two phases of formation. Mainly smaller drumlins are found superimposed on the lee side (or anywhere) of the larger drumlins of older age. Three types of superimposed drumlins may be identified. They are as follows.

i) **Superimposed classical forms** generally consist of smaller classical drumlins on the surface of larger classical forms (Fig. 59.b.i; Plate: 17). They are assigned as 'SC'.

ii) **Superimposed spindle forms** are similar to the classical spindle form, but consist of smaller superimposed drumlins at their surfaces (Fig. 59.b.ii). They are denoted as 'SSp'.

iii) **Superimposed uniform types** are those drumlins which have smaller drumlins superimposed on the larger older ones but overall shape is uniform in appearance (Fig. 59.b.iii). They re denoted as 'SU'.

c) **Dome shaped drumlins (D)** are perfect dome-shaped with elongation ratio is 1:1 (i.e. length/width = 1). These are relatively thicker in nature but their length is limited compared to classical drumlins (Fig. 59.c; Plate: 14). Dome shaped drumlins or 'D' types shows trend along long-axes, but their long-axes is rather difficult to identify in some cases.

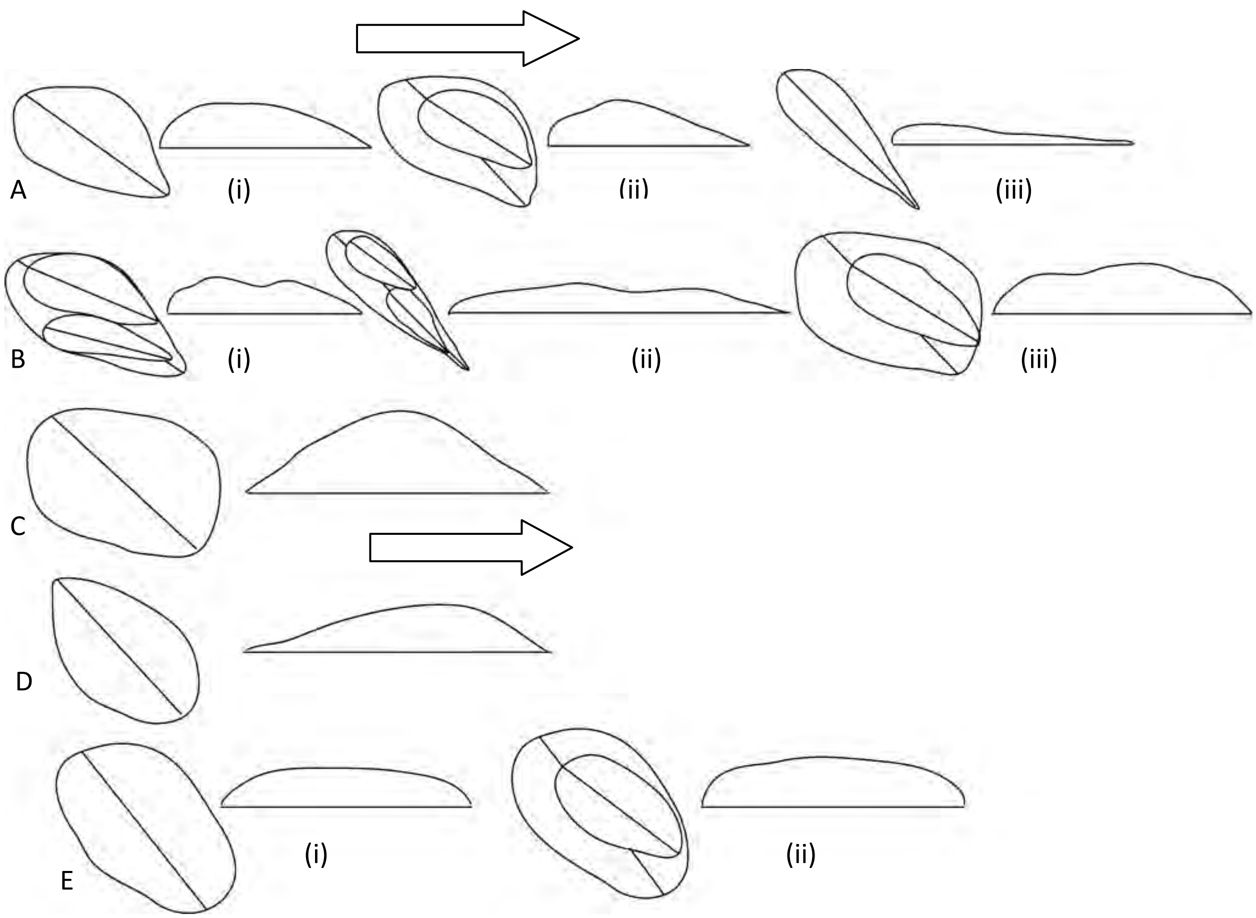


Fig. 59 Different morphological types of drumlins at the site 1. The major morphological types are: (A) classical [(i) Normal, (ii) Superimposed, (iii) Spindle], (B) superimposed [(i) Classical, (ii) Spindle, (iii) Uniform], (C) dome shaped, (D) inverse classical, and (E) uniform [(i) Normal, (ii) Superimposed] types of drumlins. These landforms are further subdivided into many subgroups. The arrows indicated the direction of ice-flow.

d) **Inverse drumlins** (I) are completely reverse in shape to the classical drumlins i.e. gentler stoss face and steeper lee face (Fig. 59.d; Plate: 63). They are more like roche moutonee types interms of outline shape, but they are mostly composed of diamicton and possess smooth drumlin like streamlined morphology.

e) **Uniform drumlins (U)** are few of those drumlins in the Chandra Tal area which appear as uniform in shape along their length i.e. their heights appear to be uniform across the entire stretch of the drumlin (Fig. 59.e; Plate: 64). They are denoted as ‘U’. Two subtypes are classified in the present study.

i) **Normal uniform shaped drumlins** are similar to those as discussed above and they are not assigned with any signatures (Fig. 59.e.i).

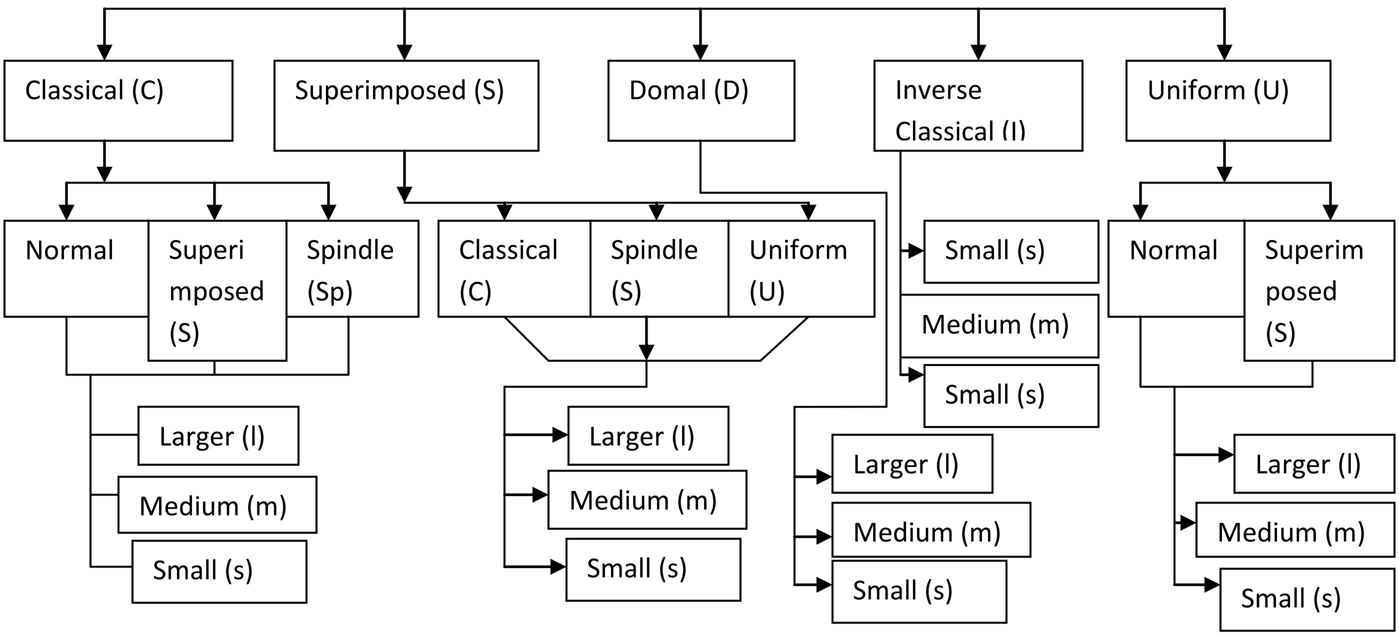
ii) **Uniform superimposed drumlins** are those which appear in general as uniform in morphology but consist of smaller superimposed drumlins at their surfaces (Fig. 59.e.ii). The uniform shape becomes more prevalent than the typical superimposed forms of drumlins. These drumlins are assigned by ‘US’ sign.

– The morphological classes can be simplified in the chart 2.

Beside, these morphological classes, drumlins are further subdivided on the basis of the lengths of their longitudinal axes, in order to find any common relationship. The major length classes are a) **Small drumlins** with long axes length less than 50m. (*s*), b) **Medium drumlins** with long axes length ranges between 50 and 100m. (*m*), c) **Larger drumlins** with long axes length more than 100m. (*l*). These length classes are arbitrarily selected and relative to site 1. It is found that medium (*m*) (43 % of the total) and smaller (*s*) sizes of drumlins (42 %) dominate the Chandra

Tal area (site 1), whereas larger sizes (*l*) are only around 15 percent of the total (Fig. 60). The median size of the drumlins in this area is ~58m. Maximum size, however, is as high as ~240m. and minimum is as low as ~15m with huge length variation ($\sigma = 44.349$). The actual frequency distribution displays multimodal classes. The height data, although not so accurate (due to the use of Handheld GPS), but also indicates multimodal distribution in the site 1 with mean height of 4m. The height range is 13m. with relatively less variation ($\sigma = 2.704$) among the different morphological types of drumlins. In the Yunan valley (site 2) although detail morphological classification is not conducted, but the available length data indicate that the smaller drumlins actually overwhelm (53 percent of the total), followed by medium size drumlins (30 percent) and larger drumlins (17 percent) (Fig. 61) in this area. However when the morphological classes are adjusted couple with the length classes of the drumlins, several important points come into the notice (Fig. 62). The Normal Classical drumlins (C) predominate in the Chandra Tal area. Medium (C*m*) and Smaller (C*s*) Classical drumlins are mostly important (18 percent) (Fig. 62), whereas the larger Normal Classical forms (C*l*) are comparatively very less in number (7 percent). Classical Spindle shape (CSp) is large in size and Classical Superimposed (CS) drumlin is small in size. Based on these data it can be inferred that classical forms may transformed into classical spindle form with very high elongation ration (i.e. length is larger than width) when subject to more shear under basal ice. Among other classes Superimposed drumlins (S) are next to classical forms (i.e. 23 percent of the total). Among Superimposed drumlins classical forms (SC) predominate in the valley (Fig. 62). Larger Superimposed drumlins (SC*l* or SSp*l*) are very well recognized in the main Chandra valley. Besides, smaller Inverse Classical drumlins (IC*s*) and medium Uniform drumlins (U*m*) are also common in the valley (Chart 2).

Chart—2. Morphological Classification of Drumlins



However, the geographical distributional pattern of these different morphological types of drumlins can be shown in Figure 63. No systematic pattern is found in the morphological distribution of different drumlins in the Chandra Tal area. However, one thing that can be brought out that the larger drumlins is mostly either classical or superimposed types. It may be because the larger classical forms provide relatively grater obstacle to the basal flow of the ice compared to others and augment smaller drumlin deposition, especially at the lee face of the drumlins during later glacial readvance; although smaller (*s*) and medium (*m*) size superimposed drumlins are equally common in this area. Not only the outline form of the drumlins but their superficial composition is also recorded during field mapping (Fig. 63). It has been found that 42 percent of the drumlins possess ice-molded bedrocks at their surfaces and/or they are ‘rock-cored drumlins’, whereas bulk of the drumlins (58 percent of the total) are composed of diamictons or

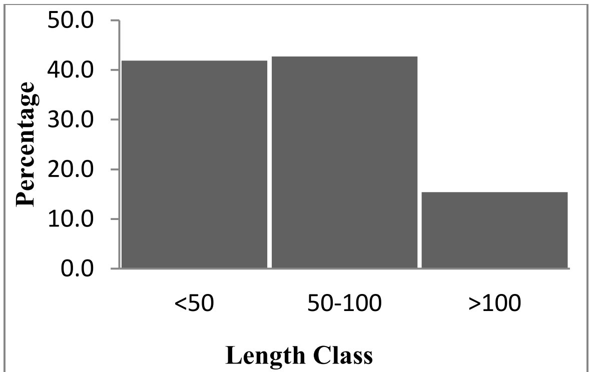


Fig.60. Lengths of Drumlins at the Chandra Tal area

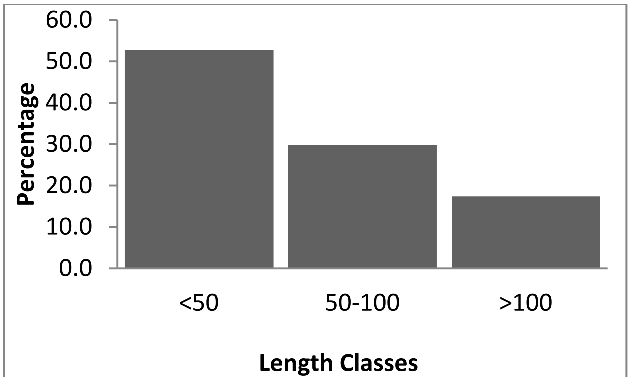


Fig. 61. Lengths of Drumlins at the Yunan Valley

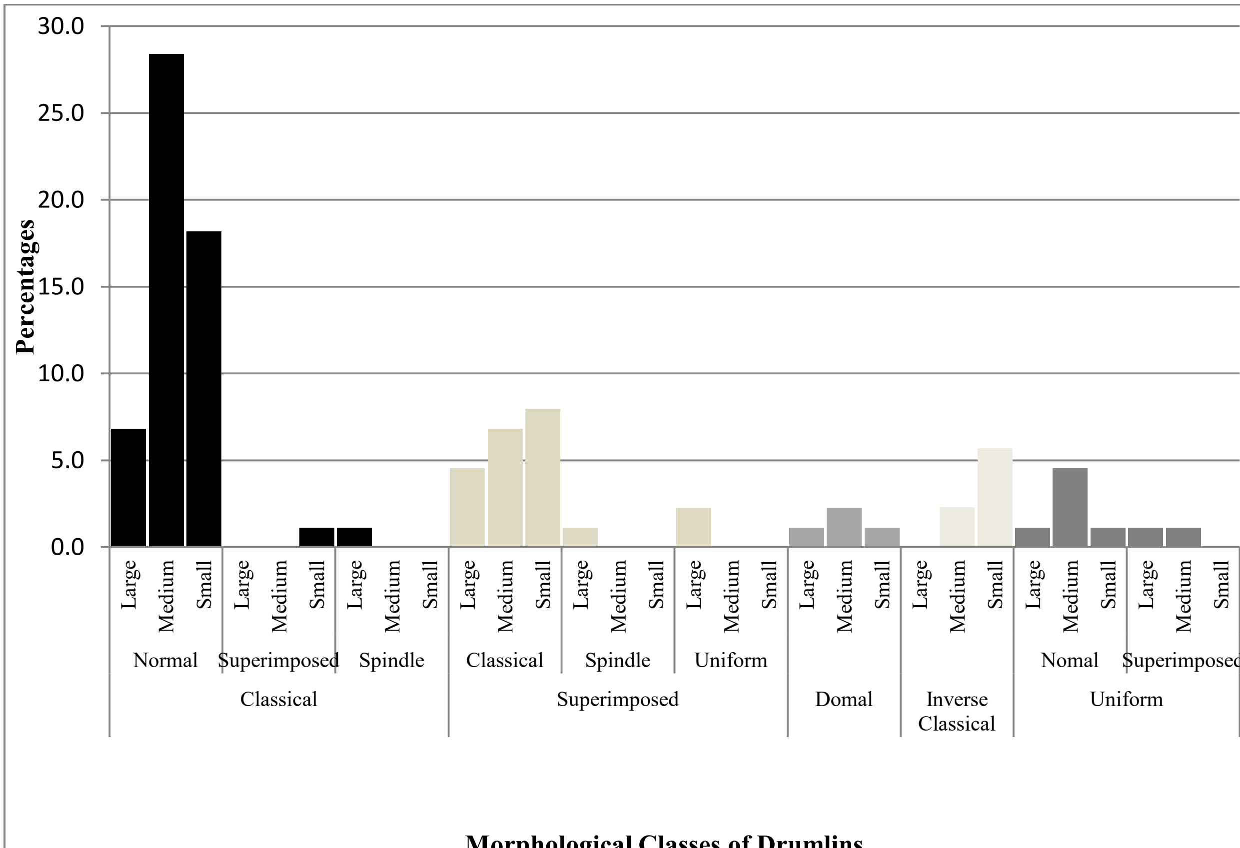


Fig.62. Morphological classification of drumlins at Chandra Tal area (Site 1)

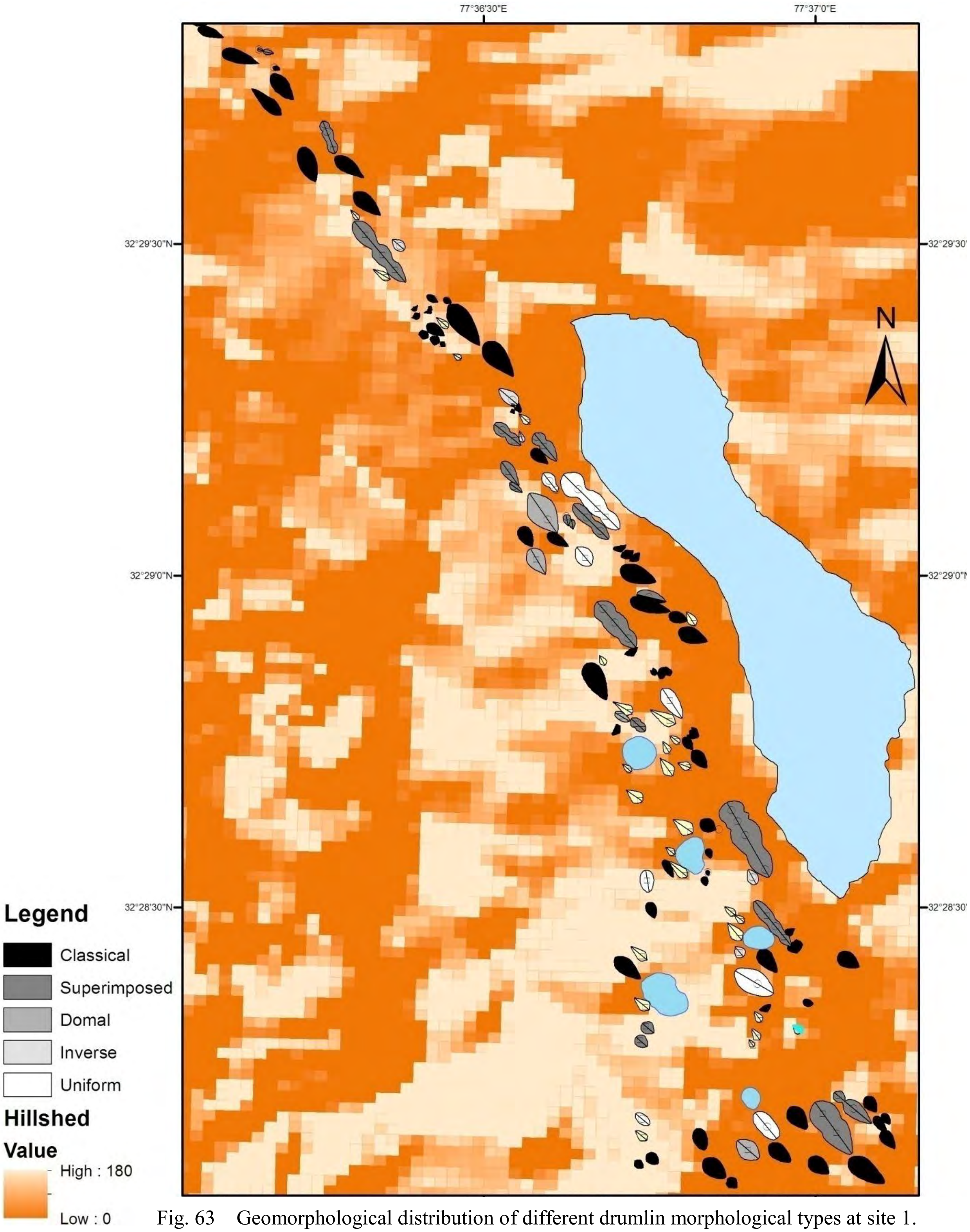


Fig. 63 Geomorphological distribution of different drumlin morphological types at site 1.

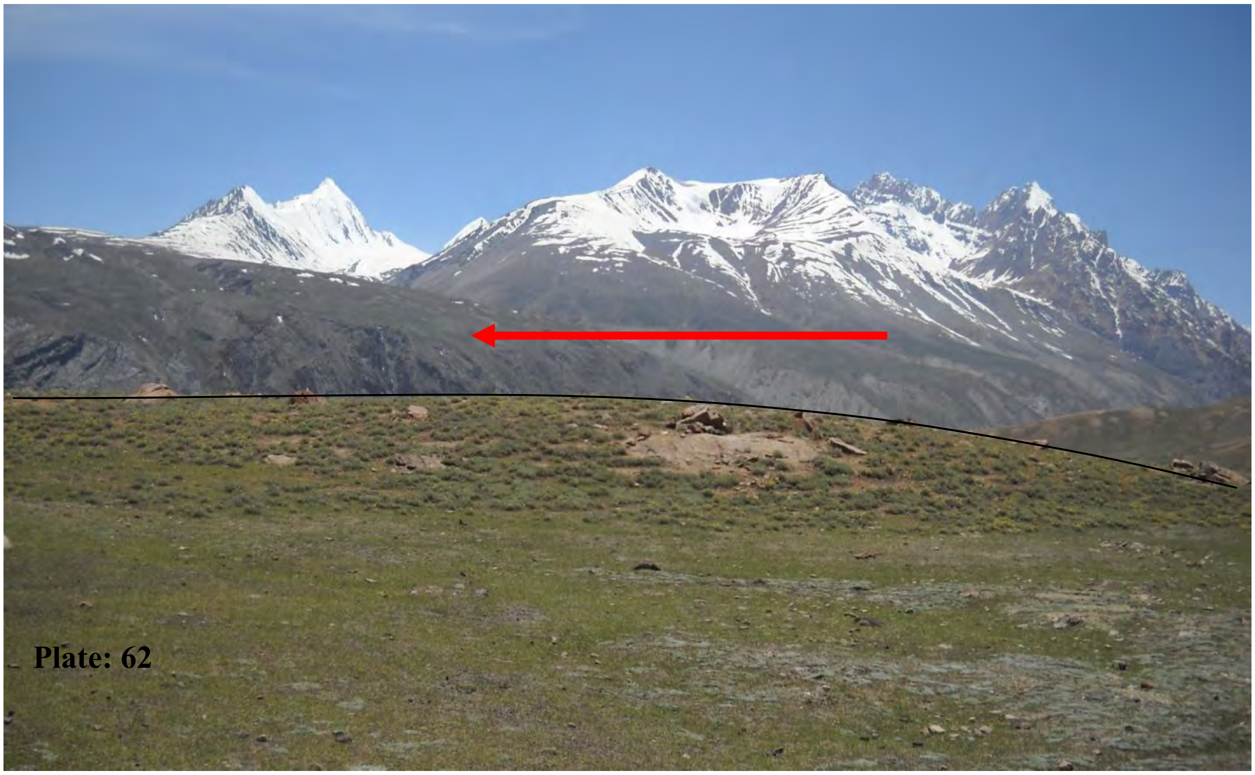


Plate: 62 Spindle type of drumlin i.e. very high length but low width with elongation ratio of very high, at the site 1, is also identified at the site 1. Arrow indicates the ice-flow direction.

Plate: 63Typical inverse type of drumlins at the site 1. Arrow indicates the ice-flow direction.

Plate: 64 Uniform shape drumlin at the Chandra Tal area. Ice-flow pattern is shown by the arrow. At the behind is the Samundri glacier.

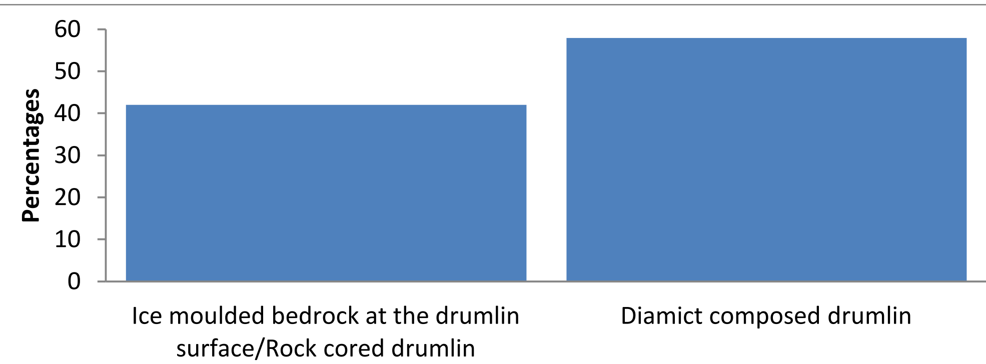


Fig.64. Drumlin superficial composition at Site 1

exhibit no visible bed rocks at their surfaces in the site 1 (Fig. 64). Since the bedrock knolls provide the initial impetus to the formation of drumlins in the site 1 (see section 6.3 of chapter

6), the initiating mechanism of the entirely diamict composed drumlins is still unknown and is scope for any future study on drumlins in this area (site 1).

In the summery note few of the very important inferences that has been made so far in this chapter on the basis of the morphological analysis of drumlins and their spatial distribution in the Lahul Himalaya and Zanskar range, may be discussed as follows. The drumlin's in the Chandra Tal area and in the Yunan valley are mostly classical in outline form and found en echelon in a field crafting a half buried basket of egg topography. Their longitudinal axes also denote the former extensive ice-flow direction in both the valleys, which is southeasterly in the Chandra valley and northeast in the Yunan valley. This directional pattern is also verified with the trend data collected from other glacial features. These data sets together help in constructing regional ice-flow pattern in this area. The detail topographical analysis of both the Upper Chandra valley and Yunan valley, signify that there is a broad and gentle and possibly shallow valley as well before post glacial modification. The widening of these valleys may initiate spreading of ice during extensive valley glaciation. The funnel like basin in the Chandra Tal area (site 1) may further augments thicker accumulation of ice compared to their up-stream section and along with spreading affect, leads to thick ice-sheet like condition and formation of drumlin streamlined forms. The similar spreading effect is reconstructed in the Yunan valley as well in the present study on the basis of the longitudinal orientations of drumlins. The in situ analysis of the rocky outcrops having deep red brown rock varnishes, as well as drumlins, further suggest that in the Chandra Tal area, the tributary Samundri glacier could deflect the main valley glacier ice during extensive valley glaciation and leads to initial convergence and subsequent spreading of ice in this area. It becomes more apparent when the long-axes of the drumlins are extrapolated to a larger size. However, these factors together may responsible for *the southerly flow of the ice in the valley, which was off the main Chandra valley course (at the present) and might cause overtopping of the Kunzum range at the Kunzum La to spread into the Spiti valley. The distribution of drumlins, striation marks, ice molded rock, and drumlinized mounds etc. at the Kunzum La and Upper Spiti valley respectively help together in verifying the statement.*

The longitudinal axes data of the drumlins also corroborate the findings of previous workers (Owen et al., 1997) and confirmed that during last extensive valley glaciation the ice-divide was possibly at the Baralacha La and not south of Zanskar Normal Fault (ZNF) near Darcha, Himachal Pradesh. Ice flowed both in the north into Yunan valley and south and west into the Chandra valley and Bhaga valley respectively. Ice possibly spread from this location and extended downstream by as much as more than 100 km. from the present glacier margins at the Lahul (Hedrick et al., 2011). Although the classical morphological types of drumlins overwhelm in both the regions (Site 1 & 2), a wide range of other outline forms are clearly identifiable. Five major morphological forms are identified in the Chandra Tal area (site 1), viz. a) Classical form, b) Superimposed form, c) Dome shaped, d) Inverse shaped, and e) Uniform shaped drumlins. However, so far no such satisfactory pattern has been identified in terms of the distribution of different morphological forms. Although it can be said, on the basis of the frequency distribution of different classical drumlins, that larger stress by the ice-mass may cause transformation of classical forms into larger spindle forms in the subglacial regime. Superimposed drumlins may indicate different phases of their formation, but until controlled numerical dates are available this remains as just speculation based on geomorphology of the landforms only. However, entirely diamict composed drumlins have little edge over the rock cored drumlins and those having ice-molded rocks at their surfaces in the Chandra Tal area (site 1); although entirely *bedrock drumlins are also not uncommon. Lastly, it may be worth to suggest that extensive numerical dates are required to determine the entire formation period of the drumlins in both Chandra Tal area (site 1) and Yunan valley (Site 2). Already the minimum age of drumlin formation was suggested as 12 to 15.5 ka in the Chandra Tal area (site 1) by Owen et al., 2001 i.e. last glacial interstadial or Batal stage glacial advance. These are CRN dates which are coming from the boulders lodged at the surface of drumlins in the Chandra Tal area and also from morainic boulders. No numerical dates are available for the drumlins in the Yunan valley, but it is quite possible that they may formed during the same period between Zanskar 3 (or Kulti stage of Zanskar valley i.e. 12.2 to 16.2 ka) in the Yunan valley and Markha valley, as suggested by Taylor and Mitchell (2000), to Historical time (~4 ka. as suggested by M.C. Sharma). Therefore, until the proper numerical dates are coming from both these areas, it may not be wise to assign age of the formation of drumlins and compare them together in the study area.*

Chapter—6

THE GENESIS AND EVOLUTIONARY HISTORY OF DRUMLINS IN THE HIMALAYAS

" ... study of the stresses on and strength of the subglacial materials is important not only for an understanding of drumlin formation but also for an understanding of the subglacial erosion, deposition, and deformation."

——Stanford and Mickelson (1985)

6.1. Introduction:

Identification of drumlins unequivocally raises the question of their genesis or production and evolution—how drumlins have formed? The mechanism of their formation not only holds the key to their genesis but rather also helps in deciphering the subglacial and submarginal erosional, depositional, and deformational history during their formation. This in turn helps in reconstructing the palaeoenvironmental condition during their formation. Previously it has been mentioned in chapter 1. that although there is little disagreement among the researchers about the formation of drumlins, very high ambiguity exists regarding their initiating mechanism under subglacial condition, and it has been essentially termed as the 'Puzzle' of drumlin study by Menzies (1979). The present study already successfully explained the morphological attributes in detail along with other evidences and possible inferences to reconstruct the palaeo environment. But morphology alone may not fruitful in bringing out the other side of the coin which can possibly be unrevealed by the detail compositional analysis. The study of the internal composition of drumlins in the study area, thus, intends to discover the mystery behind the outline streamlined forms. How the birth of the drumlins has taken place? What could be the favourable physical factors of their formation? And what could be the possible mechanism of their evolution? etc. questions are tried to answer in this chapter. A hypothetical model of their evolution is also proposed based on the existing morphological and internal compositional evidences (sedimentological). It is believed that the inferences that will be derived from this analysis not only fill the gaps regarding drumlin study in the Himalayas to a considerable extent and possible palaeoenvironmental condition during their evolution, but also scope for the futures study can also be proposed. The present study is a preliminary effort to study the drumlins and many of the key evidences require more rigorous research and incorporation of other factors.

In the present study, however, the landscape-lithofacies model is given major emphasis (see Chapter 3). While the morphology is discussed in detail in the chapter 5, in this chapter first the detail internal composition of the drumlins and allied properties are first studied, followed by the model construction explaining their mechanism of formation i.e. genesis and their gradual evolution to produce this basket of egg topography.

6.2. Analysis of the internal composition of drumlins:

The general approaches applied so far in studying the internal composition of drumlins has already been dealt with in chapter3. The similar traditional approach is followed in the present study as well. Hence, the discussion of the internal composition of drumlins is majorly restricted under two headings i.e. 1. Lithological analysis, and 2. Morphotextural analysis. The detail interpretation will certainly help in constructing a model of the evolution of the landform in concern. They are discussed as follows.

6.2.1. Lithological analysis:

Major lithological analyses that have been undertaken during the field survey and also back in the laboratory are mainly the grain size analysis of the drumlins deposits and structural analysis of the internal section of the landform. The mineralogical and geometrical study, etc. have not been undertaken in the present work but a glimpse of few of the aspects can be discussed. They are, thus, discussed through the following points.

6.2.1.1. Grain Size analysis:

The drumlins are found to be majorly composed of sands, having sand proportions range between 98.9 percent and 80.8 percent in Site 1, 94.1 present in Site 2, and 90.8 percent in Site 3. During field survey it has been recorded that sand and mud constitute 60 percent of the bulk sample, whereas gravels constitute 40 percent of the bulk. That means the drumlins consists mostly of gravelly sandy materials. In the laboratory dry sieving of sand and slit-clay sizes have been conducted; gravel proportions thus are not available for further discussion. These grain size data have been collected from a number of sites which incorporates drumlin surfaces, middle portions of drumlins and also interdrumlin depression. Not must variability of grain sizes is seen among the samples (Fig. 65), except the sample collected from the interdrumlin depression (IDPF1 in Fig. 85). This sample shows relatively higher proportions of fine sand (~28%), otherwise in all the classes of sand grains the average proportions are relatively high and more or less analogous (Annexure 1). Coarse silt also found dominating in the sample DPF 2 and IDPF 1. The proportion of medium to fine silt and clays together never goes beyond 4% except DPF 2, where the proportion of fines is slightly higher i.e. 6.7 % (Annexure 1). The higher proportion of the fines in the interdrumlin depression could be because of higher stress and grinding of the materials in the subglacial regime or most likely due to the preferential removal of the fines from the drumlin surfaces. Although DPF2 still have relatively higher proportion of fines at the ridge high, and this could led to support the former statement i.e. subglacial higher stress in the depression many cause more grinding and cursing and consequent finer particles. The mean sizes (Annexure 1) displays that medium sand dominated among Sand-Silt-Clay proportions with one exception is the interdrumlin depression (IDPF1; Fig. 65), which has fine sand as mean size. Characteristically all the samples are poorly sorted—typical to the glacigenic sediments (section 3.4.1.1.). However, the statistics provided in the Annexure 1 is not complete because the gravel sizes are not incorporated, but according to Blott and Pye (2001) since the cay and silt proportions are very low for nearly most of the samples, certain statistical data can be used with confidence. In this discussion thus only mean size and sorting (σ) of the grains are discussed and verified with the field descriptions.

6.2.1.2. Structural Analysis:

The drumlins in the Chandra Tal area (Site1) and in the Yunan valley (Site 2) are largely massive in appearance with mostly matrix-supported i.e. Dmm or Matrix-supported massive diamictons. Hence no layer structures are visible at the macro-scale (with naked eye) in situ, except the clast orientation structures which are clearly demonstrating deformational signatures and/or pseudo layering or multiphase deposition, hence given major emphasis in this chapter and discussed in detail as follows.

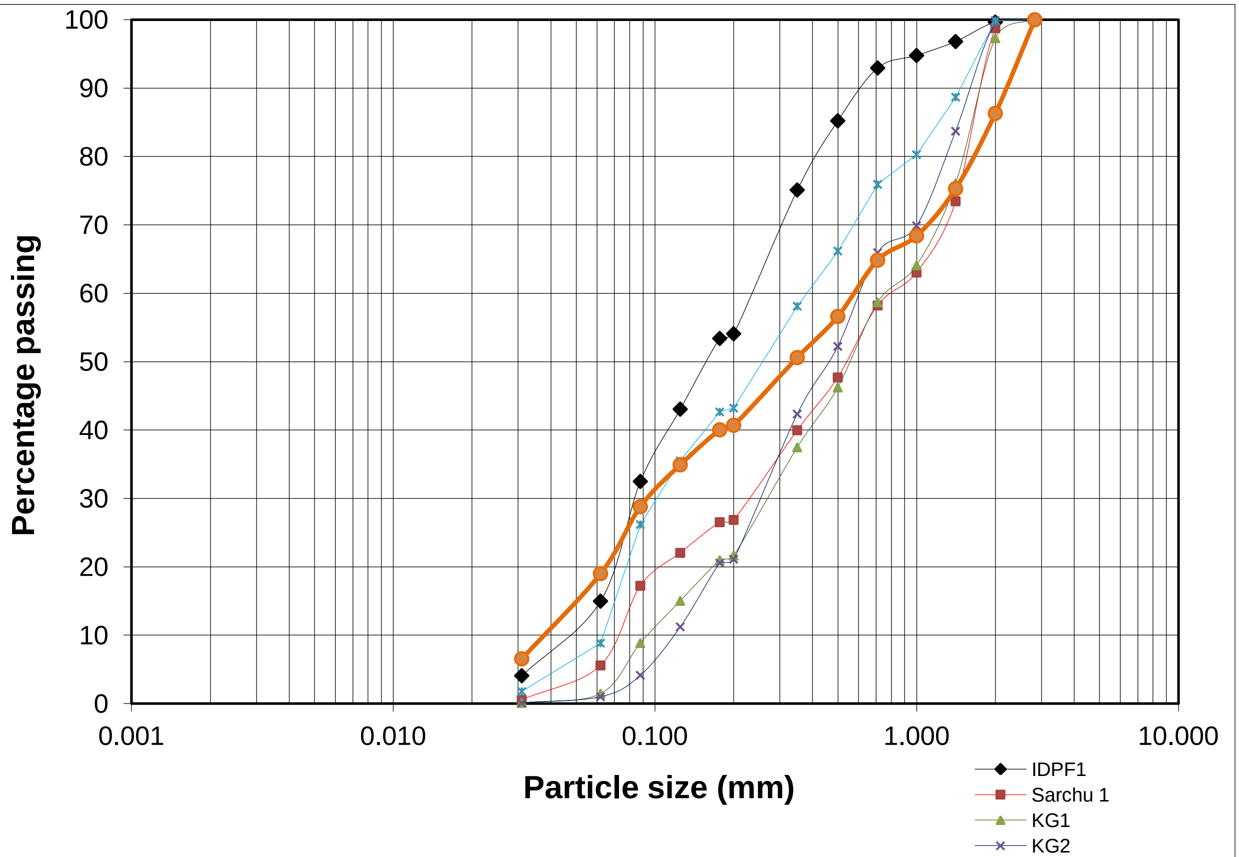


Fig. 65 Grain Size Distribution of Samples

The lithologs are prepared both for the pit exposure at the Chandra Tal area (site1) (Fig. 66.a), and for the road-cut exposure (Exposure 1 in Fig. 55) at the Yunan valley near Sarchu (site2) (Fig. 66.b). The contact surfaces are not clear and mostly gradational with distinct clast orientation pattern. The jamming of clasts (concentration of clasts) in the deposits helps immensely in identifying them as not single event of deposition rather multiphase development. This approach also helps in deciphering some other key characteristics which otherwise may not be possible to identify from these deposits which are mostly massive and homogeneous in appearance. Since no natural or artificial exposures are available at the Chandra Tal area (Site 1), a 60 cm. deep pit is artificially dug at the lee face of one of the drumlin (Sample site KG1/DPF or DPF1—32.477°N/77.614°E, 4,305m asl.) (Fig. 67a). This lee face exposure is then recorded in detail (Fig. 67b). The Plate: 65. provides detail view of the internal structure of the sample drumlin KG1/DPF (DPF1) in that area. Their simplification (Fig. 68) through sketching along with the Plate: 65. indicate that deformation may be dominant among all the processes (deformation, erosion, and deposition) under subglacial and/or submarginal condition during the formation of the drumlin(s). The lower portion of the exposure (Plate: 65 & Fig. 68) indicates a wave like pattern of the clasts with smaller clasts moving around the larger clasts. This pattern is further assisted with clast macro fabric pattern later in the section 6.2.2.4 (Fig. 84). Galaxy type rotational structures (Fig. 69), as commonly reported from thin-sections (Hart, 2007) and believed to be diagnostic of deformation processes, are clearly identified even at the macro scale. These are attributed largely to the signatures of ductile deformation. These ductile deformation structures are found generally below 15m. from the surface of the sample drumlin (KG1/DPF or DPF1). Since the drumlin (KG1/DPF or DPF1) height is not more than ~1 m. from the surface, it may be infer that deformation processes dominate within a thin layer of subglacial materials. This corroborate well with the other drumlin studies reported from the mid latitudinal glaciated (ice-sheet) areas (see section 1.3.2). Above this ductile deformation zone an increased zone of shear stress can be identified (Plate: 65) along with jamming of the clasts (Plate: 66). This shear zone results into grain-bridge i.e. network of grains (Iverson et al., 1996, 1998) formation when clast jamming takes place under subglacial condition, and greater stress heterogeneity is adjusted through grain fracturing (Fig. 70). These grain fracturing and clast shearing has also been observed during pebble fabric analysis at nearly similar depth from the respective drumlin surfaces (section 6.2.2.4). This clast jamming and grain fracturing coincidently is also found near similar to the experimental grain fracturing under laboratory stress condition using Ring-shear apparatus by Iverson et al. (1996). Although subglacial natural environment works in complex ways which may not be possible to observe directly, hence analogous clast orientation and/or disintegration pattern, developed under ideal condition, can be used to infer the possible process and mechanism of the their development. However, these clasts are believed to be supplied at the ice-marginal condition either by subglacial processes or by supraglacial processes; clast roundness analysis (see section 6.2.2.2) further support this fact. At the surface the boulder to cobble size clasts are found to be lodged (Plate: 15, 16, 32, 40) in the Chandra Tal area (site 1). Such lodgement is also previously reported from the Upper Spiti valley (site 2) at Kunzum la (Plate: 51). Later, in the section 6.2.2.4 the fabrics of the boulder materials will further clear the high degree of lodgement in this area (Fig. 93 & 94). It is also required to mention that the internal composition of the drumlin KG1/DPF indicates clast compaction and fissel structures in certain cases, but they are not extensively consolidated. If they are entirely formed subglacially such compaction can be expected, but since the evidence does not support extensive compaction, it is believed that the genesis of the drumlins in this area are initially started subglacially but their final form creation has taken place under submarginal subenvironment. More evidences in support of this are provided as follows.

Hence from the above analysis, a clear pattern of gradual change in the subglacial processes in this area (site 1) can be identified. This change is believed to be due to changes in the rheological properties of the subglacial and submarginal materials rather than any change in the glaciological condition during the formation of the drumlin; because the internal composition is massive in appearance and no discernible changes in their composition are observed. The smooth change in colour, although, can be observed from the surface to bottom i.e. from brownish yellow (10YR6/8) to reddish brown, but this is believed that leaching process is responsible for such colour differentiation.

However, this behaviour can be successfully explained by the *'Coulomb-stress law'* i.e.

$S = C + (P\text{-}Pw) \tan\Phi$ ……………………………….17.

where, S is the shear strength of drumlin forming diamicton, C is the cohesion of the till, Φ is the angle of internal friction, P is the ice-pressure, and Pw is the water pressure (Menzies, 1979; Smalley, 1981; Stanford and Mickelson, 1985; Hicock, 1990; Benn and Evans, 1996). According to Menzies (1979) the pour water pressure (Pw) is the major controlling factor of *'drumlin forming mechanism'*. In the present context as well, this seems equally relevant. Several factors again require special attention. At the surface, most of the drumlins consist of mini roche moutonee like lodged boulders—typical to the subglacial and englacial processes. These boulders may be lodged at the surface of the drumlins, possibly at the late stage of glaciation or during deglaciation, and can only be exposed after the retreat of the glaciers in the main Chandra Valley (Owen et al., 2001). This means during the deglaciation period the glacier-ice was possibly thin and hence pressure of ice i.e. P cannot be accounted for very high stress regime and such changes in the rheology of the materials and processes. It can further be simplified in terms of the concept of *Effective Normal Stress* i.e. N (Benn and Evans, 1996). N actually is total stress (s) minus water pressure (Pw), or in other words,

$N = s - Pw$ ……………………………………….....18.

Hence, when porewater pressure (Pw) is low effective normal stress (N) increases and vice-versa. It is logically, thus, believed that Pw was responsible for the changes in shear response and subglacial processes. Together if combined all the evidences, it seems that the shear heterogeneity or effective normal stress (N) increases from bottom to top over the period of drumlin genesis and with incorporation of ice-marginal deposits in the Chandra Tal area (Fig. 71) with ductile deformation at the bottom is replaced by brittle deformation and clast jamming near the surface (within 15 cm. from the surface), and ultimately clast ploughing and lodgement at the surface. Shear strength of the subglacial till also exhibits increase over time from bottom to top (Fig. 71). The changes in rheology of the subglacial deposits may thus be successfully explained in the light of Coulomb plastic behaviour and porewater content.

The pore water pressure was initially high may be due to very high pressure of thick ice in the basal ice zone, possibly more near the stoss side of the bedrock obstructions, to provide high hydrostatic pressure and ductile deformation. Under the subglacial condition this possibly was responsible for sliding of the thick glacier ice as well. Thus, sliding through the deforming till at the glacier sole was the main mechanism of the movement of the glaciers in this area during extensive valley glaciation. The glaciers in the Lahul Himalaya are warm type as well, further favoring high Pw and sliding process through deformation. However, gradually the Pw reduces may be due to water dissipation through permeable subglacial materials or bedrock, or subglacial depressions (Smalley, 1981) or it may be that thin ice during deglaciation may not have sufficient pressure to generate subglacial melting and high hydrostatic pressure. The author, although believed that during deglaciation period the subglacial drainage conduits may develop fully to dissipate the water pressure (Pw) at the basal-ice zone, which may exist previously during the advancement of thick glaciers. According to Benn and Evans (1996) subglacial drainage condition may prove to be the most important factor controlling the strength and rheology of glacier bed and it proves equally true in the present context. Since the grain size analysis indicates that the major part of the deposit is composed of medium sands (mean), they are rheologically conducive for deformation and porewater dissipation as well. Such rheological changes may be due to incorporation of submarginal materials as well along with Pw reduction. However, it is also quite possible that during lodgement and clast ploughing the grater stress may cause brittle deformation and clast jamming, but the above inference is provided from just one drumlin. More geological studies from other drumlins are required, in this area, before fully confirming the causes behind the changes in the rheological properties of the subglacial materials during drumlin formation and related processes. But until now the present evidences clearly demonstrate that ductile deformation is followed by brittle deformation and ultimately lodgement processes from top to bottom at the sample drumlin i.e. from the initiation of drumlin to their final from creation; the initiating mechanism will be covered in the next section. This picture is believed to be representative of many of the drumlins in the Chandra Tal area (Site 1). More studies in future will corroborate and/or modify the present understanding.

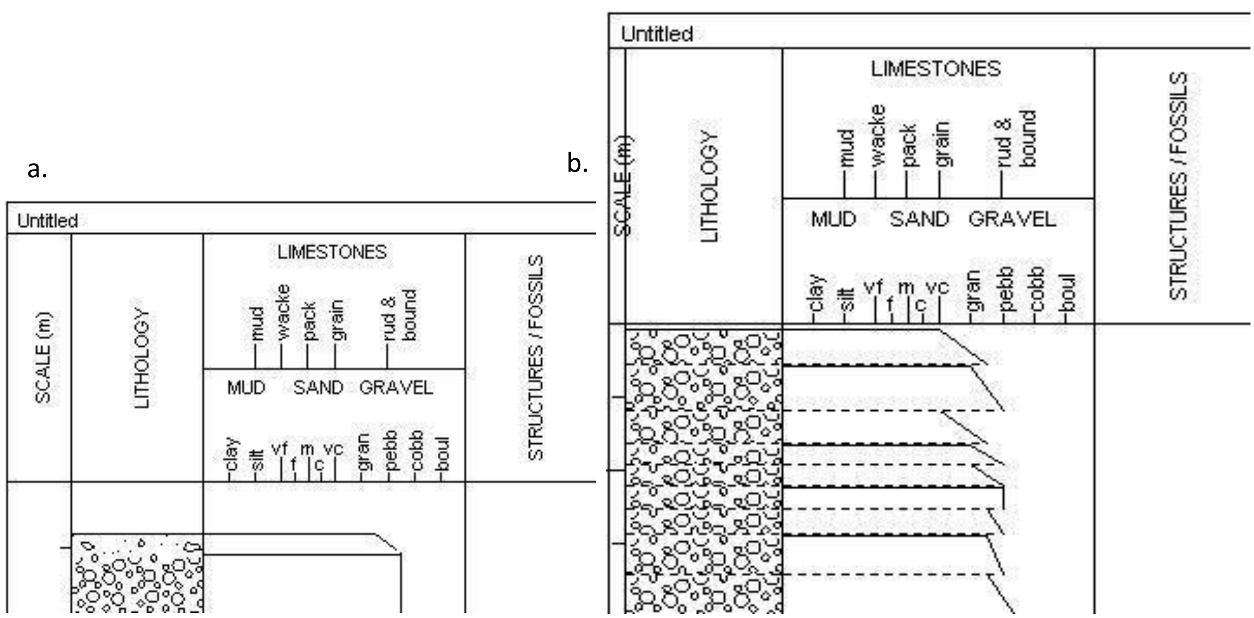
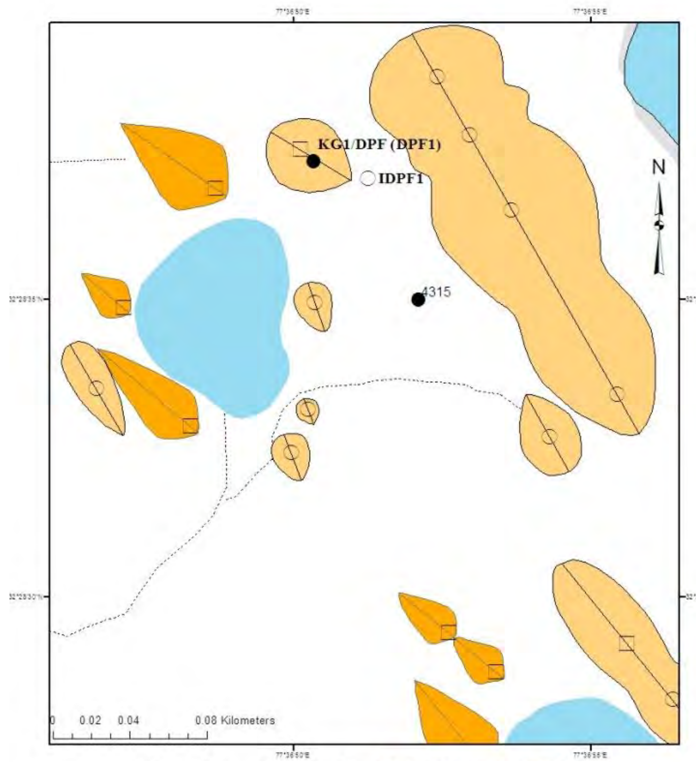
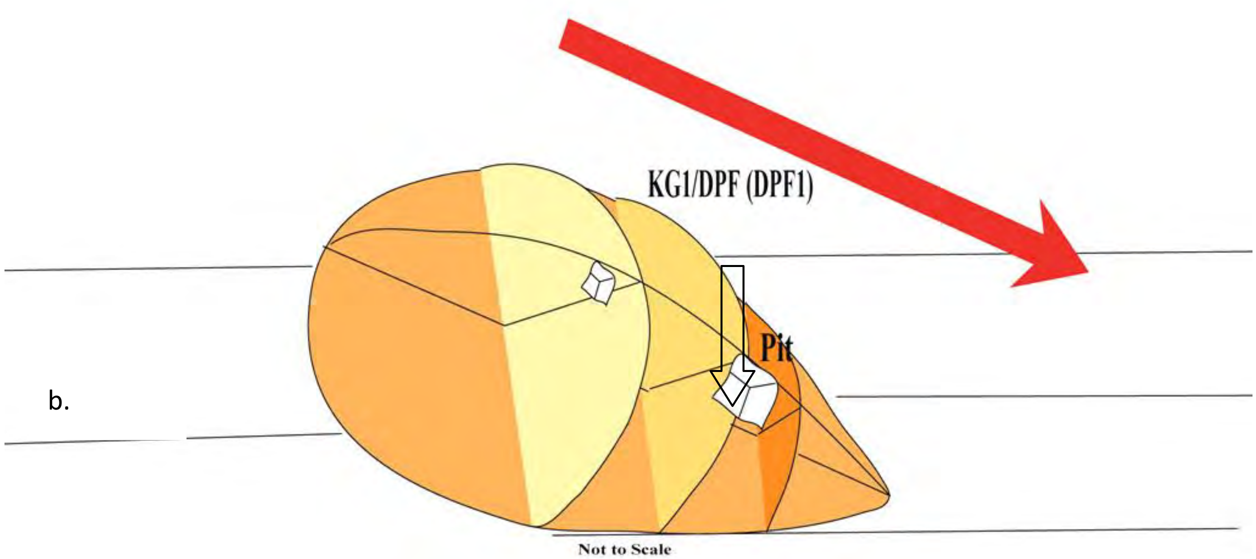


Fig. 66 Sedimentary logs showing the massive internal composition of drumlins in the Himalayas. The deposits are matrix supported and most gravelly sandy types. Clast concentration is found at places. (a) the sedimentary log of the Chandra Tal drumlin: KG1/DPF (or DPF1), (b) the sedimentary log of the Yunan valley drumlin (Sarchu 1).



a.



b.

Fig. 67 The 3D graphical illustration of the sample drumlin KG1/DPF (or DPF1). (a) Map showing the sample site of the drumlin at the site 1, and (b) is the three dimensional outline form of the drumlin with the location of stoss side and lee side pit. The fabric measurements, log preparation, and SEM samples are taken mainly from the manually digging lee face pit exposure (DPF1). Arrow indicates the ice-flow direction.

Plate: 65

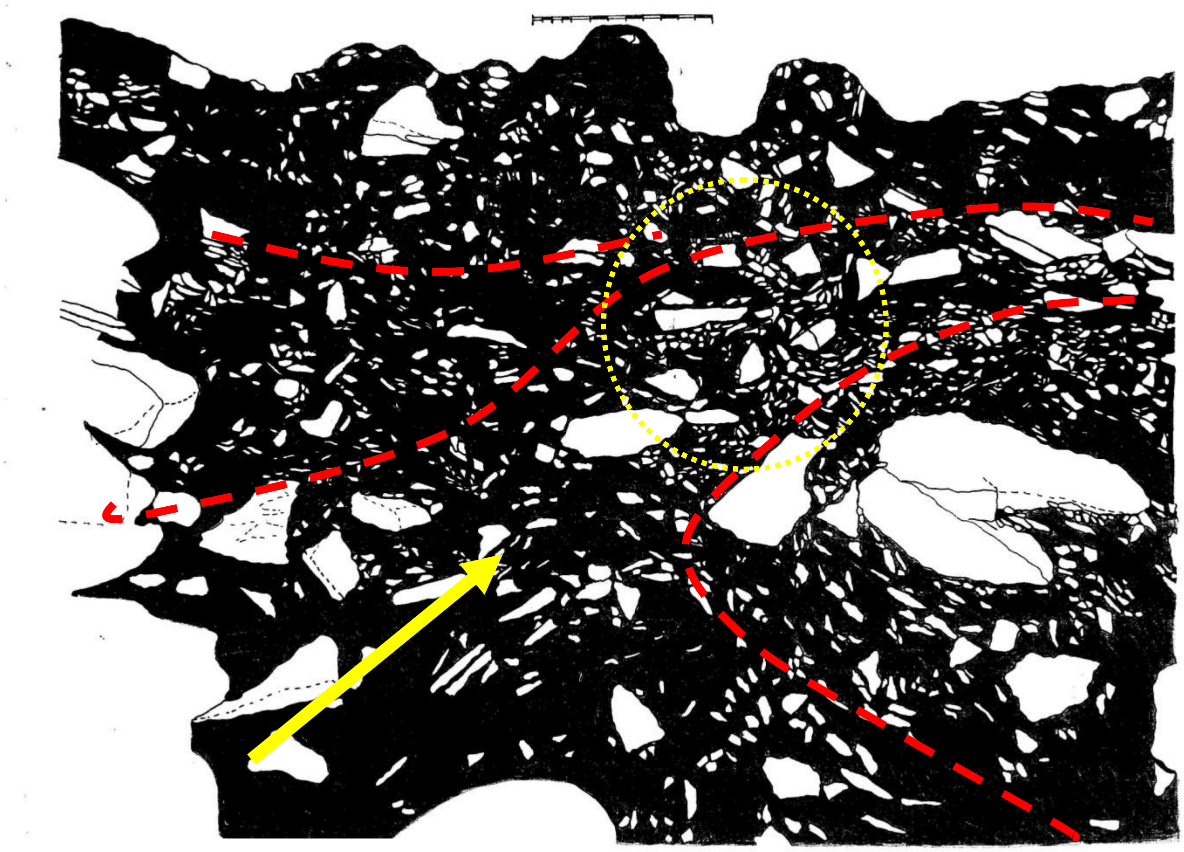


Fig. 68

Plate: 65 This is the exposed section of the manually dug pit exposure at the site 1 of the sample drumlin KG1/DPF (or DPF1). The exposure is merely 0.6 m deep from the surface of the drumlin. The apparently massive composition of the drumlin although indicates the wave like flow pattern of the clasts (lines starting from the bottom) followed by clast jamming and brittle deformation towards top (line). The pit is at the lee face of the drumlin (Fig. 67b) and ice flow was left to right. The tape is given for scale (60 cm.).

Fig. 68 The graphical sketch of the Plate: 65; this is drawn in a way that the scale and orientation of the clasts are maintained and also the two dimensional figure is clear enough to depict the pattern of the distribution of clasts, in otherwise massive structure. The lower lines indicate the wave like flow pattern (arrow) of the clasts, possibly under subglacial ductile deforming regime. Above this wave like pattern strong clast orientation pattern is visible. This is the location at the depth of 15 cm. from the surface of the drumlin which shows clast jamming and brittle deformation, possibly also undersubglacial to submarginal regime. The sketch can also be used as macro scale thin section because it also reveals galaxy type clast rotational and deformation pattern in the ductile deforming zone.

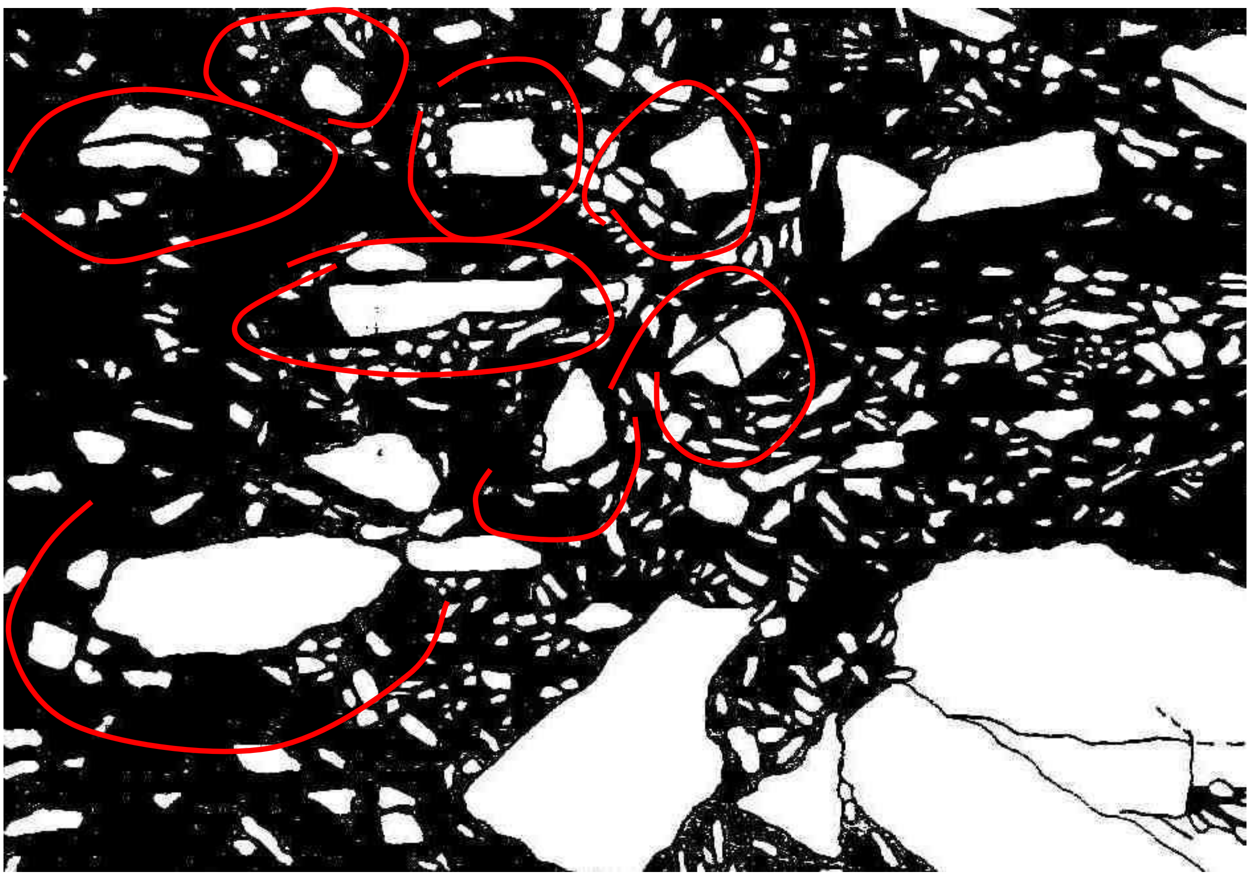


Fig. 69 This section of Figure. 68, indicates the galaxy type flow pattern of the clasts, which are often encountered for the ductile deforming subglacial flow tills under macro thin sections. Their evidences even at this scale indicate the extensive subglacial ductile deformation of the tills at depth; possibly due to increase in pore water pressure and glacier movement.

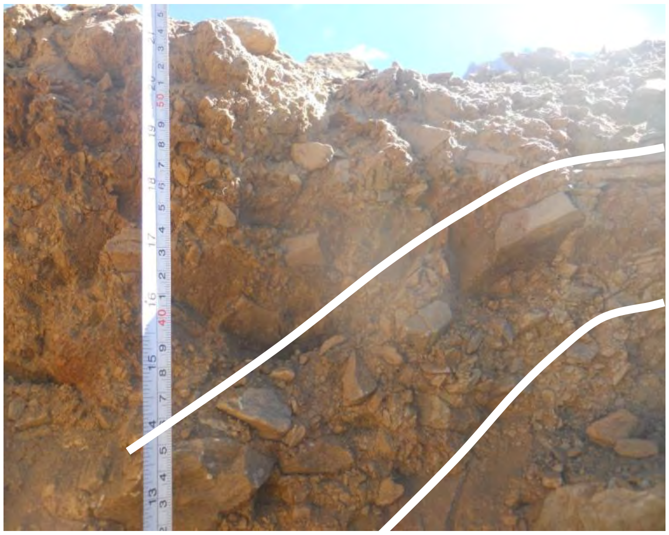


Plate: 66 The plate is showing the clast jamming pattern near to the surface of the drumlin KG1/DPF at the site 1. The lines are given for better enclosing this brittle deformation zone. Grain fracturing is also noticed in this deforming layer, and believed to be due to reducing pore water pressure and increasing stress.

In the Yunan valley (site 2) (Fig 72 a.) two back-to-back road cuts are choose for clast macro fabric analysis (Fig. 72 b). One of these sections (Exposure 1 or Sarchu 1) is logged (Fig. 66) and photographs are taken as evidence. It is found that although the section apparently consists of matrix-supported massive diamictons with sub-angular to mostly sub-rounded clasts, pseudo layering can be identified in situ (Plate: 67). These are actually identified on the basis of the typical clast concentration pattern. These clast concentrated parts are found protruding from the disturbed section. The exact reason is yet to identify, but it is believed that the environmental condition during drumlin genesis and subsequent development remains more or less same, although these drumlins are believed to be formed more of under submarginal condition than subglacial; this contrast with the drumlins of the Chandra Tal area. The apparently loose composition and extensive supraglacial deposits at the surface of most of the drumlins of this area denies their subglacial origin, but their directionality and other attributes certainly supports their submarginal development. Detail future study of the internal composition of drumlins from this area will certainly clarify this picture. However, it is to be certain that they are not formed

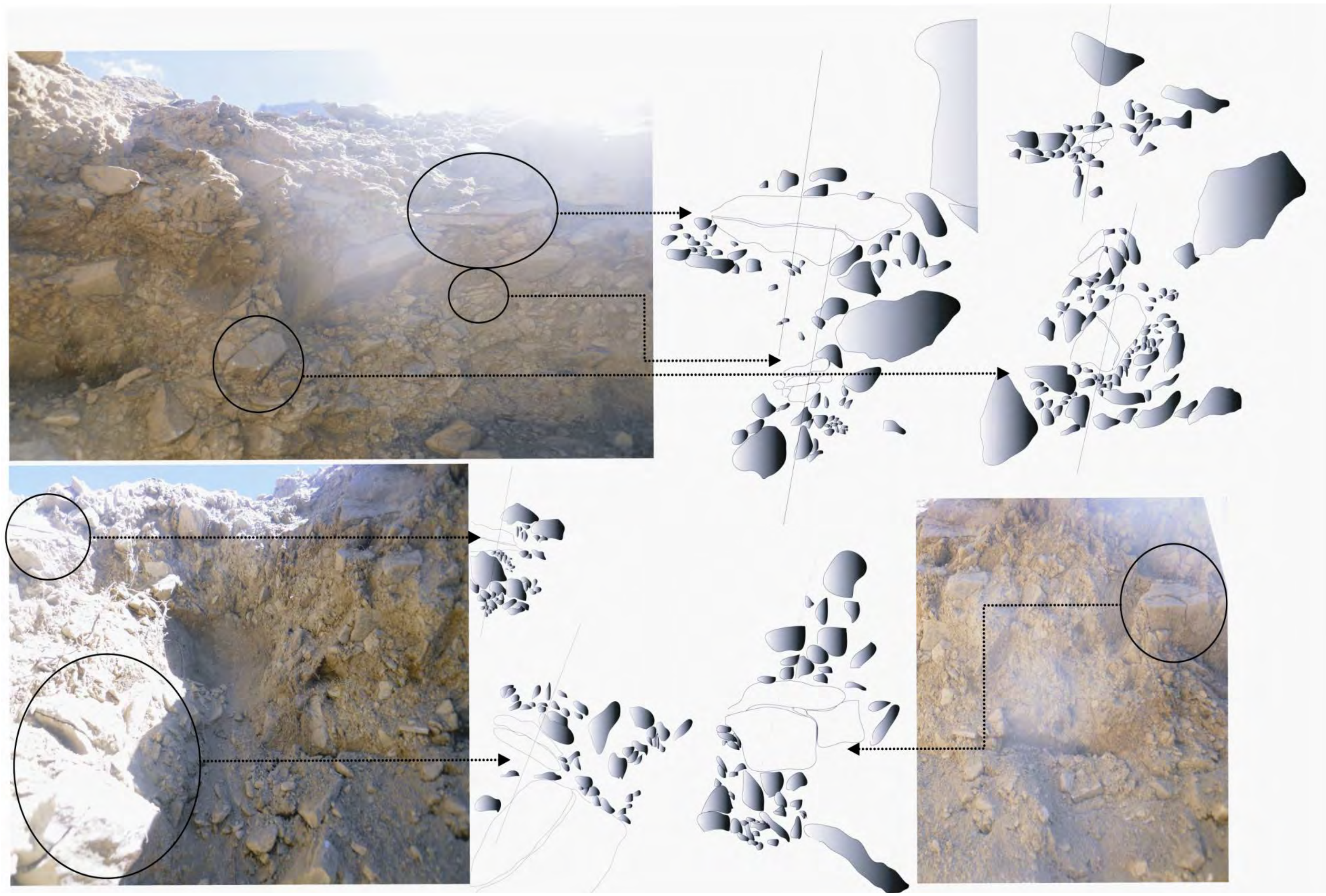
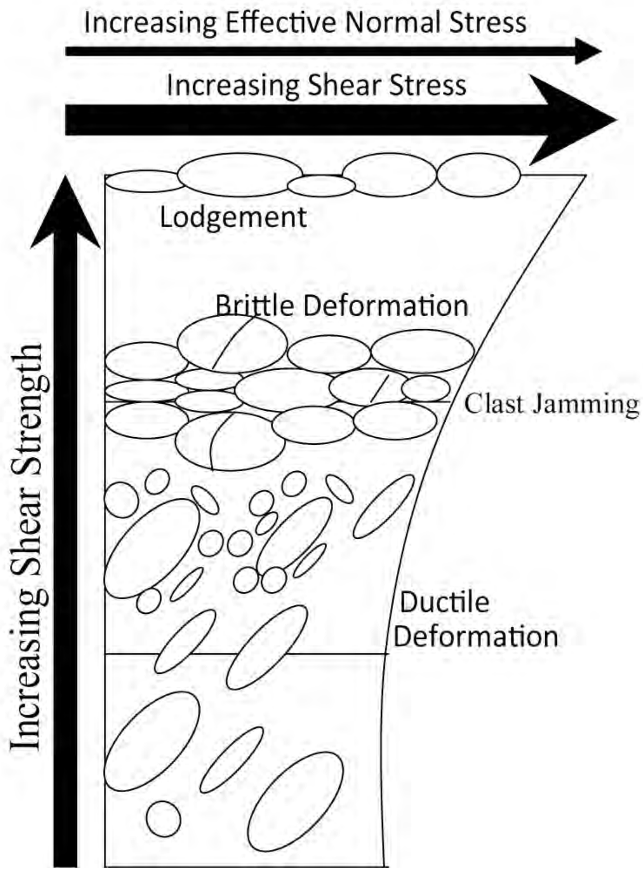


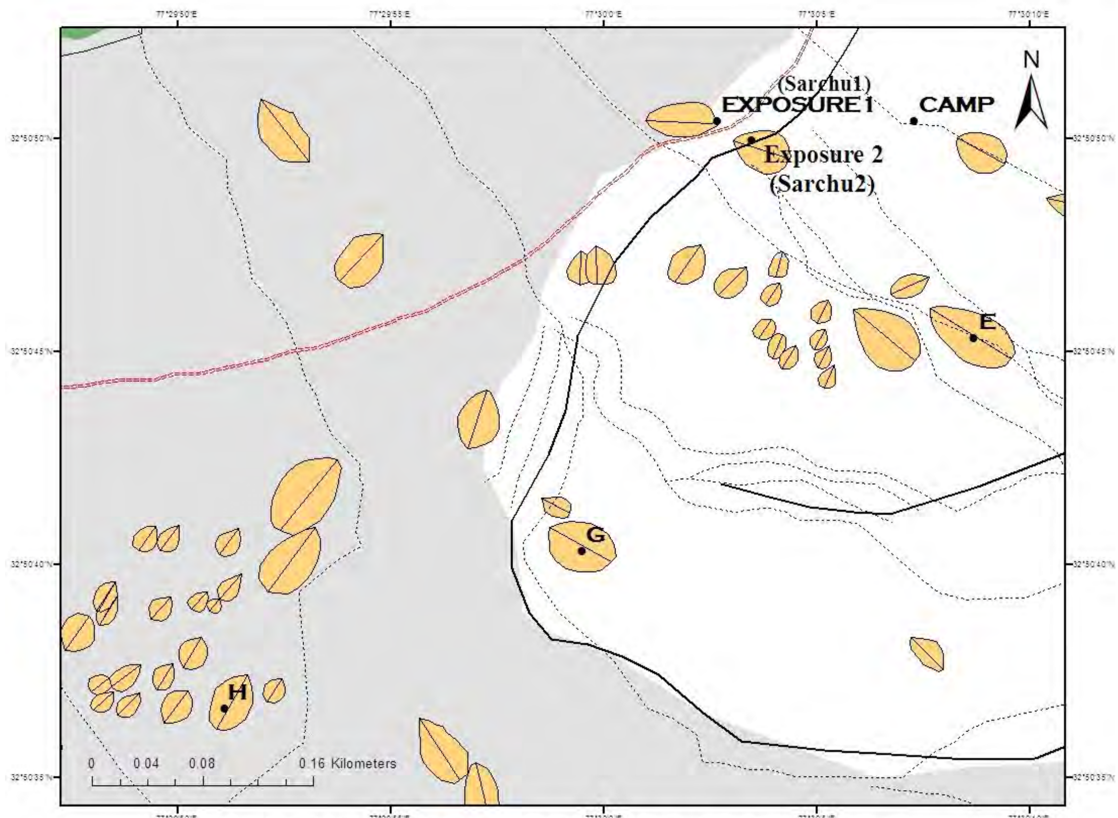
Fig. 70 These are the sections of the brittle deforming layer of the sample drumlin KG1/DPF (or DPF1) near the surface at the site 1, which shows the grain bridginh (grain networking) and grain fracturing along the shear stress gradient. Such kinds of fracture patterns are already mentioned in literature (both experimentally and in situ) as the diagnostic to form the subglacial grain fracturing and grain crushing i.e. brittle deformation. The circles from the photographs are sketched and enlarged for clear depiction. Since the photo scale is not recorded for this photograph during filed, this is not present but the no distortion has taken place during sketching, hence can be a true representative of the fractured clasts.



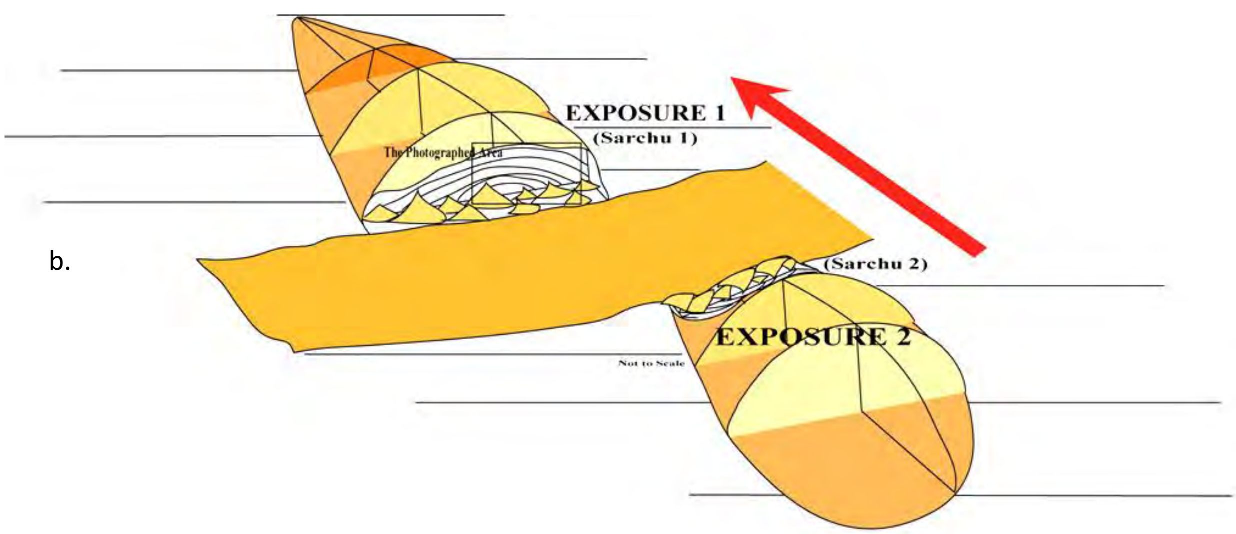
within single phase rather multiphase deposition is more realistic. Suitable thin section analysis at micro scale may further solve many of the questions. Otherwise blind research on these massive exposures may not prove satisfactory; although macro level fabric analysis yields better results (see section 6.2.2.4). However, not much has been identified in detail in terms of their lithological study in the Yunan valley.

Fig. 71 The diagram is the simplified picture of the entire pit section of the KG1/DPF (or DPF 1). This shows, from the bottom to top, the wave like ductile deformation pattern with clast rotation and galaxy type clasts, followed by brittle deformation and grain fracturing and clast jamming along the shear gradient, and at the surface the lodgement of the boulders. Hence from the bottom to top the shear strength is increasing, may be because of increasing effective normal stress and strength of the materials. The changes in the rheology of the materials possibly due to the variation of the pore water content at the glacier sole may be attributed for these changes. This also indicates that with the passage of time the glaciological condition have changed in the region.

Besides the grain size determination and detail structural analysis other lithological studies e.g. mineralogy, geometry etc. have not undertaken, although EDX measurements during SEM analysis does provide the composition of some of the important minerals. For example, according to EDX analysis, however, it has been found that important minerals are quartz, feldspar, aluminum, iron, potassium, magnesium, sodium, titanium etc.



a.



b.

Fig. 72 The 3D graphical illustration of the sample drumlinsSarchu 1 (or Exposure 1), and Sarchu 1 (or Exposure 2). (a) Map showing the sample sites at the site 2, and (b) is the three dimensional outline forms of the drumlins with the location of stoss side and lee side pits of the sarchu1 and sarchu2 respectively. The fabric measurements, log preparation, and SEM samples are taken mainly from these road-cut exposures. Arrow indicates the ice-flow direction. The disturbed parts with mass movement deposits are also shown graphically (not to scale).

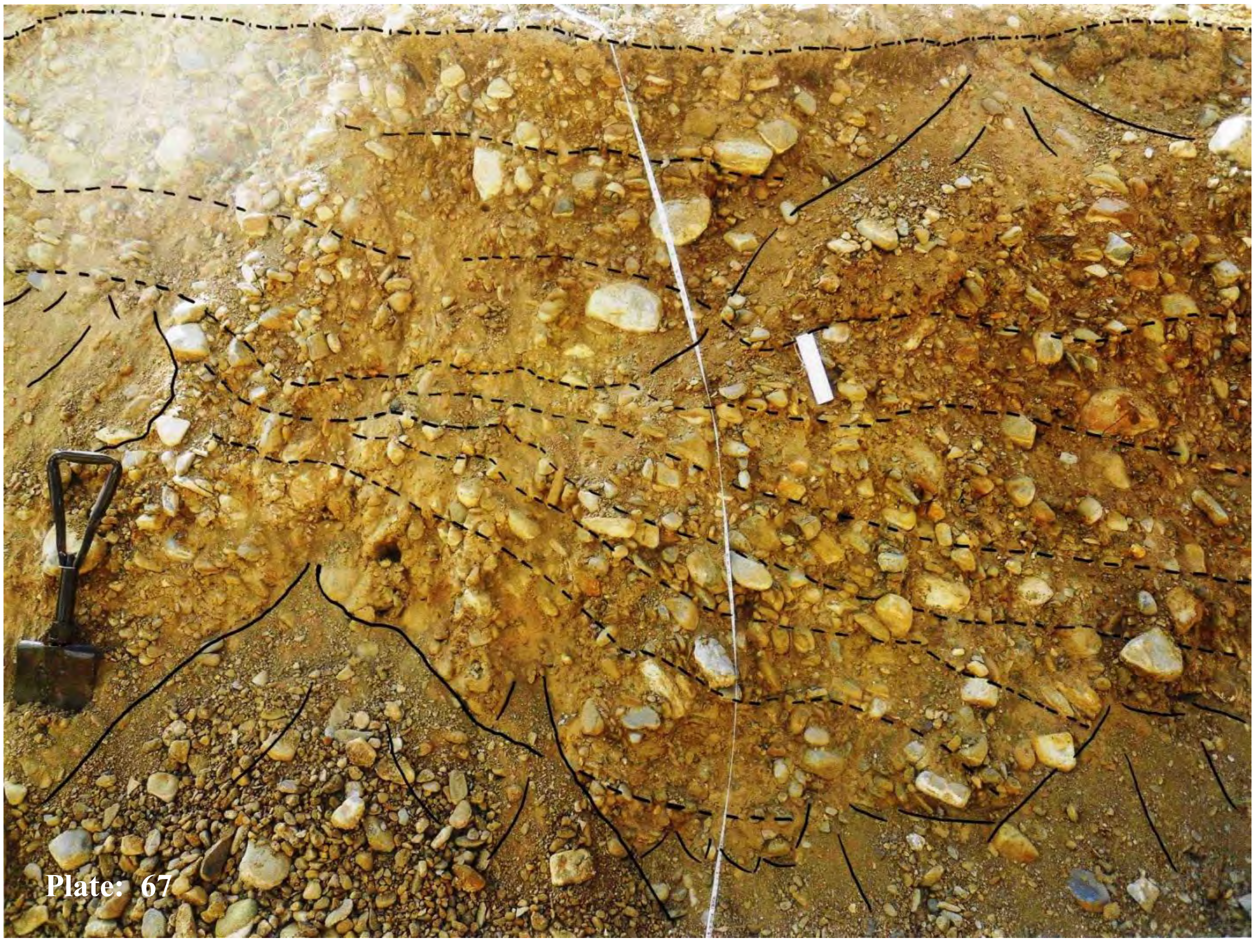


Plate: 67 The road-cut exposure of Sarchu 1 (Exposure 1) indicates the pseudo layering (dashed lines) of the typical clasts. Apparently the section is massive, but careful review of the clasts indicates continuous belts of clast concentration throughout the section with pseudo layer like pattern. This may be due to several phases of deposition. The section is at the extreme right of the stoss face of the post depositionally modified drumlin which is transverse to the valley. The position of the section is shown as the rectangle in the Figure: 72b. The white plastic scale (15 cm long) are given for scale.

6.2.2. Morphotextural Analysis:

Relatively robust morphotextural analysis has been conducted in the present study from a number of sample drumlin's surfaces. Mainly grain shape and sorting analysis, clast roundness and sphericity analysis, surface textural analysis, and clast macro fabric analysis have been undertaken. Several important facts have also been identified which certainly support the already made inferences. These are discussed through the following points.

6.2.2.1. Grain Shape Analysis:

Measurements of clast long axes (a- axes), intermediate axes (b- axes), and short axes (c-axes) data during field surveys helps in easy reconstruction of grain shape distribution in the Chandra Tal area (site 1) and Yunan Valley (site 2). In the shape analysis, however, the number of clasts (N) measured, varies from 51 to 25, and given the number of samples studied in different parts of the field, it is believed that they are representative of the entire population. Sneed and Folk classes of grain shape distribution (Graham and Midgley, 2000) are used in the present study. They are also compared with Zingg's shape classes and (although they are not represented in the present paper) it is found that the general picture remains largely similar in both the analysis. However, in the Chandra Tal area it has been found that at the sample site KG1/DPF (Fig. 67) bladed (32%) and very-bladed (~19%) clasts followed by elongate (~15%) and very-elongate (~11%) shapes predominate (Fig. 73a). The granular shape materials from the same site also indicate very high concentration very-bladed and very-elongate (25% each) clasts (Fig. 73b). Platy shape clasts, however, found relatively high (20%) among this smaller granule clasts. At the KG2/DPF (Fig. 85), very high concentration of bladed (36%) and elongate (20%) clasts are found (Fig. 73c). At the DPF2 sample site (Fig. 85) very-bladed and very-elongate (26% each) clasts overwhelm along with more elongate shape clasts (22%) in the matrix (Fig. 73d). These samples are collected from the surface deposits of the drumlins in the Chandra Tal area (site1). The general picture remains intact when studies are also undertaken in the interdrumlin depression (IDPF1, Fig. 85). That is the very-bladed (38%), bladed (20%), elongate (18%) and very-elongate (16%) shapes predominate (Fig. 73e). The general pattern, however, differ a little at the Kumzum la area i.e. Kun/07/50 (Fig. 85; Site 3). It has been found that very-bladed (36%) shapes predominate in the deposits, followed by compact-bladed, bladed, compact-elongate, and very-platy (12% each; Fig. 74). In the Yunan valley (site 2), the clast shape distribution is similar to Chandra Tal area (site 1). At Sarchu 1 (Exposure 1; Fig. 72) bladed (24%) and very-bladed (22%) clasts predominate, followed by elongate and very-elongate (22 % each) clasts (Fig. 75a). In Sarchu 2 (Exposure 2; Fig. 72), however, very-bladed and very-elongate (25% each) clasts dominate along with very-platy (20%) shapes. Hence, not much sharp difference is found among the clast shape distribution in the three sites except that in the Kunzum La bladed shape clast concentration is relatively higher compare to the near equal concentration of bladed and elongated shape clasts in the Chandra Tal area. However, in the Chandra Tal area bladed clasts are relatively more concentrated in the interdrumlin depressions than at the surfaces of the drumlins. No as such difference is found between Site 1 and Site 2.

The very high concentration of bladed and elongate clasts in the study area partly can be attributed to the local geology and partly to weathering effect. Plate: 68 display the present periglacial weathering (frost shattering) of the bedrock outcrop. Plate: 69 (at the drumlin surface) and Plate: 70 (at the interdrumlin depression) show the typical bladed and elongate clasts in the Chandra Tal area (site1). Form these evidences it can be speculate that such clasts are of local origin i.e. the role of local geology, and some of them may also have formed during interglacial warming period and later incorporated in the basal-ice zone at the submarginal subenvironment. Roundness measurements and SEM analysis of surface textures on quartz sand grains further clarify this general picture in.

Plate: 68 The local geology is highly susceptible for the periglacial weathering and leading to the production of large scale frost shattered blade shaped clasts. Their larger concentration in most of the drumlin deposits are also believed to be derived from local bedrocks subglacially as well as submarginally.

6.2.2.2. Clast Roundness analysis:

Clast roundness analysis has also undertaken during field survey but they are not robust and may also not be truly representative for the entire stretch of the field and/or even within the entire length of the internal composition of a single drumlin. In the Chandra Tal area roundness analysis is conducted at DPF2 (N= 41; Fig. 85), IDPF1 (N=30; Fig.85), and especially for the granule grains at the clast concentrated section of KG1/DPF (N= 45) (see section 6.2.1.2) below 15 cm. from the drumlin surface. However, the limited data shows that at the surface of

DPF1 drumlin, angular and very angular (A+VA) clasts dominate (56%), followed by subangular clasts (37%); proportion of sub-rounded clasts are very low (7%) (Fig. 76.a). The mean roundness is displayed by the arrow in Fig. 76.a. Even in the interdrumlin depression (IDPF1) the A+VA clasts are very high, followed by sub-angular clasts (37%), sub-rounded clasts (17%) and proportion of rounded clasts are very low (10%) (Fig. 76.b). Although the proportion of A+VA clasts is very high in these deposits in the Chandra Tal area, they contrast sharply with other subglacial environment of the Himalayas, reported elsewhere (Owen et al., 1989; Benn and Owen, 2002). However it seems that sub-rounded clasts are also present in the subglacial till deposits along with subangular and angular clasts (Plate 69 and 70) but their share are relatively very low compared to what they should be. This suggests that most of the clasts are supra-glacially at the glacier margins and later incorporated in the basal-ice zone; although few of them are also supplied subglacially. The proportions of sub-rounded and rounded clasts are although found to be slightly relatively higher in the interdrumlin depression than the surface of the drumlins. However, when the granular sample is measured at KG1/DPF at the 15 cm. depth form the surface of the drumlin (Fig. 67), it is found that the proportion of A+VA is equally very high (73%), whereas that of subangular clasts are 24 percent, and values are insignificant for other classes (Fig. 77/a). Since clasts of DPF2 and IDPF1 are collected at similar depth (i.e. 15 cm. form the surface) couple with the inferences drawn from the previous grain shape analysis, it is quite possible that the clasts are local in origin and mostly supraglacial marginal deposits. and also they have experienced greater crushing and grain fracturing near the surface when subject to higher shear stress.

When the stoss side of the KG1 drumlin is tried to dig (Plate 71), it is also found that the bedrock knoll (rock cored drumlin) is heavily fractured into blocks and blade shaped clasts. This further suggests the local bedrock origin of these clasts (section 6.2.2.1). Hence two inferences thus can further be supported with the present examples i.e. the matrix-supported clasts composing the drumlins in the Chandra Tal area (site 1) mostly local in origin and submarginally derived and have experienced brittle deformation and grain fracturing and near the surface of the drumlins.

However, sphericity of the granular grains of KG1/DPF drumlin has also been measured visually in situ (Fig. 77.b), and it is found that sub-prismoidal (38%) class dominate following spherical (27%), discoidal (20%) and sub-discoidal (18%) sphericity. The very high A+VA clasts may be attributed for high sub-prismoidal sphericity, high elongate clasts also may cause high spherical grains, and high bladed clasts may attribute for the discoidal and sub-discoidal sphericity in the sample.

No clast roundness and sphericity measurement has conducted in the Yunan valley area, but from the exposed section (Plate: 67) it can be observed that the clasts composing the drumlins in the Yunan valley are mostly sub-rounded to rounded in shape, typical to subglacial origin (Owen et al., 1989; Benn and Owen, 2002) in the Himalayas. However, it thus quite possible that the diamictons are transported relatively long distances in the Yunan valley under subglacial regime or are reworked, compared to the Chandra Tal area, where clasts are found to be mostly local origin and submarginally derived at least in the upper section of the deposits.

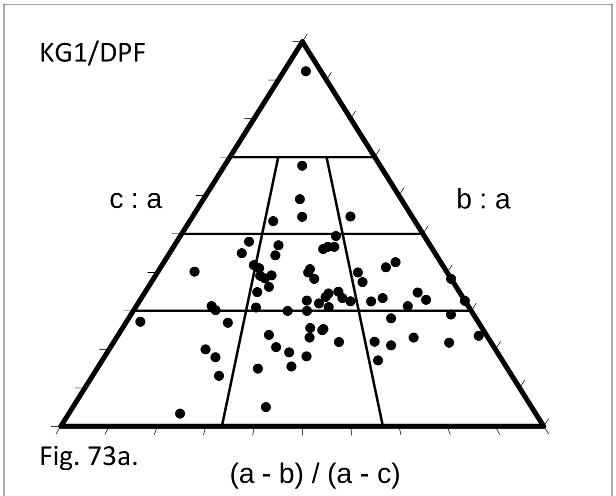


Fig. 73a.

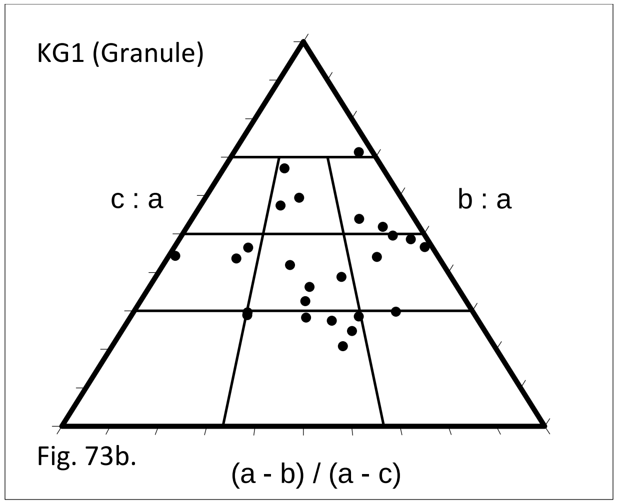


Fig. 73b.

Sneed & Folk Classes KG1/DPF	Count	Percent
Compact	1	1.33
Compact-Platy	0	0.00
Compact-Bladed	4	5.33
Compact-Elongate	1	1.33
Platy	6	8.00
Bladed	24	32.00
Elongate	11	14.67
Very-Platy	6	8.00
Very-Bladed	14	18.67
Very-Elongate	8	10.67

Sneed & Folk classes KG1 (Granule)	Count	Percent
Compact	1	4.00
Compact-Platy	0	0.00
Compact-Bladed	3	12.00
Compact-Elongate	2	8.00
Platy	3	12.00
Bladed	4	16.00
Elongate	4	16.00
Very-Platy	0	0.00
Very-Bladed	7	28.00
Very-Elongate	1	4.00

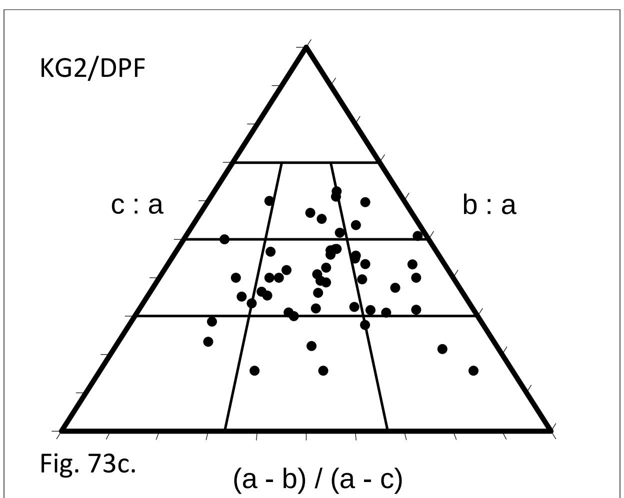


Fig. 73c.

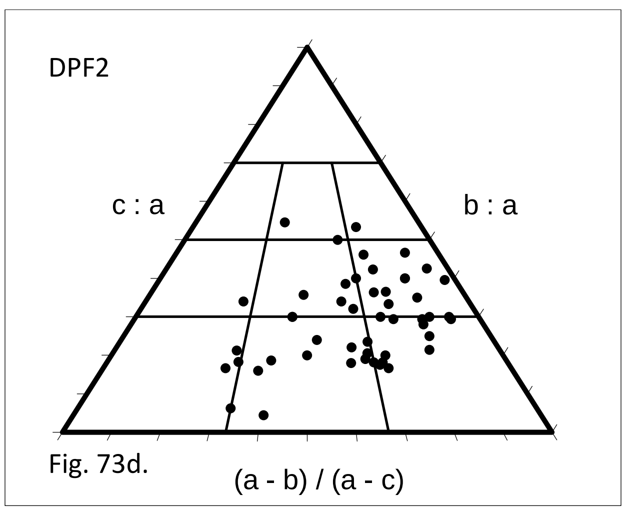


Fig. 73d.

Sneed & Folk classes KG2/DPF	Count	Percent
Compact	0	0.00
Compact-Platy	1	2.00
Compact-Bladed	5	10.00
Compact-Elongate	3	6.00
Platy	4	8.00
Bladed	18	36.00
Elongate	10	20.00
Very-Platy	2	4.00
Very-Bladed	5	10.00
Very-Elongate	2	4.00

Sneed & Folk classes DPF2	Count	Percent
Compact	0	0.00
Compact-Platy	0	0.00
Compact-Bladed	1	2.00
Compact-Elongate	1	2.00
Platy	1	2.00
Bladed	6	12.00
Elongate	11	22.00
Very-Platy	4	8.00
Very-Bladed	13	26.00
Very-Elongate	13	26.00

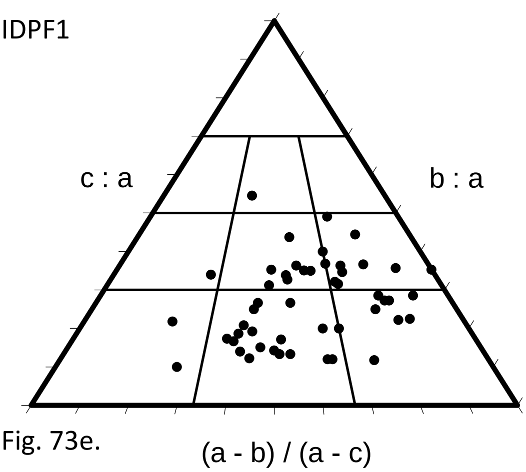


Fig. 73e.

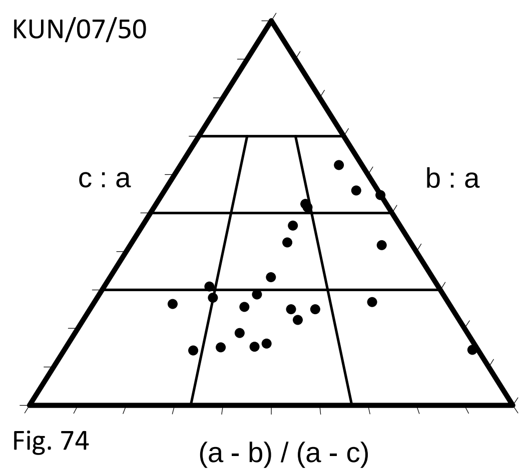


Fig. 74

Sneed & Folk classes IDPF1	Count	Percent
Compact	0	0.00
Compact-Platy	0	0.00
Compact-Bladed	1	2.00
Compact-Elongate	0	0.00
Platy	1	2.00
Bladed	10	20.00
Elongate	9	18.00
Very-Platy	2	4.00
Very-Bladed	19	38.00
Very-Elongate	8	16.00

Sneed & Folk classes KUN/07/50	Count	Percent
Compact	0	0.00
Compact-Platy	0	0.00
Compact-Bladed	3	12.00
Compact-Elongate	3	12.00
Platy	1	4.00
Bladed	3	12.00
Elongate	1	4.00
Very-Platy	3	12.00
Very-Bladed	9	36.00
Very-Elongate	2	8.00

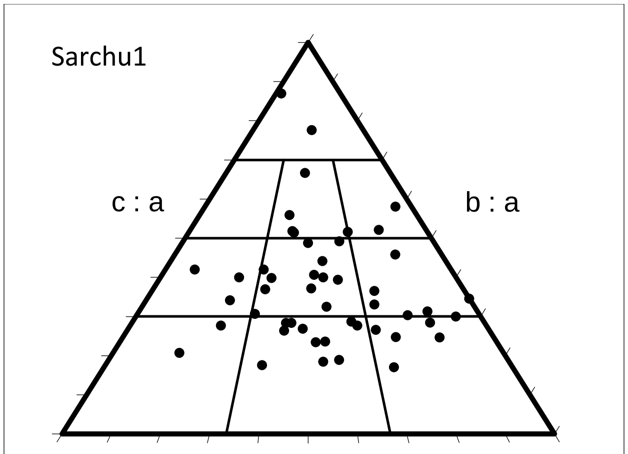


Fig. 75a.

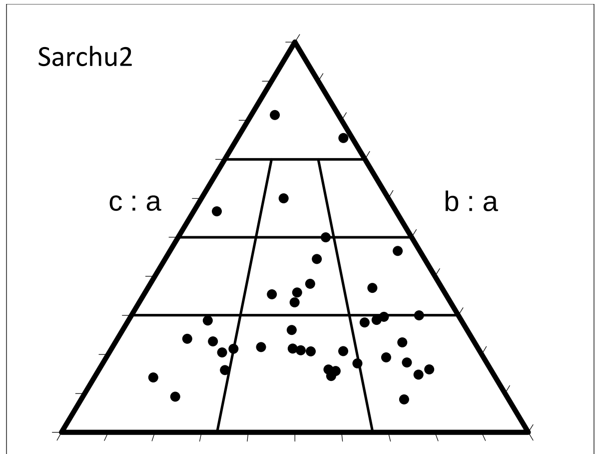


Fig. 75b.

Sneed & Folk classes Sarchu1	Count	Percent
Compact	2	4.08
Compact-Platy	0	0.00
Compact-Bladed	5	10.20
Compact-Elongate	2	4.08
Platy	3	6.12
Bladed	12	24.49
Elongate	6	12.24
Very-Platy	2	4.08
Very-Bladed	11	22.45
Very-Elongate	6	12.24

Sneed & Folk classes Sarchu2	Count	Percent
Compact	2	5.00
Compact-Platy	1	2.50
Compact-Bladed	1	2.50
Compact-Elongate	0	0.00
Platy	0	0.00
Bladed	6	15.00
Elongate	2	5.00
Very-Platy	8	20.00
Very-Bladed	10	25.00
Very-Elongate	10	25.00

Fig. 73 Sneed and Folks ternary diagrams for clast shape distribution. (a) Ternary diagram and the table showing the distribution of clast shapes in different classes proposed by Sneed and Folks, and their proportion respectively at the sample KG1/DPF; (b) Ternary diagram and the table showing the distribution of clast shapes in different classes proposed by Sneed and Folks, and their proportion respectively at the sample KG1granule grains; (c) Ternary diagram and the table showing the distribution of clast shapes in different classes proposed by Sneed and Folks, and their proportion respectively at the sample KG2/DPF; (d) Ternary diagram and the table showing the distribution of clast shapes in different classes proposed by Sneed and Folks, and their proportion respectively at the sample DPF2; (e) Ternary diagram and the table showing the distribution of clast shapes in different classes proposed by Sneed and Folks, and their proportion respectively at the sample IDPF1.

Fig. 74 Ternary diagram and the table showing the distribution of clast shapes in different classes proposed by Sneed and Folks, and their proportion respectively at the sample KUN/07/50.

Fig. 75 (a) Ternary diagram and the table showing the distribution of clast shapes in different classes proposed by Sneed and Folks, and their proportion respectively at the sample Sarchu1; (b) Ternary diagram and the table showing the distribution of clast shapes in different classes proposed by Sneed and Folks, and their proportion respectively at the sample Sarchu2.

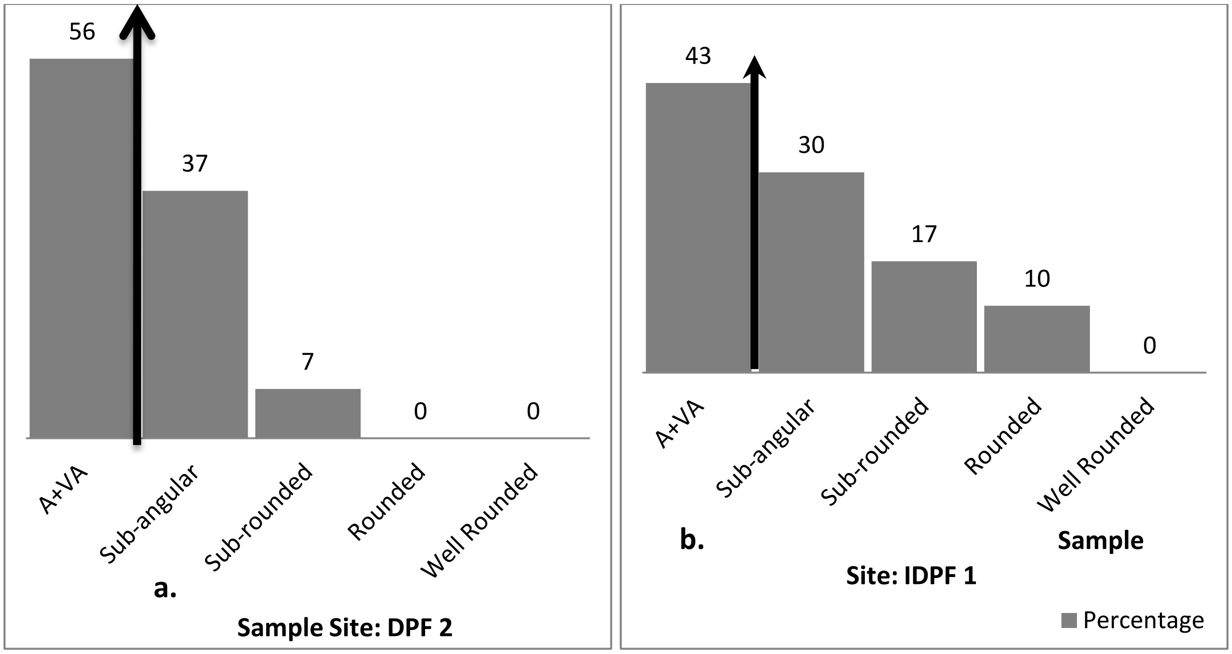
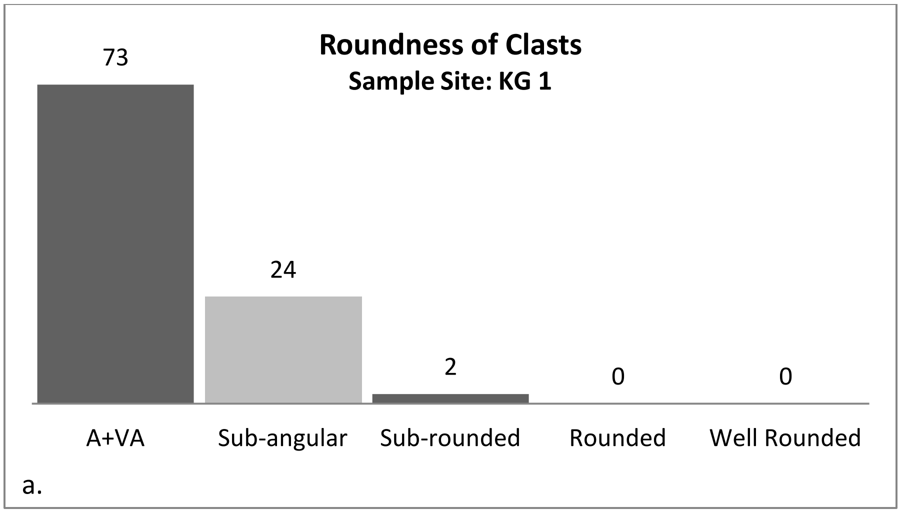


Fig. 76 Histograms showing the proportions of clasts roundness classes.The mean roundness of the clasts belongs to the mid of Angular+Very Angular and Sub-angular types (arrow). (a) Clast roundness analysis at the sample site DPF2 and (b) clast roundness analysis at the sample site IDPF 1 of the site 1.

Plate: 69 Sample clasts of the drumlin DPF2 at the site 1 for roundness analysis. As the plate indicates most of them belong to A+VA category. This strongly support that they are possibly ice-marginally derived or experience local origin with very short transport distances.

Plate: 70 Sample clasts of the inter drumlin depression (i.e. IDPF1) at the site 1 for roundness analysis. As the plate indicates clasts vary from A+VA to sourounded types. Visually it strongly supports that while some of them are subglacially derived, others are possibly ice-marginally derived or experience local origin with very short transport distances.



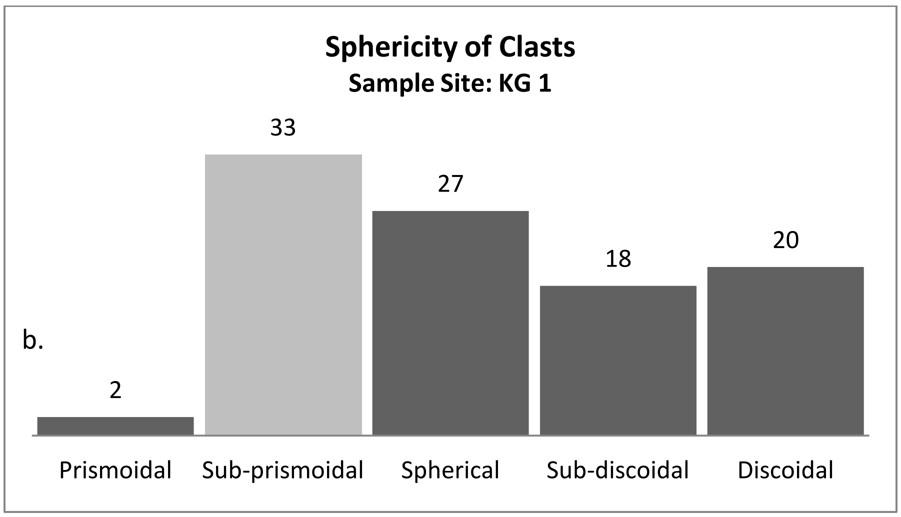


Fig. 77 Histograms showing the proportions of clasts roundness classes and sphericity of the sample drumlin KG1/DPF (at the site 1). (a) Clast roundness analysis at the sample site KG1/DPF. The mean roundness belongs to sub-angular clasts (gray bar) and (b) clast sphericity distribution analysis at the sample site KG1/DPF. The sub-prismoidalclasts are the mean sphericityof the entire sample.

Plate: 71 The lee side section of the drumlin KG1/DPF (or DPF 1). The bed rock knoll is clearly visible in this section. The bedrock is frost shattered in blocks as well. This also may responsible for the locally derived A+VA clasts with mostly elongate and blade shapes.

6.2.2.3. Surface Texture Analysis:

In the present study surface textures of quartz sand grains are studied in detail using Scanning Electron Microscope (SEM). Sufficient number (N = 52) of quartz sand grains of 200μm. to 500μm. sizes are selected for the present study. Quartz sand grains are first identified under binocular microscope and verified later using Energy Dispersive X-ray technique for each of the samples individually and in groups. Details of them are provided in the annexure 2. SEM analysis, however, is conducted in the sample site KG1/DPF, DPF2, KG2, and KUN/07/50. These sites are selected arbitrarily. However, the distance of KG1/DPF is relatively close to Baralacha La (~3.6 km.), followed by DPF2, KG2 (~5.16 km.), and KUN/07/50 (~11.4 km.) (Fig.85). This simple micro scale analysis provide some of the key insights highly relevant in the

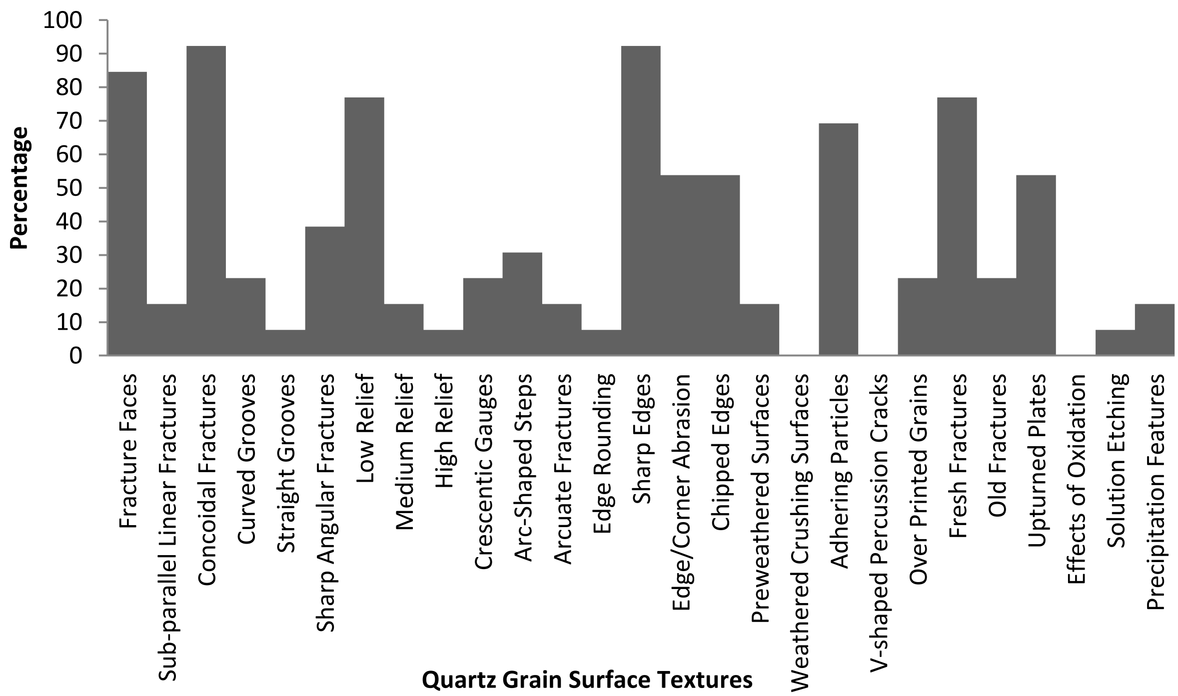
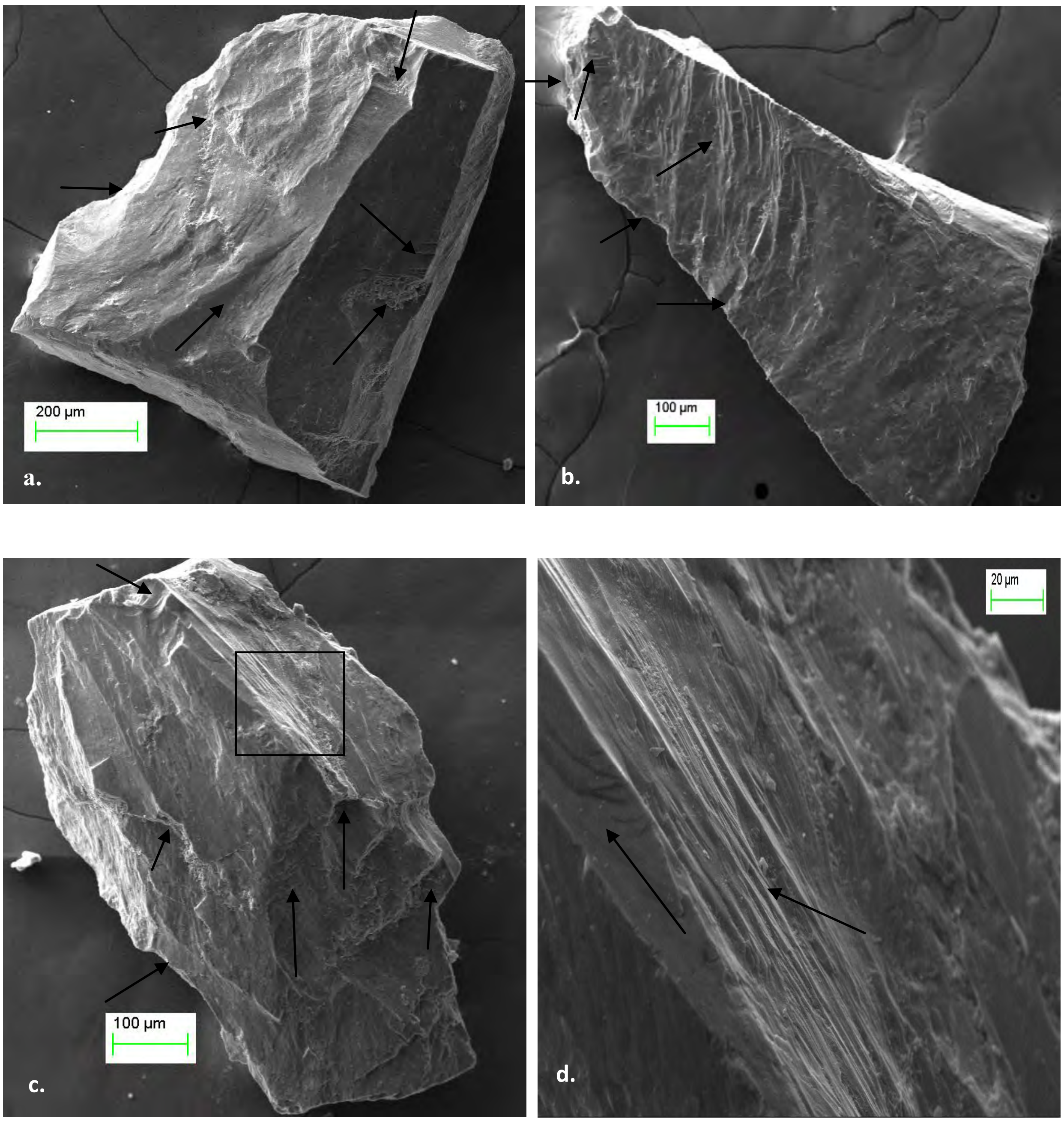
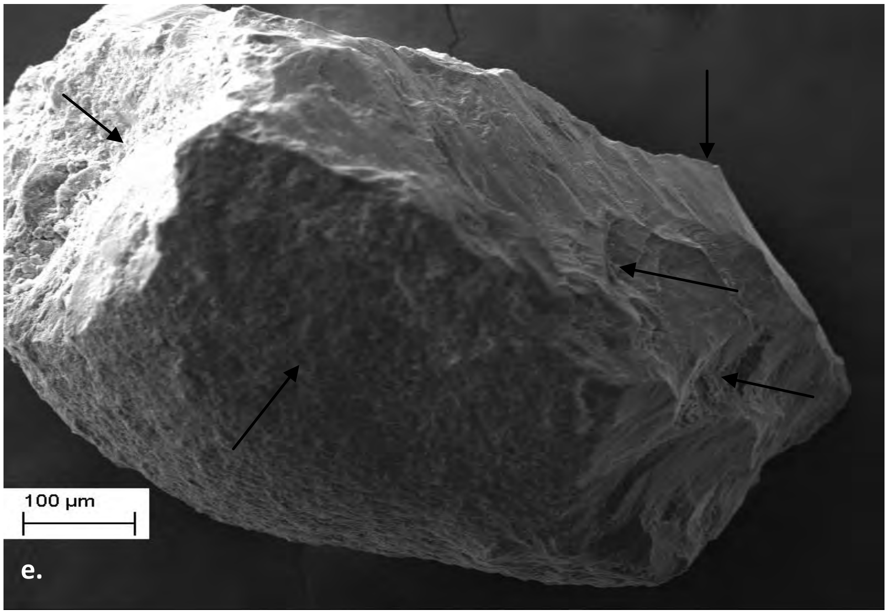


Fig. 78. SEM analysis of surface textures,
Sample Site: KG 1/DPF

present context, especially interms of supporting the landform studied so far are glacially formed and they certainly have experienced greater crushing and grinding likely to be under thick glacier-ice. Besides, the incorporation of preweathered grains, although very small, can also be corroborated with the micro-scale evidences. However, detail of the each sample sites are discussed as follows.

At the KG1/DPF sample site (Fig. 85) the surface texture analysis using SEM of sand quartz grains suggest that the most prevalent surface textures are mostly common from the glacigenic sediments and especially from the subglacial environment, which may have experienced greater crushing (Fig. 78). This sample is collected below 15 cm. depth from the drumlin surface. However, it has been found that fresh fracture faces (Plate: 72.a) and concoidal fractures (Plate: 72.b), and upturned plates (Plate: 72.b & c) dominate among the samples. Samples possess mostly low relief features (Plate: 72.a) and high adhering particles (Plate: 72.f) are the major characteristics of these samples. This means that they have experienced greater level of subglacial crushing and grinding. Sharp angular fractures (Plate:, 72.c) arc-shaped steps, edge and corner abrasion (Plate: 72.f), and chipped edges (Plate: 72.b) etc. textures are found moderate in number. On the contrary, the subparallel linear fractures (Plate: 72.d), curved and straight grooves, medium and high relief, crescentic gauges, arcuate fractures, edge rounding (Plate: 72.e), preweathered surfaces (Plate: 72.e) and over printed grains (Plate: 72.f), older fractures (Plate: 72.f), solution etching and precipitation features (Plate: 72.e) etc. are rarely found in the samples. No evidences of v-shaped percussion cracks and weathered crushing surfaces and oxidation effects have been identified so far. Hence these textural analyses firmly put the grains as mostly glacial in origin and most of the textures are subglacially derived. The influence of other geomorphological agents e.g. weathering, aeolian or fluvial etc. seem to very insignificant to none and possibly may indicate their later incorporation in the subglacial sediment when advancing glaciers overrides the marginal sediments.





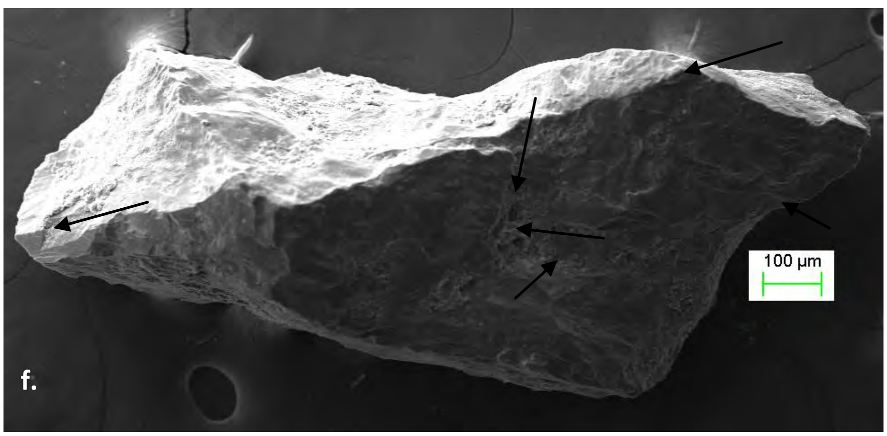


Plate: 72 The surface textural analysis of the quartz sand grains under SEM of the sample drumlin KG1/DPF. (a) Mechanically fractures face with upturned plates and chipped edges, concoidal fractures, and straight grooves, adhering particles etc. are clearly identifiable at this scale. (b) Arcuate steps and concoidal fractures are well developed in the sample grain. Besides, sharp angular edges, chipped edges and upturned plates, curved grooves etc. are also identifiable form the sample. (c) Fresh mechanical fractures, concoidal fractures, up turned plate, sharp and angular edges, adhering particles etc. are recorded from the sample grain. (d) It is the enlarged part of the grain 72c (rectangle). The fresh mechanically fractured linear faces with striation like marks are shown in the grain.

(e) Wind driven rounded gain may later incorporated with in glacial regime. The rounded part is weathered with precipitation features, whereas the young crushed part top, right and left of the grain indicates extensive grain crushing with adhering particles, concoidal fractures, sharp edges, and groove like marks as well. (f) Edge abrasion, curved grooves, concoidal fractures, extensive adhering particles, upturned plates etc. are clearly identifiable in the sample grain. Hence these samples indicate much fresh incorporation with mechanical fracturing and subglacial grinding and crushing. Some experience subglacial transport whereas few are later incorporated in the glacial regime.

At the sample site DPF2 (Fig. 85), similarly very high proportion of fresh fracture faces (Plate: 73.a & b) and concoidal fractures (Plate: 73.d), and sharp edges (Plate: 73.a & f) are found (Fig.79). The samples mostly possess low reliefs (Plate: 73.a & c), typical to glacial sediments, and very high adhering particles at their surfaces (Plate: 73.d & e), which is indicating very high degree of glacial crushing and grinding. Besides these textures, moderately dominated textural characteristics incorporates, curved grooves (Plate: 73.c & g), sharp angular fractures (Plate: 73.f), arcuate fractures (Plate: 73.h), edge and corner abrasion (Plate: 73.c), chipped edges (Plate: 73.a & h), preweathered surfaces (Plate: 73.f & g), over printed grains (Plate: 73.f), old fractures (Plate: 73.h), and upturned plates (Plate: 73.a & d). Other glacial textural signatures like straight grooves are not found significantly among the samples. Medium to high relief and arc-shaped steps are also insignificantly dominated. Similar is the case for the weathering evidences like, solution etching and precipitation features (Plate: 73.h), whereas weathered crushing surfaces, and oxidation evidences, subparallel linear fractures, crescentic gauges, v-shaped percussion cracks and evidences of edge rounding as well are not present in the samples (Fig.79).

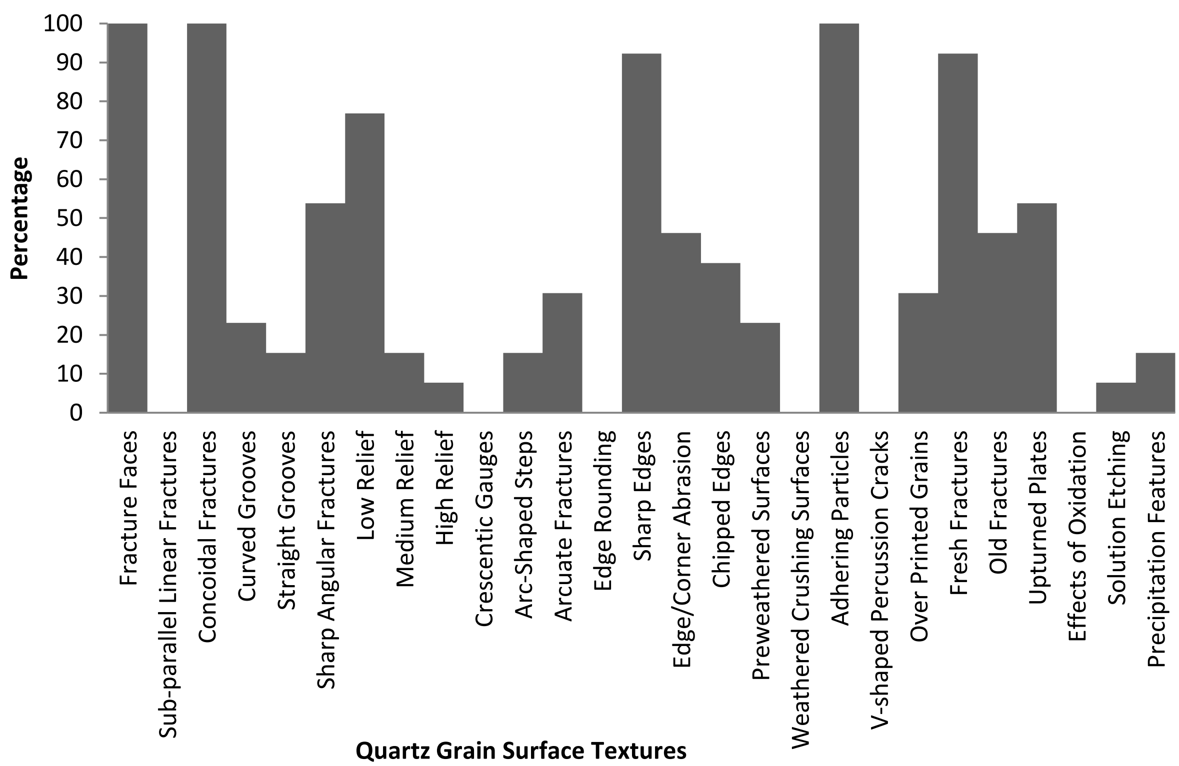
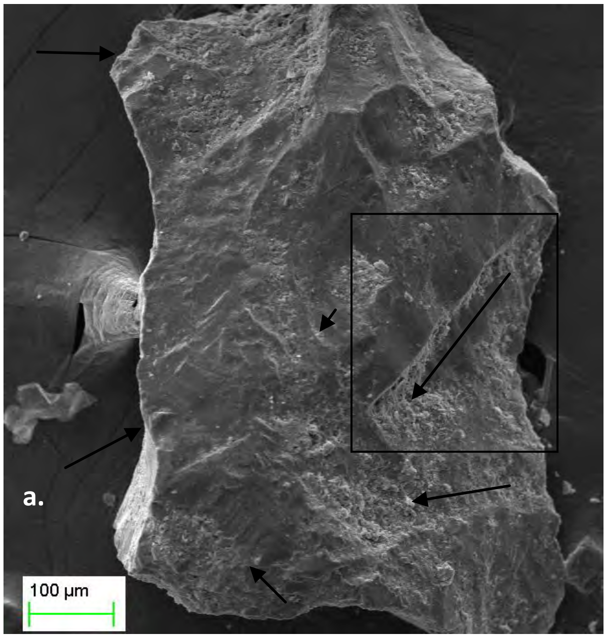


Fig.79. SEM analysis of surface textures, Sample Site: DPF 2



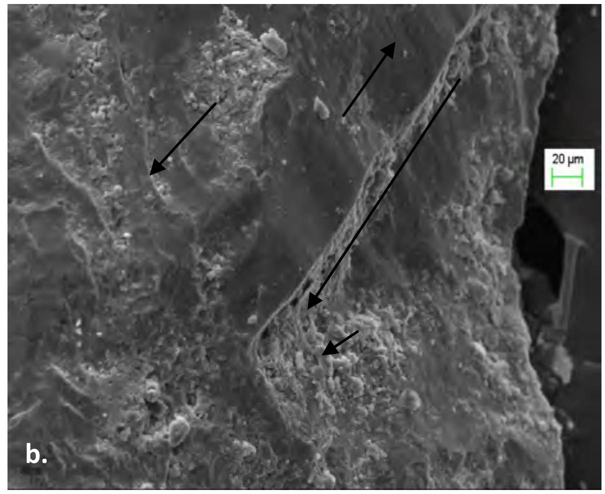
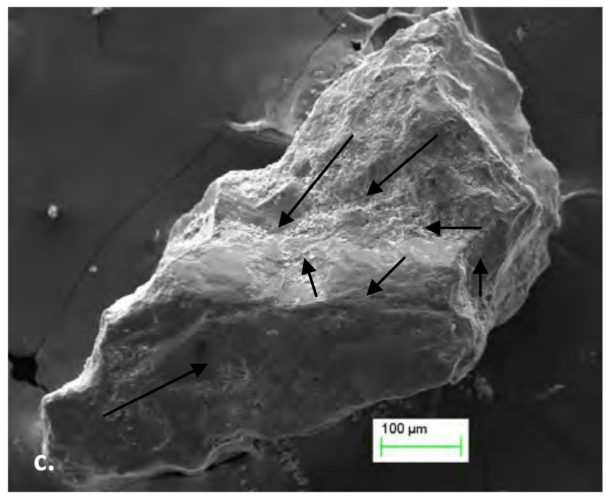
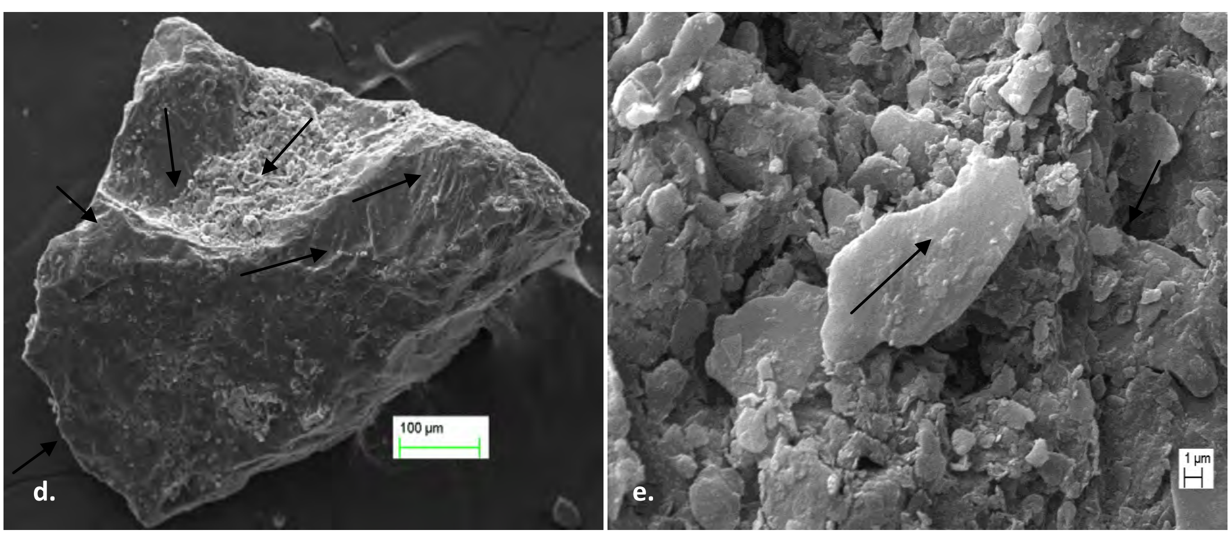


Plate: 73 SEM surface texture analysis of the sample drumlin DPF2 at the site 1. (a) Fresh mechanical fractures with sharp edges, chipped edges, concoidal fractures, extensive adhering particles, low relief, groove like scour etc. are identifiable in the sample grain. (b) The enlarged section of the sample 73a (rectangle). The concoidal fractures, fresh fractures, arcuate steps and adhering particles may be identified in higher magnification as well.





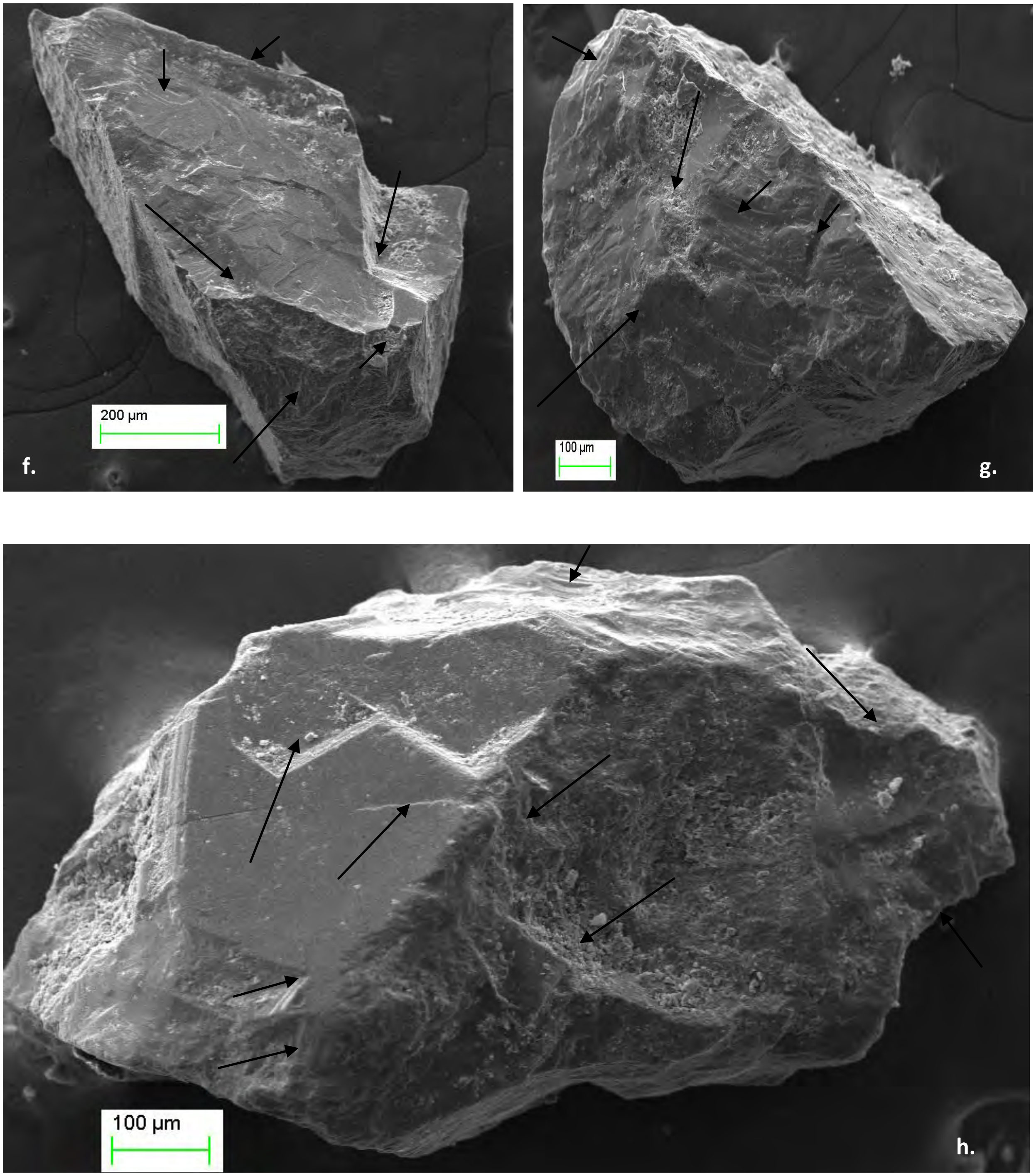


Plate: 73 (c) Edge abrasion and rounding of edge along with curved groove like structures, concoidal fractures, adhering particles, medium relief etc. may be identified easily. The curved grooves are not aligned in the same direction. This along with high abrasion indicates that this grain may have experienced long transport distance under subglacial regime. (d) Adhering particles, concoidal fractures, angular faces, abraded edges etc. can be mentioned from the grain. (e) The mechanically formed large scale adhering particles with flat faces in most of the samples, denoting their high degree of subglacial grinding and crushing. (f) Over printed grain with high angularity and sharp edges with mechanical fresh fracture faces, concoidal fractures, straight grooves etc. The older face at the bottom however, shows chemical weathering evidences. (g) This near rounded grain, possibly aeolian in origin, may have later undergone subglacial crushing. The parallel curved grooves, concoidal fractures, adhering particles support this inference.

(h) Mechanically formed fracture face later may have undergone glacial crushing with concoidal fractures, glacially crushed surfaces with extensive adhering particles etc. Hence most of these samples mechanical fracturing and subglacial grinding and crushing. Some experience long subglacial transport whereas few of mainly aeolian in origin are later incorporated in the glacial regime.

Although one evidence of relatively near round shape sand grains is found and is attributed to aeolian in origin, which may later undergo reworking and incorporation into subglacial regime (Plate: 73.g). The over printed curved grooves along with adhering particles at their surfaces signify this fact.

The sample site KG2/DPF is not only located distant from KG1/DPF and DPF2 (Fig. 85), but also it is existed on the western flank of the Kunzum range (Plate: 12) right side of the ephemeral stream emanating from the Chandra Tal. The sample is collected from the drumlin surface. Although it has similar longitudinal trend (130° from the north), as is the case with other drumlins of this area, and has classical form, speculation may arise that whether it is a drumlin or a remnant of a lateral moraine belong to Batal stage glacial advance. However, a fabric result in support of the landform is provided in the very next section. Here the micro textural evidences are also provided in support of the landform all these evidences point it as drumlin. However, the sample exhibits that quartz sand grains have higher proportion of fresh fracture faces (Plate:74.e), concoidal fractures (Plate:74.f), and sharp and chipped edges (Plate:74. C) (Fig. 80). Unlike to the previous two samples where edge and corner abrasion (Plate:74.g) evidences are moderately observed, such textures are very high in the KG2/DPF (Fig. 80). Possibly the distance resulted into more abrasion of the grains. Moderately developed surface textures include sharp angular fractures (Plate:74.a), low and medium relief features (Plate:74.d), arc-shaped steps (Plate:74.f), arcuate fractures, over printed textures with old fractures (Plate:74.g), and upturned plates (Plate:74. C) (Fig. 80). Curved grooves (Plate:74.d), crescentic gauges, preweathered surfaces, v-shaped percussion cracks, solution etching, precipitation features are found to be very insignificant among the sample grains. No evidences of straight grooves, edge rounding, weathered crushing surfaces, and effects of oxidation etc. are identified. However, from the analyses of individual sand grains, it has been found that two sets of population actually predominate. They are: *a) glacially crushed sand grains which have under gone high edge abrasion and consist of over printed structures*, and *b) the fresh highly crushed sand grains with no significant evidences of edge and corner abrasion*. The later also shows that except mechanically crushed surfaces and fresh fractures, not many structures develop on their surfaces. Few of them possess notable mechanically formed wide fresh fractures (Plate:74.e) which have not been found so prominent in the previous samples.

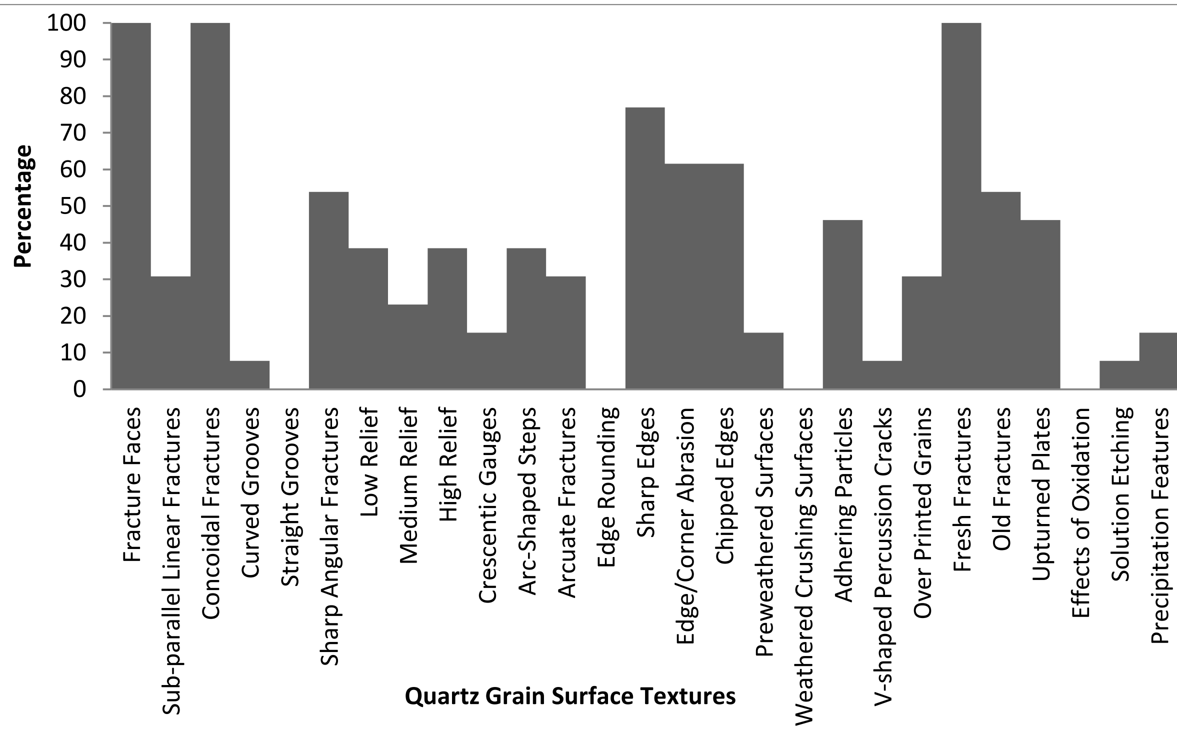


Fig.80. SEM analysis of Surface tectures,
Sample Site: KG 2

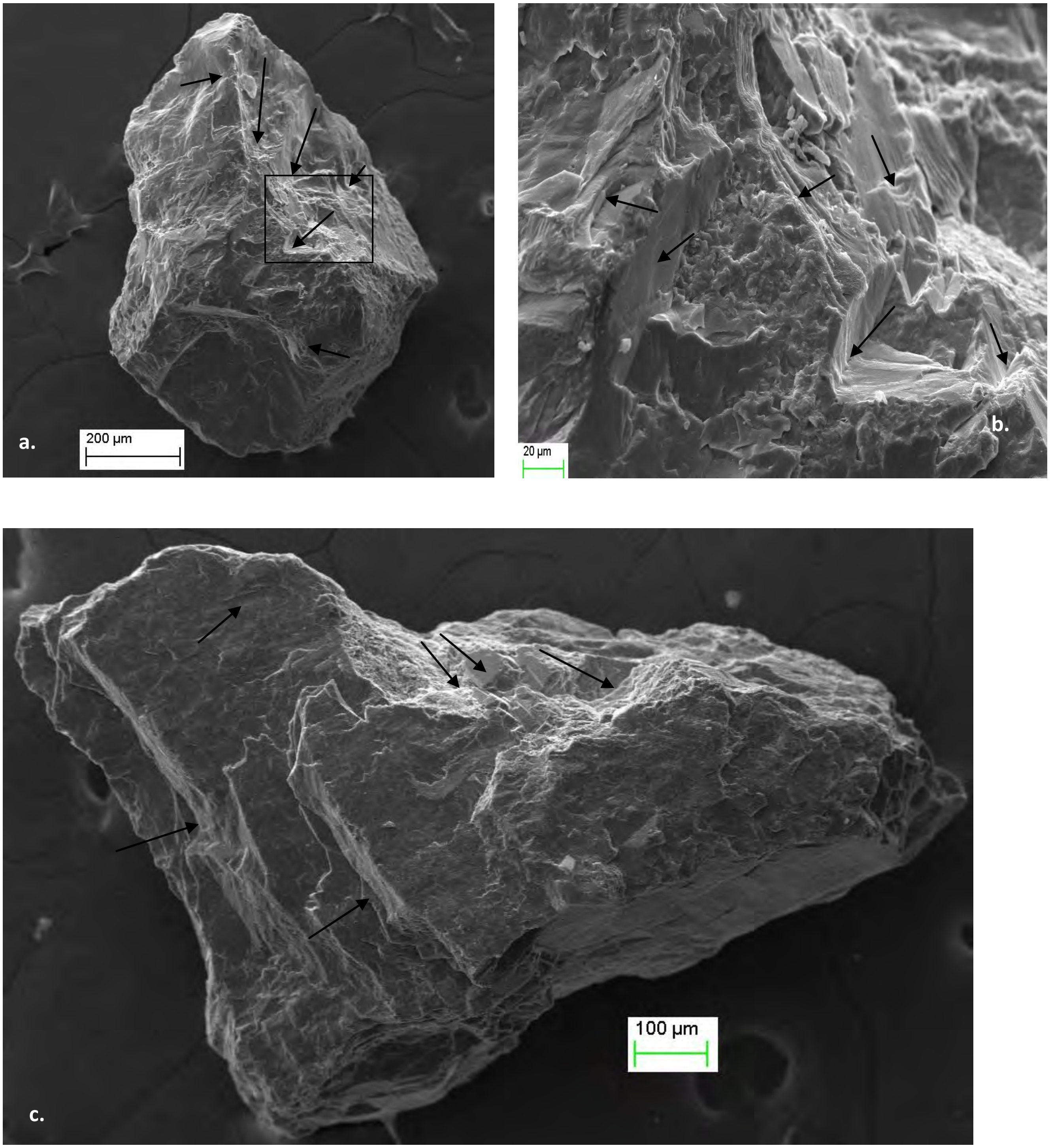


Plate: 74 SEM analysis of the sand grains from the drumlin KG2/DPF of the sample site 1. (a) Extensively crushed quartz grains with concoidal textures and groove like scours. Most of the fractures are fresh and exhibits fracture faces. (b) The enlarged part of the plate 74a. This is clearly showing the fresh fractures faces and groove like scours, extensive mechanical crushing, concoidal fractures, crescentic gauges etc. (c) Similar fresh fractures with medium relief. Mechanically formed fracture faces are clearly identifiable. Concoidal fractures are also common. The grain also believed to be undergone extensive glacial crushing. (d) Irregular surface textures with curved groove, concoidal textures, upturned plates etc. The grain may have experienced abrasion. (e) Mechanically formed fresh fracture face, concoidal textures and angular fractures and sharp edges.

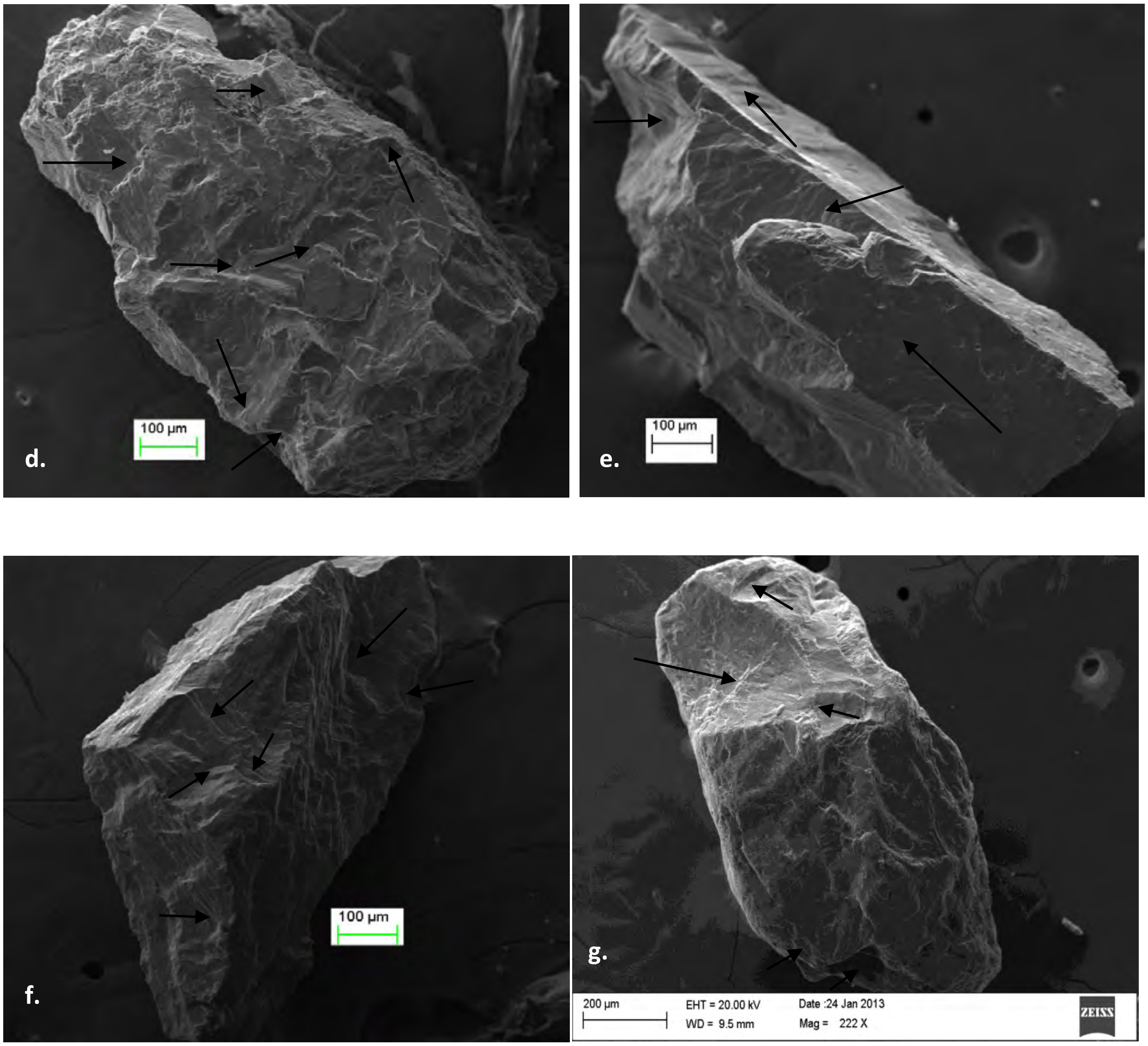


Plate: 74 (f) Well developed glacial signatures are observable. Striking grooves, concoidal fractures, chipped edges etc. are clearly visible on the grain surface. (g) High degree of edge abrasion has experienced by this sand grain. Older fracture faces, concoidal fractures, angular fractures etc. are still preserved in the sample grain. Hence mostly are extensively grinded sand grains which are believed to be locally in origin because edge abrasion is not present, whereas there are other grains which have experienced edge abrasion of high degree and believed to be transported long distances and/or are the reworked grains.

These evidences suggest that while one set of sand grains are relatively older in origin and possibly reincorporated in the subglacial regime and/or have very long transport distances, the other set is possibly supraglacially derived but most of them are locally originate. They lack weathered evidences and are characterized by high degree of mechanical fracturing and crushing. It means they soon incorporated under basal-ice in the submarginal subenvironment. However, some of the grains also possess groove like structures (Plate: 74.a, d, & f) which further support that they are subglacially developed and are not morainic deposits.

The sample site KUN/07/50 is collected from the Upper Spiti valley (Site 3) near Kunzum La (Fig. 85), which is very much distant from the KG1/DPF and others. Distance possibly has some key influence on the surface textures of quartz sand grains. Since, the sample is collected from the drumlinized mounds, it is important to have subglacial textural signatures on the sand grain surfaces, which possibly prove or disprove that these are subglacially formed or at least override by the glacier ice to have drumlinizing effect at the submarginal position.

However, dominant quartz grains indicate very high fresh fracture faces (Plate: 75.a) and concoidal fractures (Plate: 75.d), low relief (Plate: 75.c), and adhering particles (Plate: 75.c & f). Similar to KG2/DPF sample, edge and corner abrasion (Plate: 75.f) predominate. Moderately developed textures includes curved grooves (Plate: 75.c), medium relief (Plate: 75.f), chipped edges and upturned plates (Plate: 75.c), preweathered surfaces and precipitation features (Plate: 75.e) etc. (Fig.81). These textural signatures are indicative of the fact that the sand grains may have covered long distances to produce sufficient edge abrasion and/or couple with preweathered surfaces and precipitation features it also can be possible that they are reworked and transported by wind (Plate: 75.b) (given the size is finer sands) or simply incorporated in the basal ice zone during overriding of the glacier-ice (Plate: 75.e). However, straight grooves, crescentic gauges , arc-shaped steps and arcuate fractures (Plate: 75.e), edge rounding, weathered crushing surfaces, overprinted grains, solution etching etc. (Fig.81) are also found among the sand gains of the sample but very insignificant in proportion. Edge rounding of the grains is possibly due to aeolian activities (Plate: 75.b) because v-shaped percussion cracks etc. which are diagnostic to fluvial activities are not present. Similarly the grains having solution etching and precipitation textures may also experience later stage of subglacial crushing (Plate: 75.e); at least the presence of grooves support that idea. No sign of subglacial linear fractures, high relief, old fractures and oxidizing textures are identified so far among the samples grains (Fig.81).

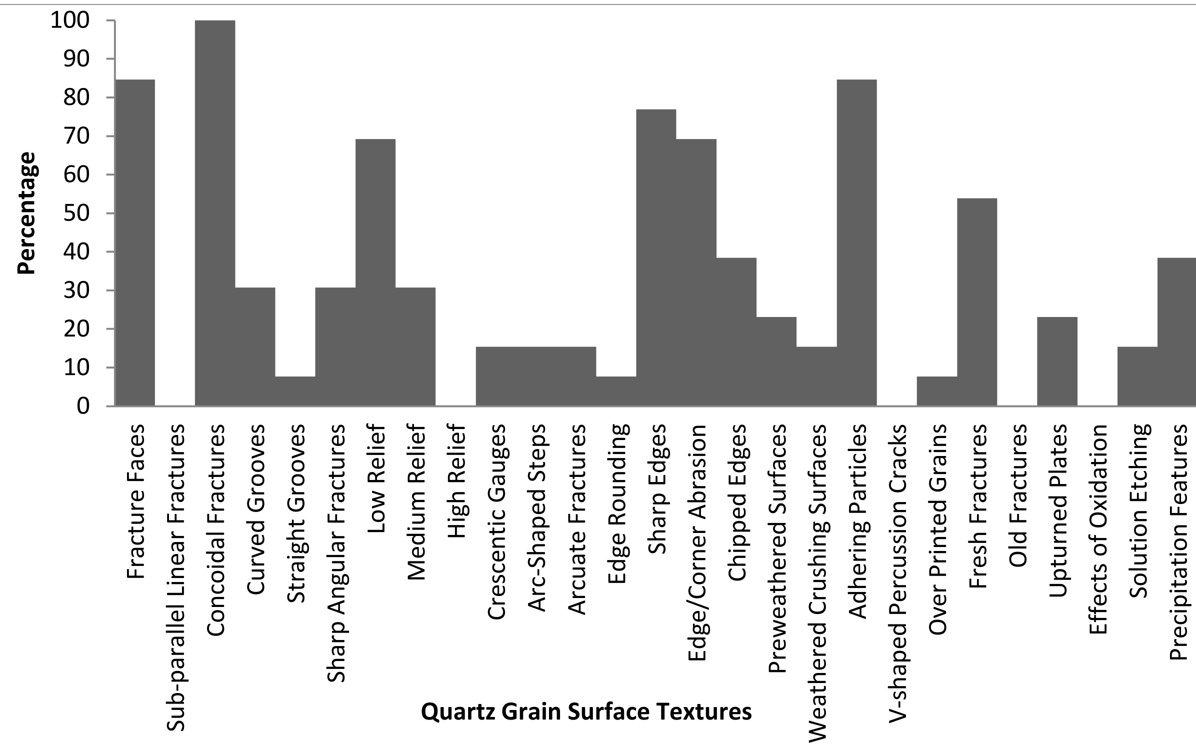


Fig. 81. SEM analysis of surface textures,
Sample Site: KUN

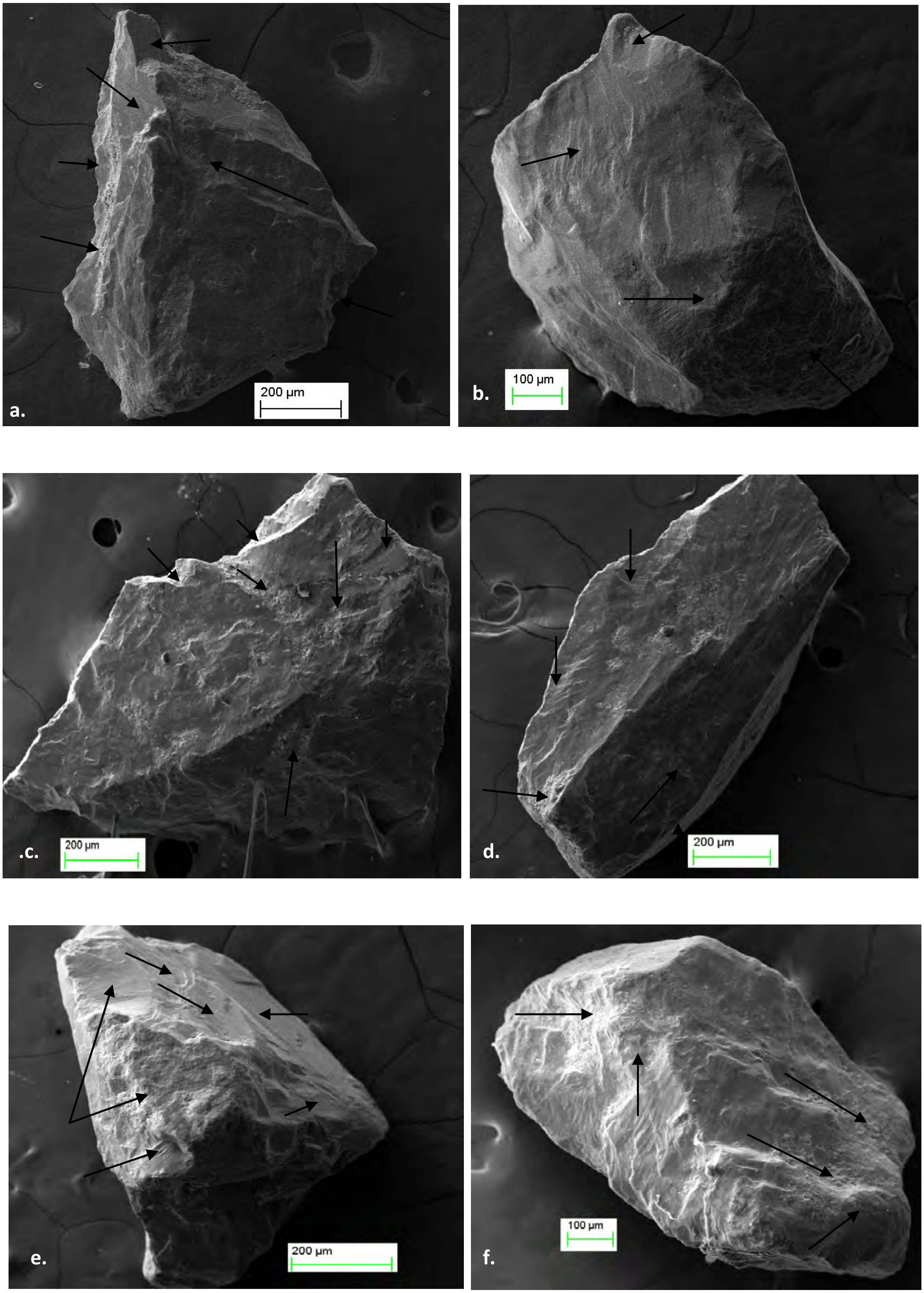

a.
200 µm
b.
100 µm
.c.
200 µm
d.
200 µm
e.
200 µm
f.
100 µm

Plate: 75 The surface textural analysis of the quartz sand grains under SEM of the sample drumlin KUN/07/50. (a) The grain has sharp angular fracture faces and fresh fractures, sharp edges and chipped edge, concoidal fractures, upturned plates, adhering particles etc.(b) The surface textures supports that the grain is aeolian in origin with later incorporation under glacial regime. Concoidal fractures are only developed; in the middle and top of the photograph. The bottom part may suggest precipitation features. The edges are smooth and near rounded. (c) Extensive grain crushing under subglacial condition is the characteristics of the grain. Angular fractures, and sharp edges, concoidal textures, irregular and curved grooves, adhering particles, upturned plates, and chipped edges etc. are the major characteristics of the grain. (d) Mechanically formed fracture faces, concoidal fractures, abraded edges are mainly visible at the surface at this scale. (e) The grain shows over printed textures; the older surface with precipitation (weathering) features at the middle higher part, and fresh mechanically (glacially) formed fracture faces at the top and right side of the grain. Concoidal fractures, crescentic gauges and arcuate fractures are identified. (f) The grain shows extensive edge abrasion with visible concoidal textures, grooves, adhering particles etc. this indicate that this is glacially formed but undergone long transport distances and/or reworked grain. However, over all the drumlin includes mostly reworked materials (especially at the ice marginal zone), although solely glacially formed grain textures are also present in the sample; hence they believed to incorporate both subglacial and ice-marginal material during drumlin formation.

Hence from the overall SEM analysis of quartz sand grains at the micro scale, it can be firmly confirmed that these streamlined landforms are subglacial in origin and possess a number of evidences of subglacial crushing, grinding, plucking and most importantly edge and corner abrasion (Annexure 2). Fresh fracture faces along with concoidal fractures are most predominant among the sample with more than 92 percent to 98 percent sand grains posses these surface textures respectively. Sharp edges (85%)[1] are equally found dominant along with low relief of the grains (65%). These textures are the main diagnostic signatures of glacial origin. Adhering particles are extensively found (75%) which often cover the surface of the grains rendering identification of other surface textures difficult. The presence of very high degree of adhering particles means that extensive subglacial crushing and grinding (along with other evidences) predominates. Apart from these, moderately found textures are sharp angular fractures (44%), chipped edges (48%) and upturned plates (44%). These are especially the characteristic of subglacial plucking. Edge and corner abrasion (58%) of some of the grains indicates either the

[1] These percentage values are calculated from the total number of grains studied so far of all the samples i.e. KG1/DPF. DPF2, KG2/DPF, and KUN/07/50.

long distance of travel, especially those identified from KG2/DPF and KUN/07/50 samples, or the reincorporation of previously glacially formed grains when couple with old fractures (31%) and over printed signatures (23%) i.e. reworking. Low frequency textural signatures among the samples are subparallel linear fractures (12%), curved grooves (21%), crescentic gauges (13%), arc-shaped steps (25%), and arcuate fractures (25%)—typical to glacially modified grains; and preweathered surfaces (19%), solution etching (9%), and precipitation features (21%). On the other hand, straight grooves, weathered crushing surface, v-shaped percussion cracks etc. are very insignificant (not more than 8 percent) to account for. No oxidizing signatures are identified so far. These evidences clearly pointed out that majority of the grains are mostly subglacially formed with reworking and reincorporation took place for others. These are possibly submarginally derived materials and later on incorporated under the basal ice zone to finally form the drumlin streamlined forms. These micro evidences thus, further supported that the Chandra Tal drumlins are subglacially to submarginally formed. Effects of other geomorphic agents are absent to very insignificant, except a few of the reworked aeolian grains.

6.2.2.4. Clast Macro Fabric Analysis:

Clast fabric analysis is considered as one of the most robust and effective techniques of studying the principle flow direction in geologic deposits. Since drumlins are formed under the glacial-ice i.e. the fluid medium, clast fabrics thus are used extensively in literature to identify the principle flow direction of ice along with consideration of the long axes of the drumlins. Hence fabric analysis not only corroborates the flow direction along with longitudinal orientation of the drumlins, they are also diagnostic signatures to identify drumlins and help immensely to understand the genesis and evolution of drumlins under subglacial condition as well. Although it has been suggested that putting too much emphasis on the fabrics only as genetic signature, may be tricky since a lot of overlaps can be found (Bennett at al., 1999), but they are most effective when they are used in combination with other evidences. Details of the fabrics and their significance in drumlin study have already been discussed in chapter 1 (see section 1.3.2.1) and they not elaborated here again. However, it needs to note here that in the present study only the macro scale analysis of clast fabrics are undertaken due to following two major reasons. Firstly, the drumlins in the study area are apparently found as massive and homogeneous, and clasts are found to have certain distributional pattern, and secondly, this preliminary study intends to gather evidences to either prove or disprove that these hillocks are drumlins or simple hummocks or morainic deposits, respectively. However, a numbers of samples sites have been chosen for the macro fabric analysis in site 1, site 2 and site 3. Both small boulders lodged at the surface and clasts with size (a-axes) range between 4cm. and 14 cm. at more than 15 cm. depth are measured to determine the dip and trend (fabrics) of them from the selected drumlins. Sample sizes vary from 25 clasts to 50 clasts at places. However, the clast macro fabric results mostly indicate parallel to transverse trends of the clasts when compared to the long-axes (a-axes) of the drumlins. This kind of pattern is expected from any medium which has experienced flow under fluid condition. Since previously it has been shown that deformation was possibly the major mechanism of ice-flow in this region (see section 6.2.1.2) during extensive valley glaciation, such flow pattern is expected. These results thus, further improve our understanding of subglacial dynamics in the study region in particular and the Himalayas in general. They can be discussed as follows.

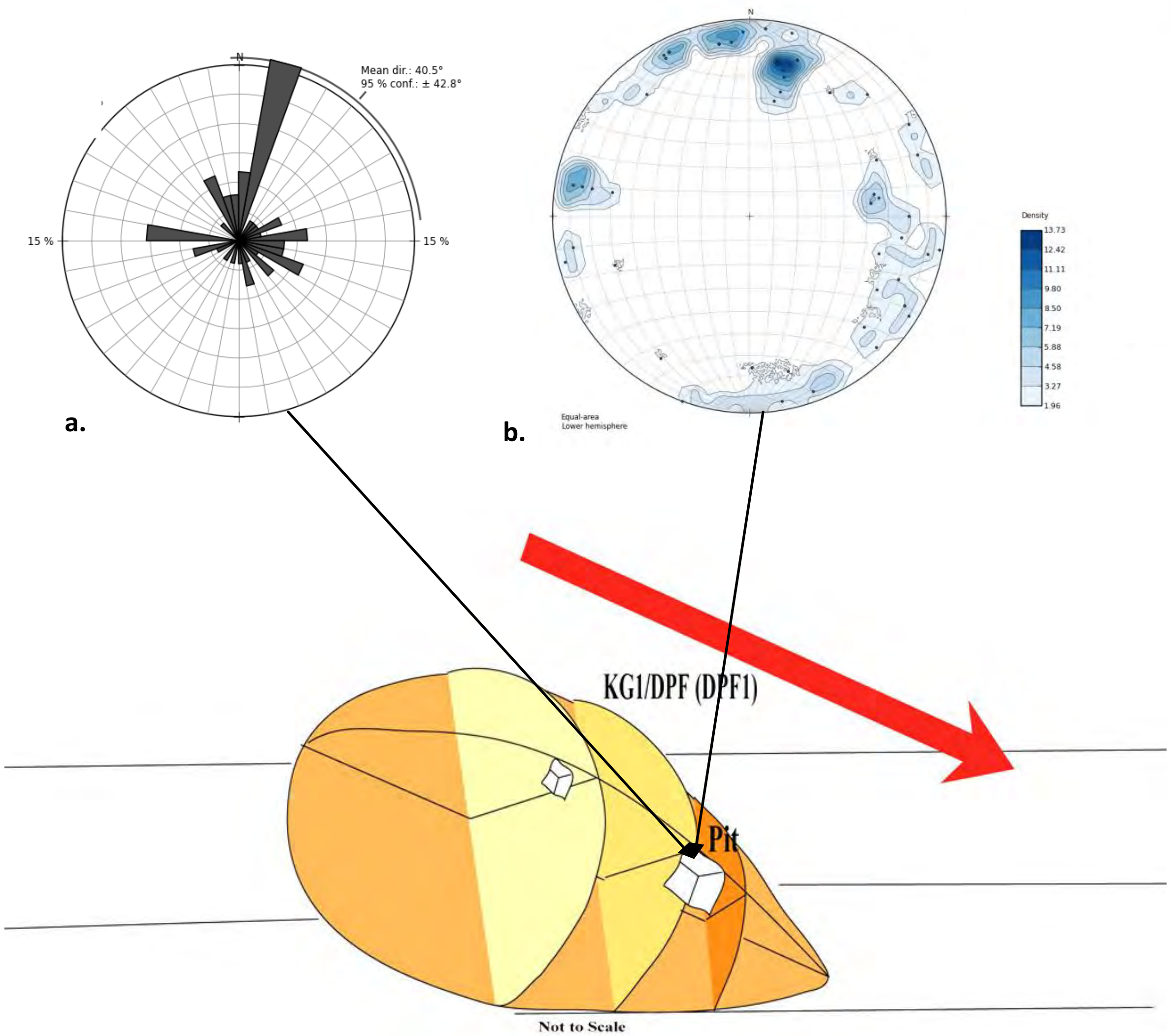


Fig. 82 The fabric distribution of the clasts measured form the surface of the drumlin KG1/DPF. (a) The rose diagram (2D) showing the trend of the longitudinal axes of the clasts, which is parallel and transverse to the long axis of the drumlin. (b) The lower hemisphere stereonet diagram (3D) also incorporates the dip distribution (contours) which is mostly low. The 3D figure of the drumlin at the bottom displays the location of the sample.

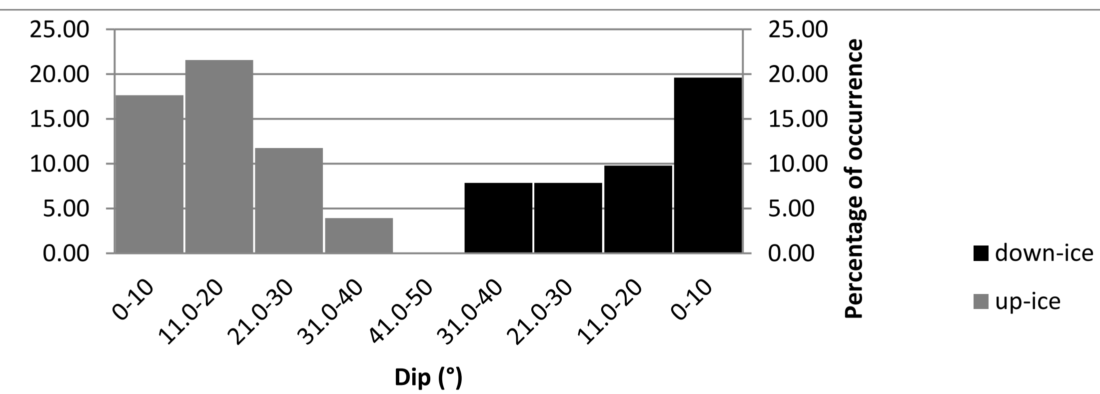


Fig. 83. Dip amount at sample site KG1/DPF

The clast macro fabric analysis at the sample site KG1/DPF (Fig. 85) in the Chandra Tal area (site1) indicates that clasts have general trend parallel and transverse to the long-axes of the drumlins i.e. the flow direction (Fig.82.a). The both up and down dip are common (Fig.82.b). The general direction of the long-axes of the drumlin is 120° from the north. One-half the clasts are found parallel to the mean orientation of the drumlin's long axes, which is 135° from the north (Fig. 51), and one-half are found transverse to the mean orientation. Very low dip is the characteristics of the drumlin (Fig. 83), typical to the deformation and lodgement processes. The S_1 and S_3 eigen values for the fabric measurement are 0.49 and 0.084 (Table: 6), further confirming their deformational origin. Expected distribution (Fig. 97) of the clast fabric is girdle.

At the same drumlin site (KG1/DPF or DPF1) another fabric analysis is undertaken with the aim of deciphering the wave like flow pattern as discussed in the section 6.2.1.2. (Plate: 65; Fig. 68).

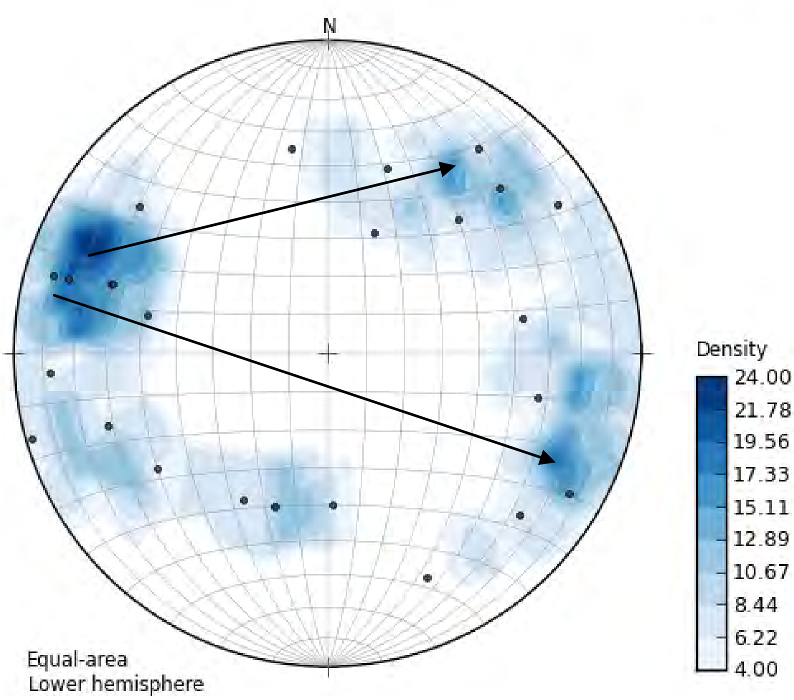


Fig. 84 The lower hemisphere stereonet diagram (3D) indicates the two possible trends of the long axes of the clasts and their dip distribution (contours) of the sample drumlin DPF 1 (or KG1/DPF). The two population of clast fabric are from left to right-up and left to right-down.

However, the fabric pattern does shows the similar wave like clast orientation pattern from bottom left to top right and also from top left to bottom right (showing by the arrows in Fig. 84), which, thus, further support the ductile deformation of the section at the 60 cm. depth form the surface of the drumlin. It certainly depicts the general picture shown in the Fig. 68. (or Plate: 65). The clasts are also having low to relatively high dip.

In the front of the drumlin KG1/DPF (or DPF1) in the site 1, an interdrumlin depression (IDPF1) is also chosen for the macro fabric study (Fig. 85 and 86). This section, however, indicates more strong and consistent fabric trend (Fig. 87.a) with 68 percent is oriented parallel to the direction of the drumlin and 32 percent is exactly transverse to the flow with mostly down dip (Fig. 87.b). Of these oriented clasts 38 percent of the total is oriented within 20° of each side of the mean drumlin orientation (i.e. 135°). The majority of the dip distribution is concentrated within 20° from the horizontal (Fig. 88). That is low dip is also predominant in the interdrumlin depression. May be relatively higher stress at the interdrumlin depression compared to the surface of the drumlin, where possibly ice deflection may takes place[2], is responsible for such consistent fabric orientation with S_1 and S_3 eigen values are 0.573 and 0.112, respectively (Table: 6). The clast fabric is expected to have girdle distribution.

[2] Since the drumlin KG1/DPF is a small drumlin and the effect of ice deflection may be quite low, but the possibility cannot be ruled out.

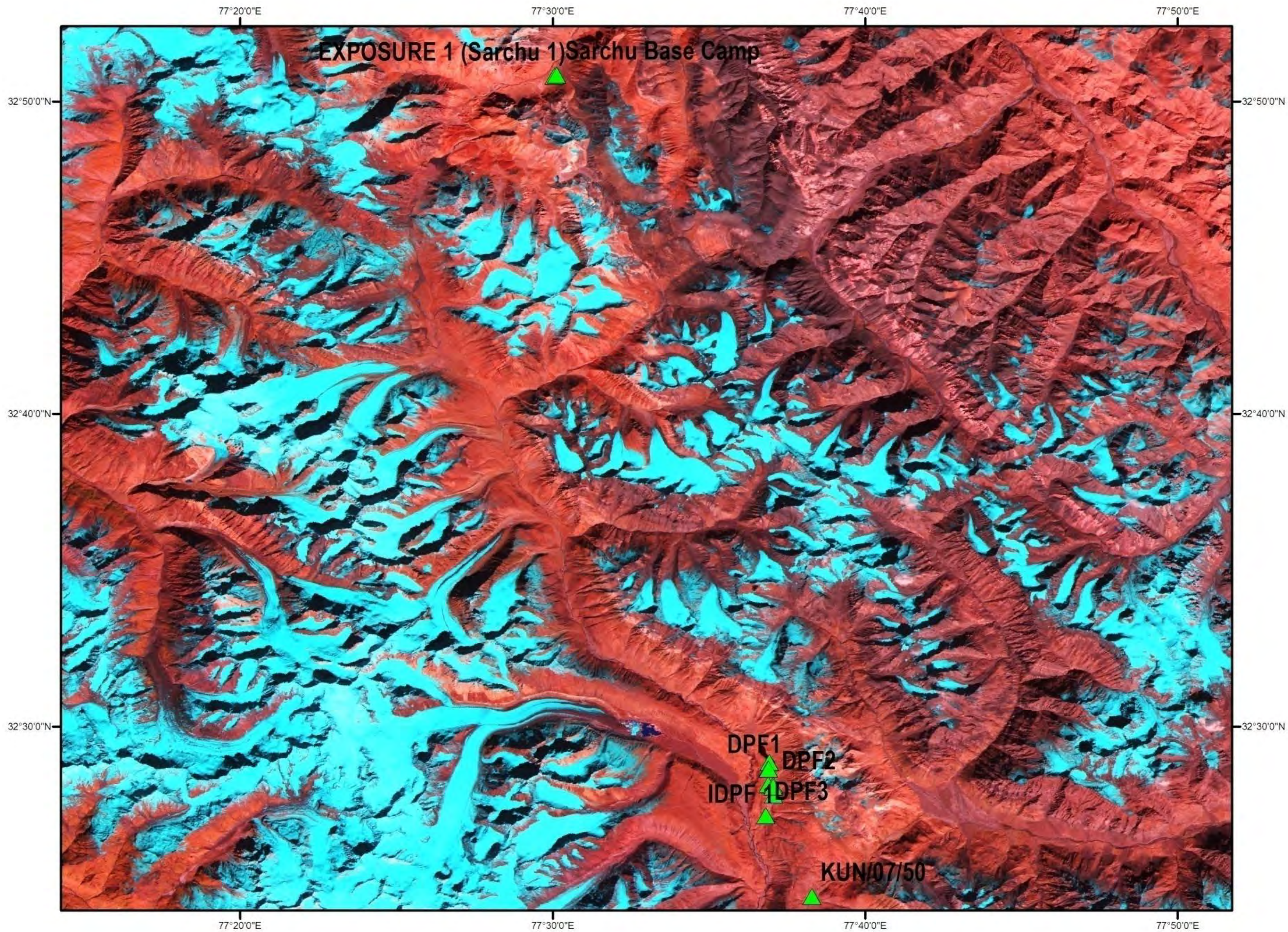


Fig. 85 Map showing the location of the samples collected form the surface of the drumlins at the site 1, 2, and 3. Sample locations are shown by the triangles.

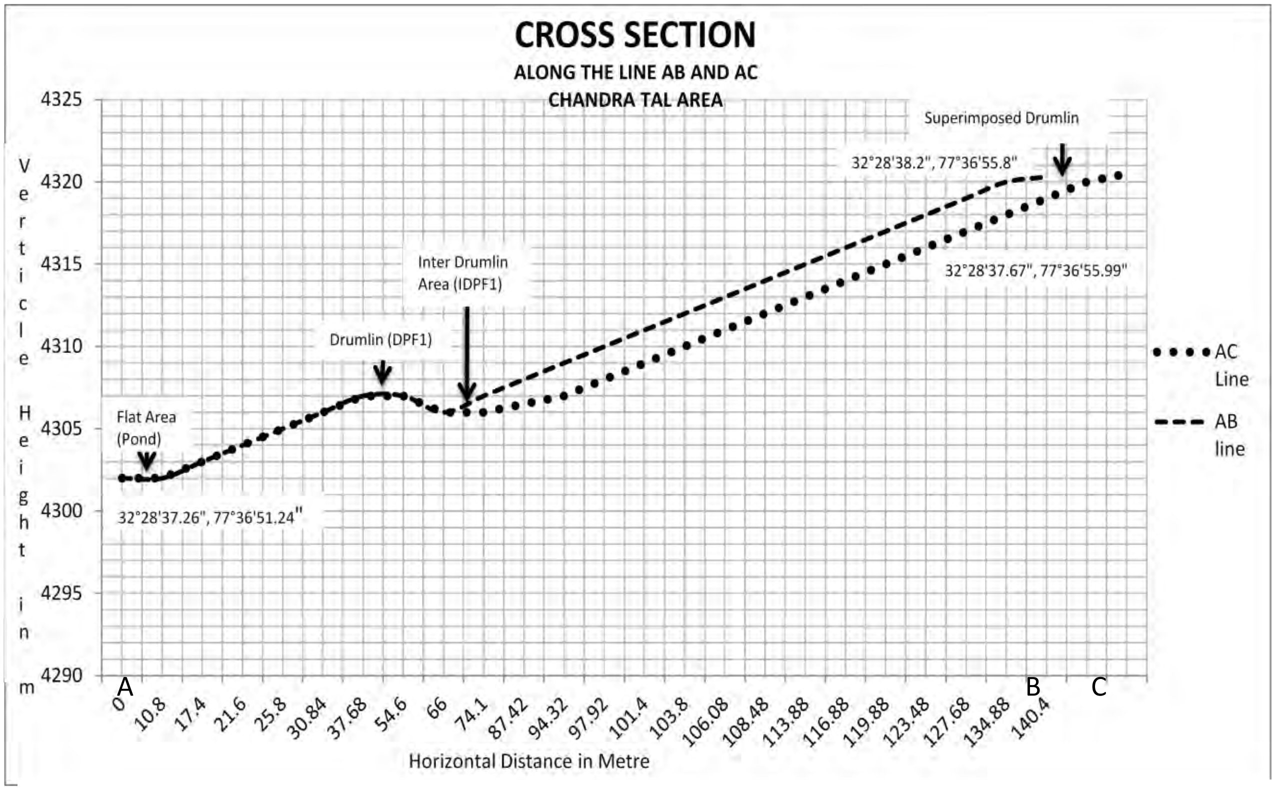


Fig. 86 Cross section along the line AB and AC. This is showing the relative position of the sample IDPF1 in the Chandra Tal area. The cross section is drawn based on the GCPs recorded during field survey.

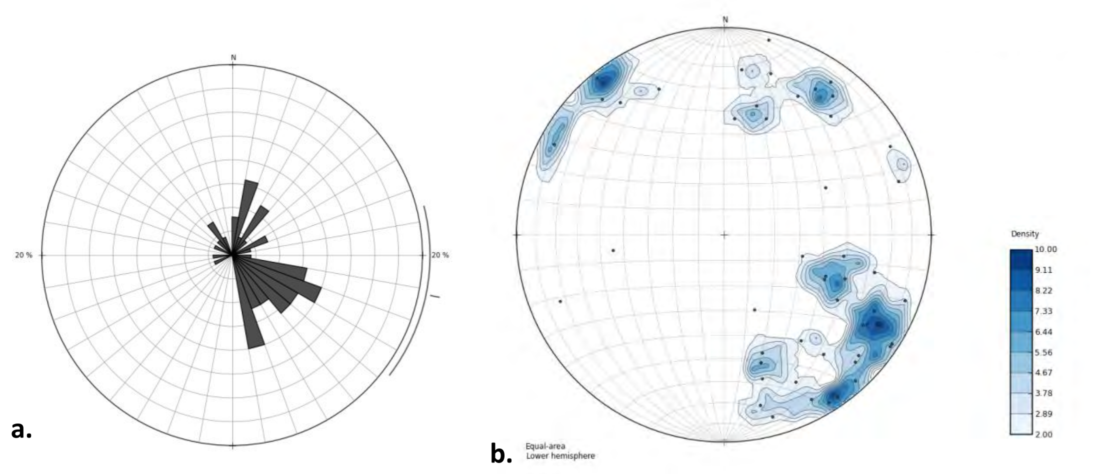


Fig. 87The fabric distribution of the clasts measured form the surface of the drumlin IDPF1. (a) The rose diagram (2D) showing the trend of the longitudinal axes of the clasts, which is mostly parallel to the general long axis of the drumlins in the site 1. (b) The lower hemisphere stereonet diagram (3D) also incorporates the dip distribution (contours) which is mostly low with few towards higher dipping.

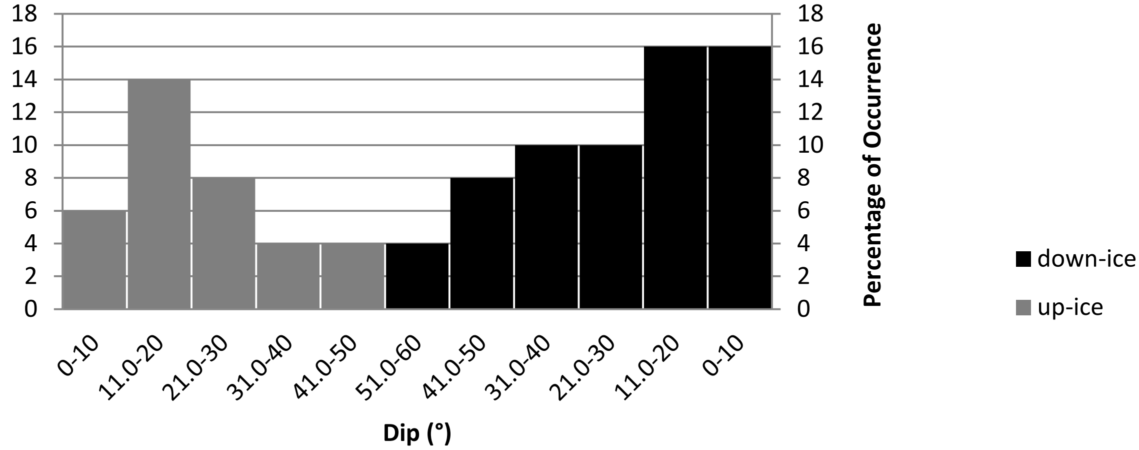


Fig. 88. Dip amount at the sample site IDPF1

Another drumlin in the Chandra Tal area is selected for clast macro fabric analysis, located in the same low ridge area on which most of the drumlins are mapped. This sample site is coded as DPF2 (Fig. 85). The long-axis orientation of the drumlin is 130° from the north. The fabric is also found to be highly consistent with 84 percent of the clasts are having parallel to drumlin axis trend (Fig. 89.a). Out of the total 56 percent is concentrated with 20° of each side of the mean drumlin orientation in the region. Clasts are mostly having up-ice dip, although down-ice dipping is equally common (Fig. 89.b). The amount of dip distribution, however, indicate that while the down-ice dipping clasts have low inclination (dip) the up-ice dipping clasts have low to very high dip i.e. up to 50° from the horizontal (Fig. 90). S_1 eigen value (0.628) is also relatively very high in this drumlin; although S_3 eigen value (0.164) is also slightly higher compared to KG1/DPF and IDPF1—fall well with the limit of deformation till (Table: 6). The expected distribution (Fig. 97) of the clast fabric is clustered.

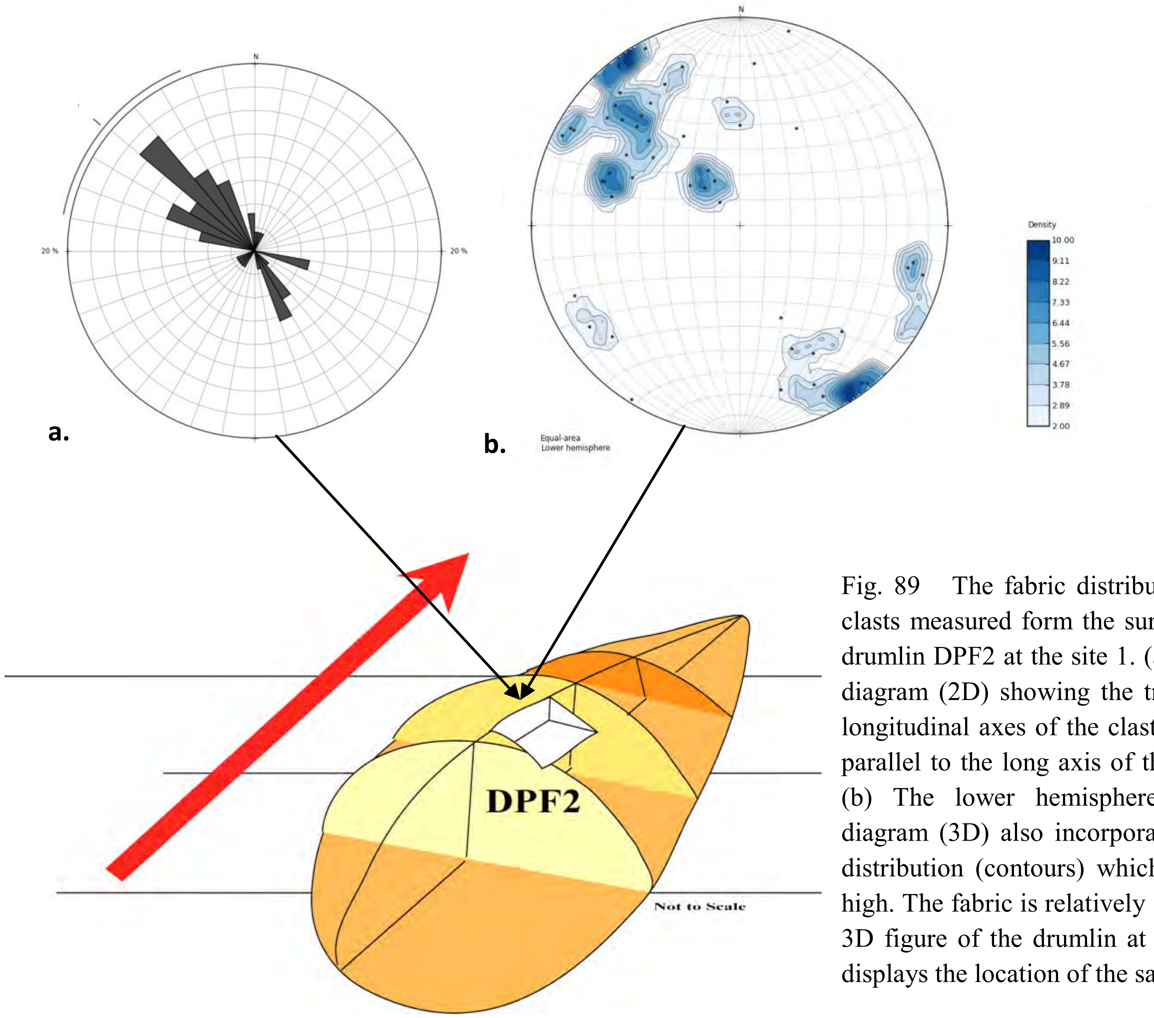


Fig. 89 The fabric distribution of the clasts measured form the surface of the drumlin DPF2 at the site 1. (a) The rose diagram (2D) showing the trend of the longitudinal axes of the clasts, which is parallel to the long axis of the drumlin. (b) The lower hemisphere stereonet diagram (3D) also incorporates the dip distribution (contours) which is low to high. The fabric is relatively strong. The 3D figure of the drumlin at the bottom displays the location of the sample.

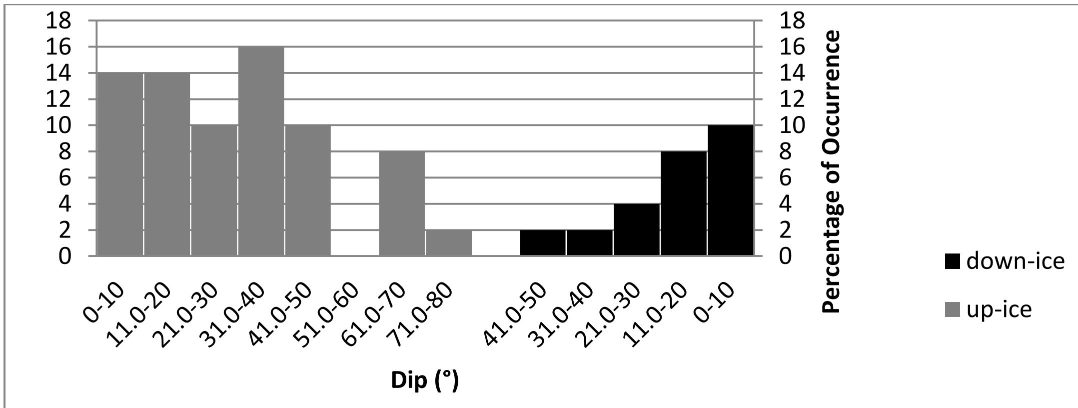


Fig. 90. Dip amount at the sample site DPF2

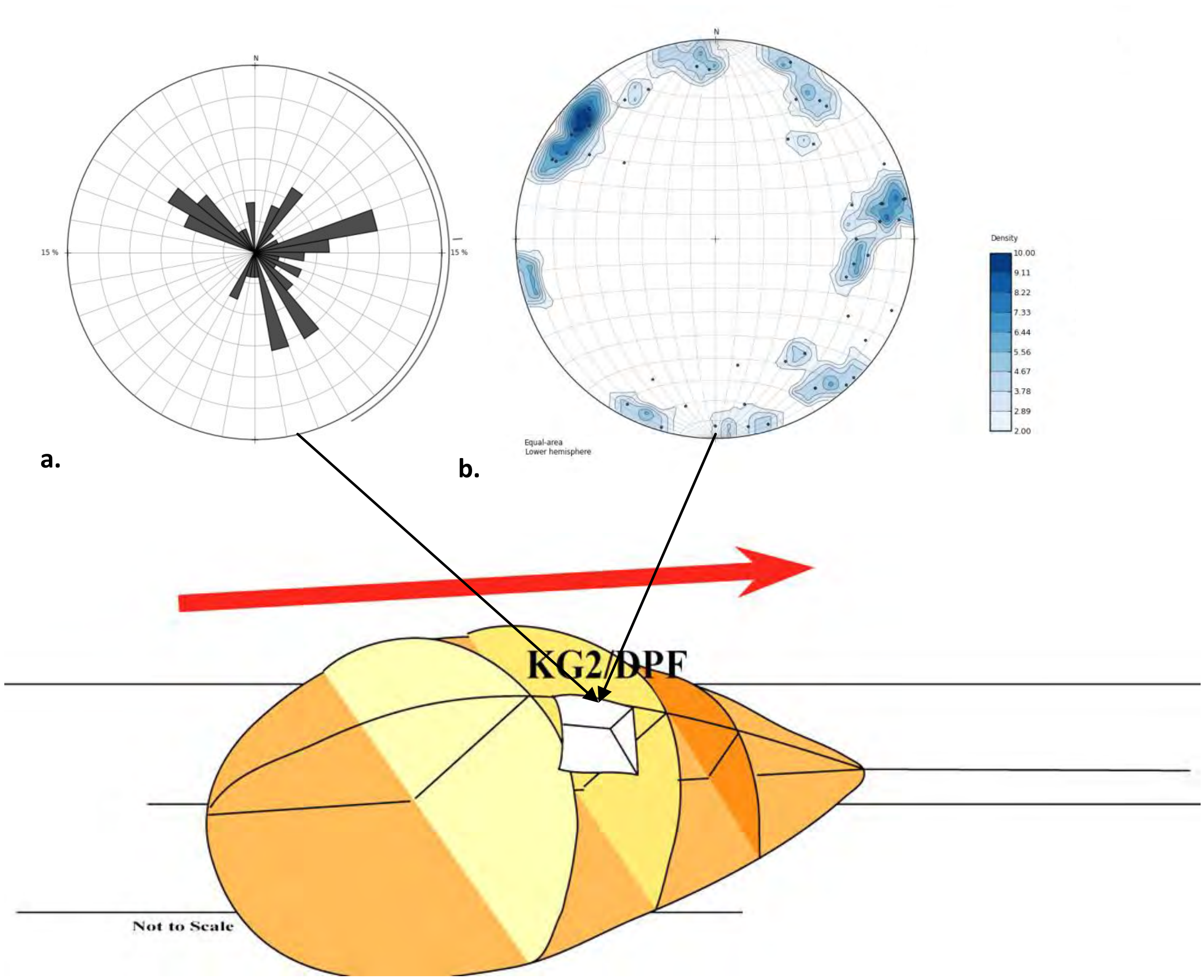


Fig. 91 The fabric distribution of the clasts measured form the surface of the drumlin KG2/DPF at the site 1. (a) The rose diagram (2D) showing the trend of the longitudinal axes of the clasts, which is parallel in the up-ice direction and oblique in two sets in the down-ice direction to the long axis of the drumlin; in general near parallel trend. (b) The lower hemisphere stereonet diagram (3D) also incorporates the dip distribution (contours) which is mainly low. The fabric is relatively weak. The 3D figure of the drumlin at the bottom displays the location of the sample.

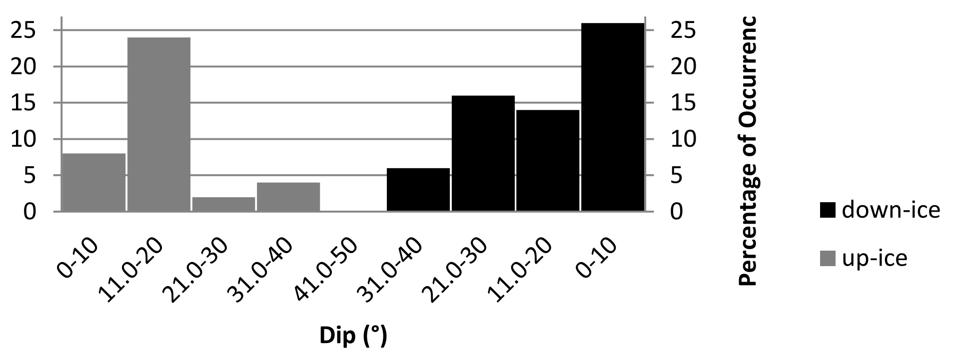


Fig.92. Dip amount at sample site KG2/DPF

The sample drumlin KG2/DPF (Fig. 85) in the Chandra Tal area, as discussed previously, is situated on the western flank of the Kunzum range with heavy post glacial debris cover deposits, surrounding the drumlin. The morphology is classical (Cs) tear-drop shape with long axes orientation of 120°. The SEM surface texture analysis of quartz sand grains in the previous section, also supports that this landform is composed subglacially crushed grains. Evidences of submarginal supraglacial grains are present in the deposit too. Here the clast macro fabric data is provided to indicate the principle flow pattern. However, it is found that fabric trend is near parallel to the long axis of the drumlin but down-ice fabric trend is rather oblique in two (down-ice) directions (Fig.91.a). This data is surprising since oblique pattern is not identified so significantly on the other drumlin surfaces in this area (site 1). Although the general pattern is southeasterly (Fig. 91.b) and sample is collected right from the top of the drumlin ridge high, such parallel to oblique pattern requires further fabric support before deriving any conclusion. The dip amount distribution is mostly concentrated between 0° and 30° (Fig. 92). However, the S_1 eigen value for the sample is 0.55 and S_3 eigen value is 0.088, and expected distribution (Fig. 97) is girdle (Table: 6). This is also fallen in the range of deformation till.

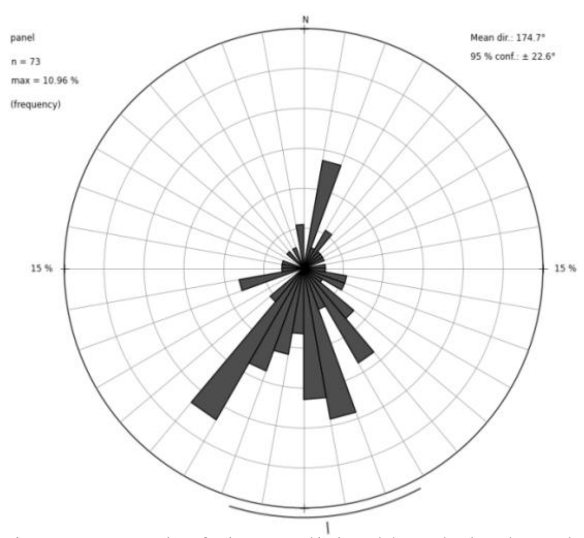
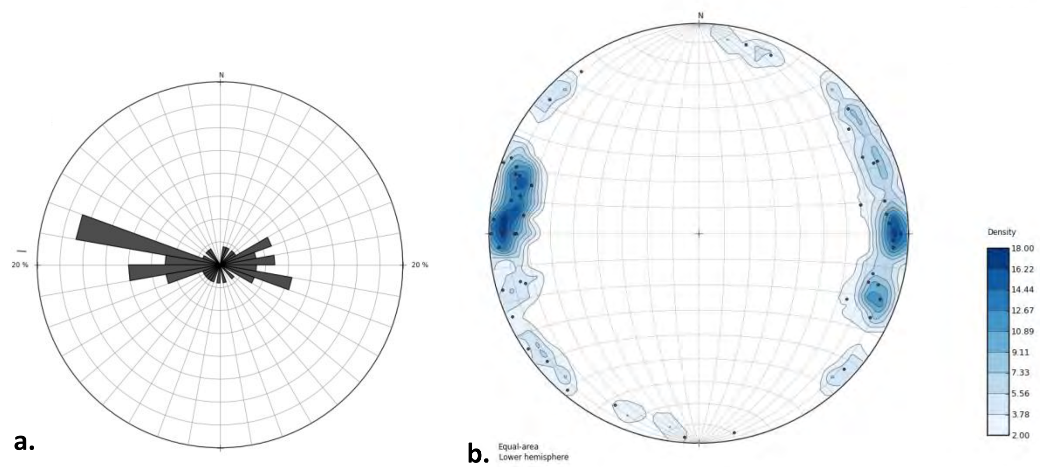


Fig. 93 Trend of the small boulders lodged at the surface of the drumlin DPF3 at the site 1. The trend is strongly north-south with mostly down-ice dip of the clasts. Dip although not measured.

Apart from the pebble size clasts near the surface of the drumlins, the typical lodged boulders at the surface of the drumlin are also measured for the trend analysis. The drumlin DPF3 (Fig. 85; Plate: 15 & 40) has chosen for such measurements, which is located further south of the low ridge on which most of the drumlins are mapped. The drumlin possesses smooth classical tear-drop shape with well concentration of lodged boulders. The longitudinal axis of the drumlin has a general orientation of 120° from the north. It is found that the lodged boulders posses a strong fabric which is not necessarily southeast but down the valley (southerly) (Fig. 93). Since the observation is recorded from the entire lee face of the drumlinDPF3, the down valley trending both right and left flank lodged boulders may be responsible for this kind of distribution. It is also possible that during the final stage of drumlin formation i.e. before deglaciation, glacier-ice of the valley attained parallel to valley course further south, unlike the southeasterly course during thick and extensive valley glaciation (Batal stage) in the region. Further, since the drumlin is large and also formed at the lee of a huge bedrock outcrop (Plate: 32), the deflection of the ice may also be possible leading to such trends of lodged boulders. The lodged boulders at the surface of the drumlins in the Chandra Tal area, however, possess a strong general trend, although not necessarily always the trend of the drumlins but near analogous to that. Study from more of the drumlins in site 1, will clear the general picture much better way.

However, the similar fabric analysis of the lodged boulders at the surfaces of drumlinzed mound KUN/07/50, at the Kumzum la area (site 3) in the upper Spiti valley (Fig. 85; Plate: 22), on the contrary, shows much better and strong fabric orientation (Fig. 94.a). The mini roche moutonee type lodged boulders (Plate: 51) typical to englacial and subglacial genesis, are thus mostly having very low dipping (Fig. 94.b). The general trend of the sample drumlinzed mound is 110° from the north, i.e. parallel to the orientation of the surface lodged boulders. The pebble fabric data from the same site at the depth of 15 cm. from the surface also yield the similar orientation picture (Fig. 95.a) with overwhelming down-ice dip direction (Fig. 95.b). Nearly 76 percent of the clasts (of the total) thus, constitute parallel to the drumlinzed mound's long axis orientation and 44 percent (of the total) is found well within the 20° of each side of the long-axis of the drumlinzed mound KUN/07/50. This thus further strengthen the hypothesis along with surface textural analysis of the quartz sand grains that these mounds are somehow over ridden by the ice coming from the Chandra Tal area and possibly drumlinization had taken place. More evidences



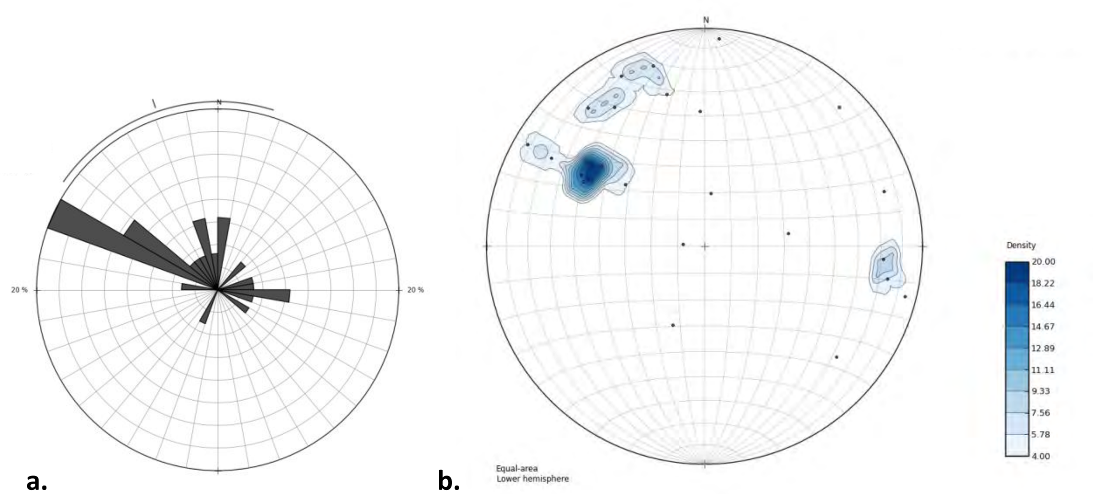


Fig. 94 The fabric distribution of the lodged boulders measured form the surface of the drumlin KUN/07/50 at the site 3. (a) The rose diagram (2D) showing the trend of the longitudinal axes of the clasts, which is strongly parallel to the long axis of the drumlin. (b) The lower hemisphere stereonet diagram (3D) also incorporates the dip distribution (contours) which is low. The fabric is relatively strong and consistent.

Fig. 95 The fabric distribution of the clasts measured form the surface of the drumlin KUN/07/50 at the site 3. (a) The rose diagram (2D) showing the trend of the longitudinal axes of the clasts, which is parallel to the long axis of the drumlin. (b) The lower hemisphere stereonet diagram (3D) also incorporates the dip distribution (contours) which is low to medium inclination. The fabric is relatively persistence in parallel orientation.

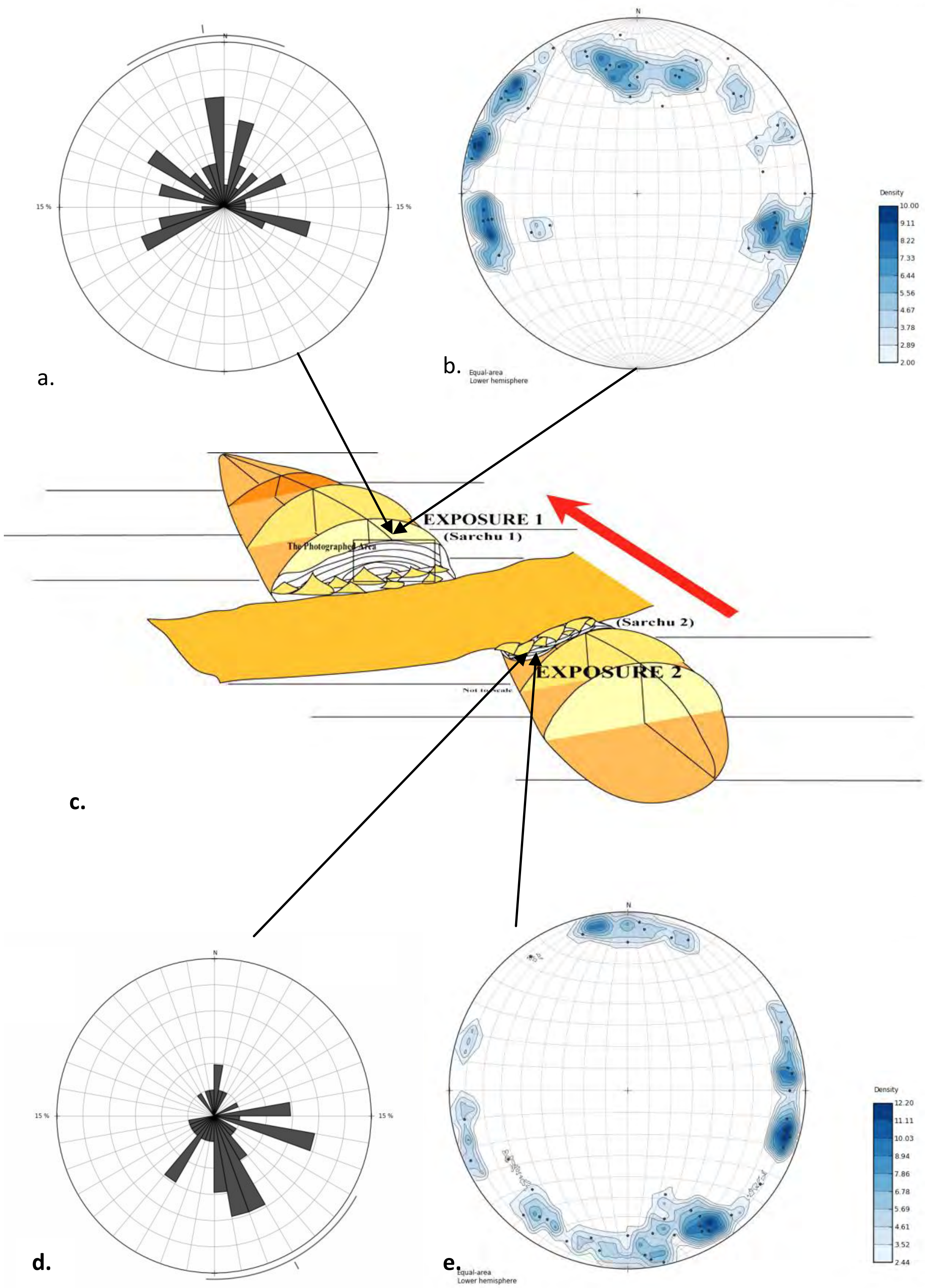


Fig. 96 The fabric distribution of the clasts measured form the internal sections of the drumlin Sarchu 1 (or Exposure 1) and Sarchu 2 (or Exposure 2) at the site 2. (a) The rose diagram (2D) showing the trend of the longitudinal axes of the clasts of the drumlin Sarchu 1 (or Exposure 1), which is diffuse in pattern; although parallel and transverse fabric, to the general long axis of the drumlins in the valley, is still can be roughly inferred. (b) The lower hemisphere stereonet diagram (3D) also incorporates the dip distribution (contours) which is inclined low to medium. The fabric is weak. (c) The 3D

figure of the drumlins displays the location of the samples.(d) The trend of the long axes of the clasts of the drumlin Sarchu2 (or Exposure 2) is transverse in patternto the general long axis of the drumlins in the valley but parallel to the post depositionally modified drumlin. (e) The lower hemisphere stereonet diagram (3D) also displays similar pattern with low dip distribution (contours).

of the internal composition of these drumlinzed mounds are required from this area (site 3) in order to have much better understanding of the limit of the distribution of the valley glaciers in the Lahul Himal during drumlin forming stage (Batal stage glacial advance). However, the S_1 and S_3 eigen values for this section are 0.596 and 0.143, respectively with expected distribution (Fig. 97) is mostly clustered (Table: 6).

Clast macro fabric analysis is also conducted in the Yunan valley area (site 2) from the two back to back drumlins i.e. *'Sarchu 1'* (from Exposure 1) and *'Sarchu 2'* (from Exposure 2) (Fig. 85), exposed due to road cuts along the stoss and lee face of them respectively (Fig. 96.c). However, the Sarchu1 drumlin has a general long axes orientation of 280° and Sarchu 2 has 330°, from the north (Fig. 72.a). The Sarchu1 clast macro fabric data, however, indicates very weak parallel and transverse trend compared to the long-axis of the drumlin (Fig. 96.a), with mostly diffused clast fabrics. The fabric data do not show clear concentrated of directions, but majorly they are parallel and transverse to the general flow direction of the ice[3] (Fig.96.b). Very low to relatively high dip characterizes the entire population (Fig. 96.b). The expected distribution (Fig. 97) of the clast fabric is mostly girdle. The S_1 and S_3 eigen values for this exposure are 0.51 and 0.078, respectively (Table: 6) i.e. within similar range to those studied at the Chandra Tal (site 1) and Kunzum La (site 2) area. Another clast macro fabric study at Sarchu2 (Exposure 2; Fig. 96.c), however, indicates more well distributed parallel (44 % of the

[3] General flow directions of the ice are inferred in the present study from distributional pattern of the long-axes of the drumlins in both the Lahul Himalaya, and Zanskar range (Fig. 58).

clasts) and transverse (56% of the clasts) trends of clasts to the mean northeast trend of the long axes of the drumlins (Fig.96.d & e) in the valley. The expected distribution (Fig. 97) of the fabric is girdle with S_1 eigen value is 0.59 and S_3 eigen value is 0.042 (Table: 6).

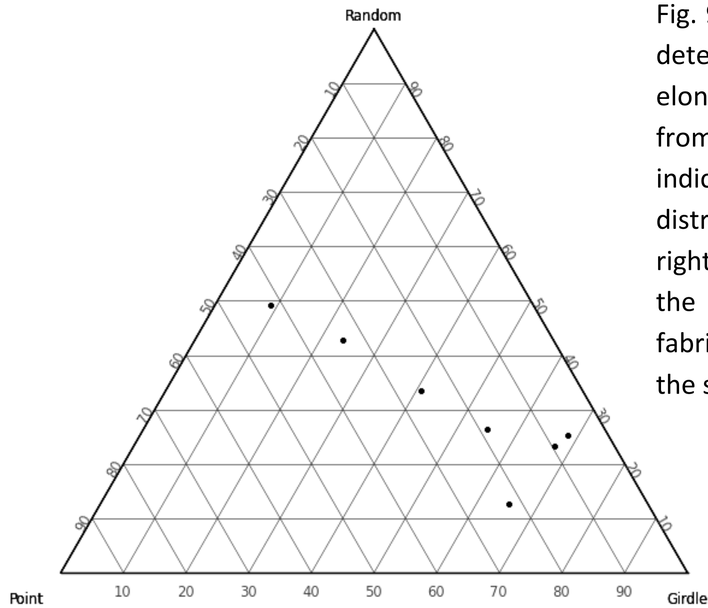


Fig. 97. Isotrophic Ternary diagram to determine the Isotrophy and elongation of all the fabrics measured from Site 1,2, & 3. The distribution indicates mostly Girdle to Random distribution i.e. high elongation at the right to medium isotrophy at the left of the diagram. This is due to the strong fabrics in some and weak in some of the samples.

Fig. 98 **TWO DIMENSIONAL BIVARIOGRAPH COMPAREING EIGENVALUES S1 AND S3**

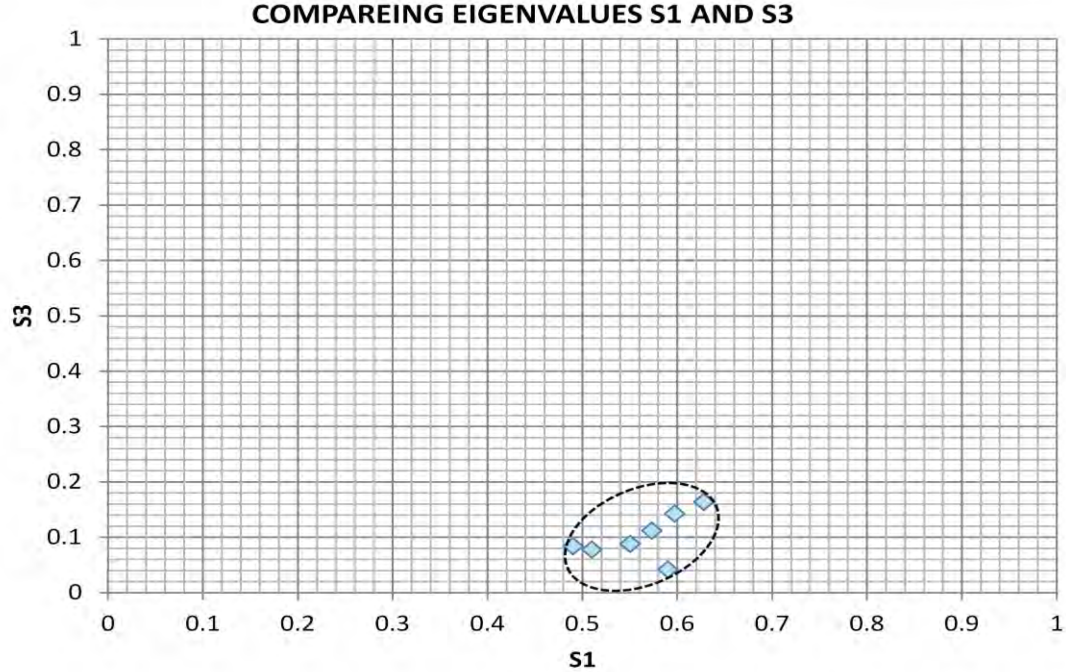


Table: 5 Showing the Fabric Eigen Vectors and Eigen Values for the Samples

Sample Code	**Number of Sample Clasts (N)**	**Expected Distribution**	**Eigen Vectors**			**Eigen Values**			**Mean Vector Direction**		**Imp. Direction**
			V_1	**V_2**	**V_3**	**S_1**	**S_2**	**S_3**			
KG1/DPF	51	Girdle	353.7	86	227.7	0.49	0.425	0.084	40.5	220.5	40.5
IDPF1	50	Girdle	135.4	36.1	254	0.573	0.315	0.112	101.5	281.5	102
DPF2	50	Cluster	316.3	178.6	53.7	0.628	0.208	0.164	309.2	129.2	129
KG2/DPF	50	Girdle	131.7	40.7	242.1	0.55	0.362	0.088	86.3	266.3	86.3
KUN/07/50	25	Cluster	313.7	72.1	201.9	0.597	0.261	0.143	341.2	161.2	161
Sarchu1	50	Girdle	283.1	14.3	188	0.51	0.413	0.078	353.2	173.2	173
Sarchu2	41	Girdle	169.6	2:24	336.1	0.59	0.368	0.042	151.1	331.1	151

Hence from the clast macro fabric analysis it is clear that the fabric data do provide the evidences of clear principle flow direction which are analogous to the long axes of the drumlinsand mostly parallel to transverse in character, except the Sarchu1 clast fabric data which have somehow diffusive fabric pattern although parallel and transverse orientation dominate (Fig. 96.b), and the (lodged) boulders orientation data at DPF3 (Fig. 93) in the Chandra Tal area (site1) which shows rather north-south flow direction and analogous to the present Chandra Valley at the upper reach. However, these fabrics results also indicates rather low to medium isotrophy and relatively high to medium elongation (Fig. 97). This proves that they do show directionality of the flowing medium. More number of fabric data is required to compare them with other studies to determine, although not full proof, but whether they do possess any diagnostic pattern or not. However, while comparing the general S_1 and S_3 eigen values of the samples through bivariate plotting (Fig. 98), they are found to be clustered in a position more close to lodgement deformation till as find in other literature (Dowdeswell and Sharp, 1986; Hicock, 1991). Thus fabric data not only support the principal ice-flow direction in the study area but also further strengthen the previous inferences made from the structural analysis. Deformation process, is, thus, the major subglacial process under the basal-ice in this region during Batal stage glacial advance.

However, the parallel and transverse orientations of the clast fabrics, measured on the surfaces of many of the sample drumlins, require explanation. In this context it is first assumed that the flow is a laminar viscous type. In such flow without particle interactions, a-axes initially align parallel to flow but eventually rotate transverse to it which represent the minimum energy required by the clasts to move with the flow. The transverse position also represents the least velocity gradient across the stone during flow (Hicock, 1990). This explanation may be describe more effectively through the following equation which determines the Torque (*M*) on a rotating ellipsoid in a viscous fluid (Rusnak, 1957) , i.e.

$$M = — \pi \rho (a2 - b2) u2 \sin\beta \cos\beta \text{ ....19.}$$

Where, *a* is the stone's a-axis, *b* is the b-axis, *ρ* is the fluid density, *u* is the flow velocity, and *β* is the angle between flow direction and stone a-axis. According to this equation two stable positions into the flow are *end-on* or *parallel* i.e. when $\beta = 0°$; $\sin\beta = 0$, and broad-

side or *transverse* i.e. $\beta = 90°$; $\cos\beta = 0$ (Rusnak, 1957; Hicock, 1990). However, any perturbation in the flow could cause the end to flip so that the end-on or parallel position is a kind of meta-stable compared to the broad-side or transverse flow position of the clast, which is truly stable. This kind of clast rotation is also observed in the present study while the section is prepared for the clast fabric measurement in the interdrumlin depression (IDPF1) (Fig. 99). The parallel type of clast rotation is mentioned as ***Jeffrey rotation*** and transverse rotation as ***Taylor rotation*** by Carr and Rose (2003). The rotation within deformation till is also found in the pit section of KG1/DPF (DPF1) drumlin (Fig.68 & 69) where galaxy type clast rotation occurs. Clast rotation is also observed in the road-cut exposure (Exposure1) in the Yunan Valley area (Plate: 67). Hence both parallel and log type transverse rolling of the clast is the major characteristics to determine the clast fabric in the study area. In the literature many factors are discussed which can be account for the parallel and transverse orientation of the fabric. These are: a) compressional flow of ice may account for the parallel orientation of the fabric, whereas extending flow of ice may cause transverse orientation as dominant fabric in the sample, b) given the sufficient time and distance clasts are tend to orient transverse rather than parallel, c) in supersaturated till with extensive clast composition, clast collision may favour parallel orientation of the clasts and in the clast free till, transverse orientation is most predominant etrc. (Hicock, 1990; Stanford and Mickelson, 1985; Rusnak, 1957). However, while the present study confirmed that clast rolling is predominate under the subglacial deforming-till in the study region and both parallel and transverse orientation of clasts is common, more systematic study of clast fabrics is required to account for any of the reasons mentioned above for such fabric pattern and to determine the overall past glaciological condition during the formation of the drumlins.

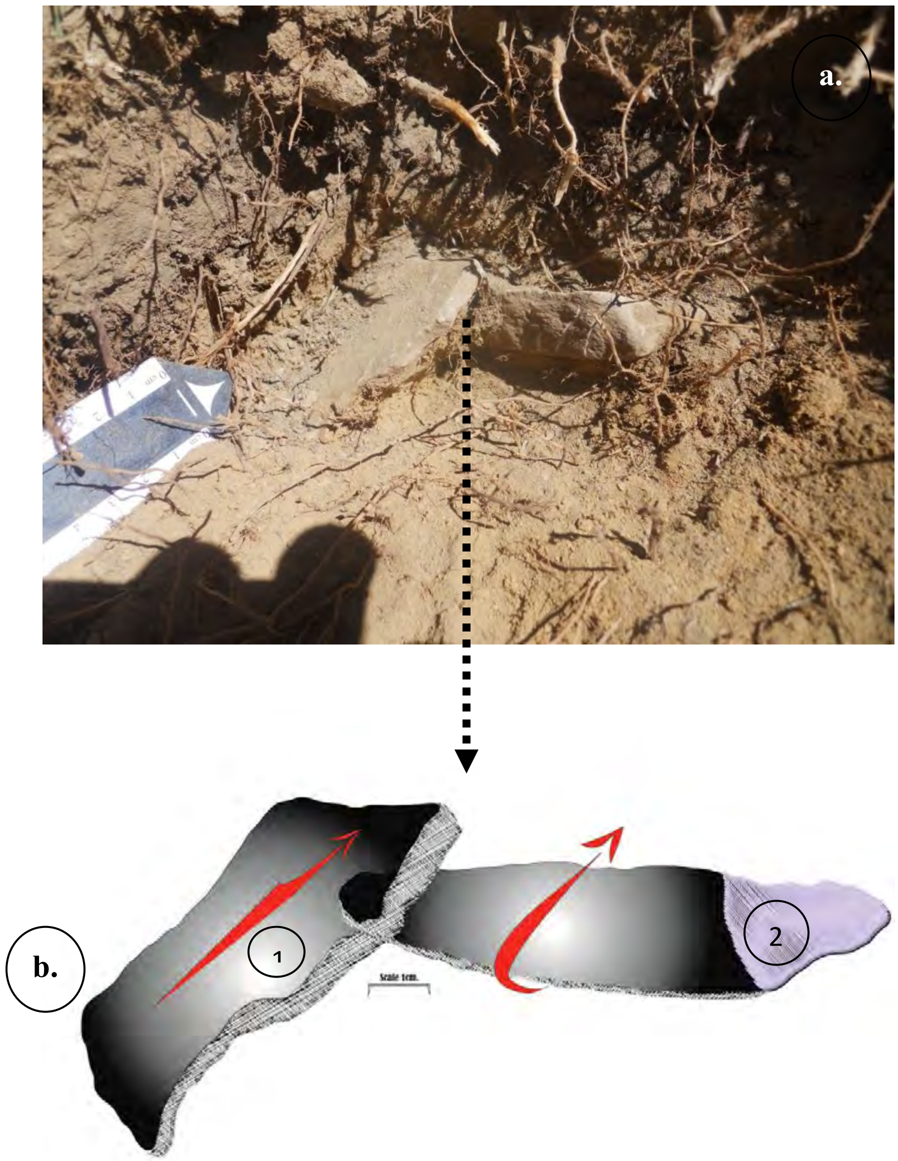


Fig. 99. Clast Rotational pattern in the Inter Drumlin Depression at the site 1. (a) Photograph showing both the long axes of the clasts are rotation parallel and transverse (log type) to the principle flow direction at the basal-ice zone within ductile deforming layer. (b) Graphical representation of (1) Jeffrey Rotation i.e. parallel rotation, and (2) Taylor Rotation i.e. transverse rotation.

6.3. The Genesis and Evolutionary History of the Himalayan Drumlins:

On the basis of the above discussion the genesis and evolution of drumlins in the Chandra Tal area (site 1) can be proposed. A theoretical model can be reconstructed to explain the development of drumlins in the study area. This model is proposed considering all the topographical, morphological and sedimentological evidences discussed so far in the present study. The validity of any theory depends upon two major characteristics. They are: firstly, the ability of any theory to incorporates and explains as much evidences as observed in the field, and secondly, the ability to predict the natural conditions. Keeping these basic properties of a theoretical model, the present model of drumlin formation in the Himalayas is proposed. In order to have time transgressive sequence of drumlin evolution the model is segregated in five stages (Fig. 100). Each stage explains the distinct developmental sequence of the Himalayan drumlins.

Stage: 1 During Batal stage glaciation in the Lahul Himalaya thick glacier ice advanced having relatively thick basal deposits. Bedrock outcrops act as obstacle to the ice flow and allow the deposition initially at the both stoss and lee faces of the outcrops. Supra glacial debris supply is limited to the submarginal areas whereas englacial debris may have sheared down towards basal-ice zone. Ice pressure is relative high in the stoss face and allowed more basal melting and increasing porewater pressure. Sudden drop in pressure of the overlying thick ice may have experienced in the immediate lee face of the bedrock knoll.

Stage: 2 With the advance of the more thicker ice extensive diamict deposition at both the stoss and lee face continue. Ice movement is aided by ductile deformation with relatively high porewater pressure at the base. Hydrostatic condition possibly is optimum favouring constructional deformation in the basal-ice zone. The pressure over overlying ice is more in the stoss side of the bedrock knoll and in the interdrumlin depression relative to the lee face of the drumlins. Local bed materials are also incorporated within the basal-ice at the submarginal zone and subsequently lead to the growth and evolution of drumlins.

Stage: 3 During this stage as well the reduced effective normal stress persists due to high hydrostatic (porewater) pressure. At the lee side, however, an optimum size is attained after which pressure equals and growth of the drumlin may cease and final size of the drumlin is attained. Ice possibly also reached at its maximum thickness during this stage. Constructional deformation may still continue.

Stage: 4 Recession of the glacier may have taken place during the later phase of the last glacial interstadial. Ice thinning also takes place. Porewater dissipation is most likely cause to the changes in the rheology of the subglacial bed materials. Possibly, seepage occurred through the permeable diamict deposition or most likely due to the full development of subglacial drainage conduits under the basal-ice zone or may be that thin ice may not have sufficient pressure to generate subglacial melting and high hydrostatic pressure, which cause low porewater content. This results into increase in effective normal stress and brittle shearing, clast jamming, grain crushing and grinding, and sheared displacement of clasts occurred. Brittle shearing followed by boulder lodgement determines the final outline form of the drumlins. Englacial and subglacial boulders gradually lodged at the drumlin surfaces and constructional deformation ceases.

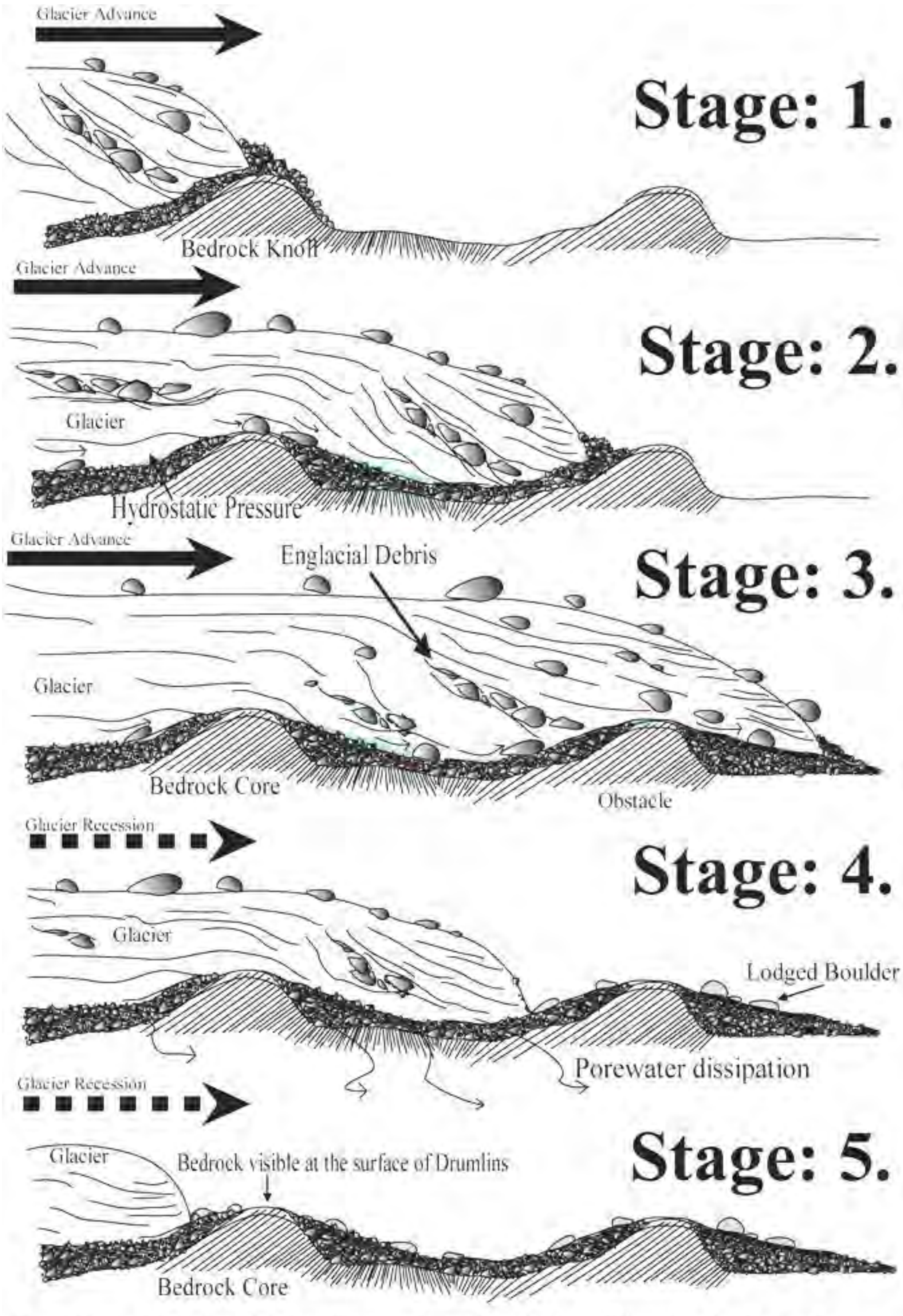


Fig. 100. Model explaining the genesis and evolution of drumlins in the Study Area.

Stage: 5 At the final stage of glacier retreat rock cored drumlins are fully developed with lodged (sometimes ploughing) boulders exposed at the drumlin surfaces. It is hypothetically, thus, proposed that the drumlin formation in the study area (especially at the Chandra Tal area possible has taken place at the subglacial and submarginal areas of the main valley glacier. Hence, drumlins can be effectively used as the submarginal landforms in the Himalayas as well and can thus be also account for reconstructing the palaeoglacial extent in the Himalayas.

The above model of drumlin formation is, thus, explained on the basis of the available evidences. It is although believe that the model fits well for the rock cored drumlins in the Chandra Tal area (site 1), the entirely till (or diamict) composed drumlins with no visible bedrock evidences at their surfaces need further hypothetical support based on their internal composition, especially the drumlins in the Yunan valley of Zanskar range (site 2) require more effective hypothetical explanation of their genesis and evolution because they are composed of unconsolidated and loose deposits with often supraglacial deposits at their surfaces, unlike most of the drumlins in the Chandra Tal area (site 1). These drumlin are believed to be more of ice-marginal streamlined forms rather than subglacial streamlined landforms. However, since bedrock cores are not distinctly identified in this area, future study must compare the internal composition of both rock-cored and till-cored drumlins in both site 1 and site 2, in order to come up with more robust model of drumlin formation in the Himalayas.

In summary, the several key points that have been inferred so far in this chapter can be mentioned as follows. The grain size analyses indicate that the diamict deposits are matrix supported massive type with more than 90 percent of sand. They are actually gravelly (40 percents) sandy (56 percents) in nature in the Study area. Interdrumlin depression consists of relatively finer grains (fine sand and Course silt) than the drumlin surface. It is possibly due to higher stress level and grain crushing in these areas. The internal section also reveals that ductile deformation predominates at the depth not more than 1 meter from the surface of the drumlin, followed by brittle deformation near the surface and ultimately surface lodgement of boulders. These boulders are typical shape and look like mini roche moutonnee. They are typical to englacial and subglacial in origin. At the ductile deformation section wave like flow pattern of the clasts are clearly identifiable along with clast rotation and macro scale galaxy like structures. Example of clast rotation is also found in the interdrumlin depression during clast fabric analysis. Followed by ductile deformation clast jamming and brittle deformation has been identified. The possible porewater dissipation and increase in the effective normal stress may responsible for similar increase in shear stress and shear strength of the materials upwards and ultimately, after brittle shearing and clast fracturing, lodgement of the boulders occur at the surface of the drumlins. This indicates that although basal flow of the glacier-ice during extensive valley glaciation in this region is by sliding of the ice due to deformable till beds at the glacier sole, but the rheology of the diamictons (till) have changed over time due to changes in glaciological condition and porewater pressure at the basal-ice zone. Grain shape analysis on the other hand displays that blade shaped and elongate clasts predominate in general, and most likely due to local geology and partly to local bedrock source. The supraglacial deposits at the ice submarginal subenvironment is also determined on the basis of relatively higher proportion *of angular and very angular (A+VA) clasts in the matrix in the Chandra Tal area. At the Yunan valley, on the contrary, sub-rounded to subangular clasts overwhelm and they are believed to be reworked materials, and/or also brought form longer distances under subglacial regime. The SEM analysis of surface textures of quartz sand grains also provides similar picture to support many of the locally derived grains in certain sample sites. However, in general the SEM study confirms broadly that the quartz sand grains are glacially modified with crushing and grinding, plucking and abrasion mechanism. Fresh fracture faces, concoidal fractures, sharp edges, low relief of the grains are identified extensively. Besides, the presence of very high degree of adhering particles at the grain surfaces, are also mentioned from the present study area. These along with many other superficial textural evidences e.g. grooves, striations etc. clearly pointed out that the grains also mostly subglacially formed. Some have undergone reworking and reincorporation. Effects of other geomorphic agents are absent to very insignificant, except a few of the reworked aeolian grains. Clast macro fabric analyses, at the last, confirm the principle flow direction of the ice in the study area which is found extensively parallel to transverse-parallel in orientations to the general long-axes of the drumlins in respective study sites; except at Sarchu 1 (i.e. Exposure 1) where the fabric pattern is near diffusive in nature, other fabric results are satisfactory. The surface lodged boulders also indicate near similar flow direction, especially at the KunzumLa. At the Chandra Tal area, the boulders do possess strong directionality but they are more of southerly than southeasterly. The* S_3/S_1 *comparison also indicates that deformation may account for such kind of fabric orientations. While it is quite common in literature that parallel and transverse positions of an elongated grain is the most stable position and most likely as well, the reasons for such orientation in the present study area is not clear from this study, but it is clear that clast rolling within deforming till must have been* *the dominant subglacial process and largely account for the genesis and evolution of the drumlins in the study area. Based on these evidences a theory of rock-cored drumlin formation has been proposed. The validity of the present theory depends largely on the future study from this area which must incorporates further detail internal compositional study from number of drumlins along with numerical dates and other morphological study. Providing the circumstances, comparison with palaeoclimate data is also very much required in the future study; only then the essential relevance of studying the drumlins in the Himalayas can be fulfilled. The present preliminary study thus, provides the base on which any further study on drumlins in the Himalayas may be effectively conducted.*

Chapter—7

CONCLUSION AND FUTURE SCOPE

"Progress in the understanding of geological processes is largely dependent upon ...the ability to ask the right question".

——Andrews (1971, cf. Menzies 1979).

7.1. Introduction:

The preset study is the first detail study of the drumlins in the Himalayas. Many of the questions that have been raised at the onset in the research gaps of the present paper (section: 1.10), are satisfactorily explained, if not all, in the present study. It also successfully defends the objectives of the study based on the in situ observations and laboratory results. Some of the hypotheses of previous workers are corroborated with further evidences and some of them are discarded as well. A theoretical model of drumlin formation is also proposed for the Chandra Tal area. These together when bring into one platform provides the picture of reconstructed palaeoenvironmental condition in the study region in particular and the Western Himalayas in general. Many aspects still require greater attention in the future studies. The inductive methodology adopted in the present context, thus, proved to be satisfactory and must be exercised more systematic and rigorous way. However, the major conclusions that are derived so far may be listed as follows.

7.2. Conclusions:

This section only lists the major inferences that are derived so far in the present study based on the available evidences. Many of them may require more evidences to support whereas many of them may be subject to future modification, but in general it is believed that the general picture remains similar and also fits well within the existing knowledge of the glaciation history in the Lahul Himalaya and Zanskar range. However, the major conclusions are:

i) In terms of **morphology or outline** forms, the drumlins in the Chandra Tal area and Yunan valley are mostly classical tear-drop shape. They are found en echelon in a field crafting a basket of egg topography. Their longitudinal axes also denote the former ice-flow direction in both the valleys, which is southeasterly in the Chandra valley and northeasterly in the Yunan valley. This directional pattern is also verified with the trend data collected from some of the other glacial features. These incorporates roches moutonnee, striations, ice polished and ice molded rocks, whaleback structures and clast fabric etc. These data sets together help in constructing regional ice-flow pattern in this area.

ii) The detail **topographical analysis** of both the Upper Chandra valley and Yunan valley, signify that there is a broad and gentle and possibly shallow valley as well before post glacial modification. The broad opening of these valleys may initiate spreading of ice during extensive valley glaciation. The funnel like basin in the Chandra Tal area (site 1) may further augments thicker accumulation of ice compared to their up-stream section and along with spreading affect, leads to thick ice-sheet like condition and formation of drumlin streamlined forms. The similar spreading effect is reconstructed in the Yunan valley as well in the present study on the basis of the longitudinal orientations of drumlins.

iii) The in situ analysis of the rocky outcrops having deep red brown rock varnishes, and drumlins, further suggest that in the Chandra Tal area, the tributary **Samundri glacier could deflect the main valley glacier-ice** during extensive valley glaciation and leads to initial convergence and subsequent spreading of ice in this area. It becomes apparent when the long-axes of the drumlins are extrapolated to a larger size. However, the tributary glacier may partly responsible for the southeasterly flow of the ice in the valley, which was off the main north-south trending Chandra valley course at the present in the upstream reach and as the other evidences suggest, could cause overtopping of the Kunzum range at the Kunzum La to spread into the Upper Spiti valley. The distribution of drumlins, striation marks, ice molded rock, and drumlinized mounds etc. help together in verifying the statement at the Kunzum La and Upper Spiti valley respectively.

iv) The longitudinal axes data of the drumlins also corroborate the findings of previous workers (Owen et al., 1997) and confirmed that during last extensive valley glaciation the **ice-divide** was possibly at the Baralacha La and not south of Zanskar Normal Fault (ZNF) near Darcha, Himachal Pradesh. Ice flowed in the north into Yunan valley and south and west into the Chandra valley and Bhaga valley respectively. Ice possibly spread from this location and extended downstream by as much as more than 100 km. from the present glacier margins (Hedrick et al., 2011).

v) Although the classical morphological types of drumlins overwhelm in both the regions (Site 1 & 2), a **wide range of other outline forms** are clearly identifiable in the field. Five major morphological types are identified in the Chandra Tal area (site 1), viz. a) Classical form, b) Superimposed form, c) Dome shaped, d) Inverse shaped, and e) Uniform shaped drumlins. However, so far no such satisfactory pattern has been identified in terms of the distribution of different morphological types. Although it can be said, on the basis of the frequency distribution of different classical drumlins, that larger stress by the ice-mass may cause transformation of classical forms into larger spindle forms in the subglacial regime. Superimposed drumlins may indicate different phases of their formation, but until controlled numerical dates are available this remains as just speculation based on geomorphology of the landforms only. However, entirely diamict composed drumlins have little edge over the rock cored drumlins and those having ice-molded rocks at their surfaces in the Chandra Tal area (site 1) interms of dominance; although entirely bedrock drumlins are also not uncommon.

vi) The **grain size analyses** indicate that the diamict deposits are matrix supported massive type with very high concentration of sand. They are actually gravelly (40 percents) sandy (56 percents) in nature in the Study area. Interdrumlin depression, however, consists of relatively finer grains (fine sand and Course silt) than the drumlin surface, may possibly due to higher stress level and grain crushing.

vii) The internal section of the sample drumlin KG1/DPF (or DPF1) also reveals that ductile **deformation predominates** at the depth not more than 1 meter, followed by brittle deformation near the surface and ultimately surface lodgement of boulders. These boulders have typical shape and look like mini roche moutonnee. They are typical to englacial and subglacial in origin. At the ductile deformation section however, wave like flow pattern of the clasts are clearly identifiable along with clast rotation and galaxy like structures at the macro scale. Example of clast rotation is also found in the interdrumlin depression during clast fabric analysis. Followed by ductile deformation clast jamming and brittle deformation has been identified in the pit section. The possible porewater dissipation and increase in the effective normal stress along with incorporation of ice-marginal deposits at the submarginal regime may responsible for the increase in shear stress and shear strength of the materials upwards and results in the brittle shearing and clast fracturing. Ultimately lodgement of the boulders occurs at the surface of the drumlins. This indicates that although basal flow of the glacier-ice during extensive valley glaciation in region is by sliding of the ice due to deformable till beds at the glacier sole, but the rheology of the diamictons (till) have changed over time due to changes in glaciological condition, basal constituents and porewater pressure at the basal-ice zone.

viii) **Grain shape analysis** on the other hand displays that blade shaped and elongate clasts predominate in general, and most likely due to local geology and also local bedrock source. The supraglacial source of clasts at the submarginal regime is also determined on the basis of relatively higher proportion of angular and very angular (A+VA) clasts in the matrix in the Chandra Tal area. At the Yunan valley, on the contrary, sub-rounded to subangular clasts overwhelm. These are believed to be reworked materials or brought form longer distances under subglacial regime.

ix) The **SEM analysis of surface textures of quartz sand grains** also provides similar picture to support many of the locally derived grains in certain sample sites. However, in general the SEM study confirms broadly that the quartz sand grains are glacially formed and also experienced extensive crushing and grinding, plucking and abrasion mechanism. Fresh fracture faces, concoidal fractures, sharp edges, low relief of the grains are identified extensively. Besides, the presence of very high degree of adhering particles at the grain surfaces along with other surface textural evidences e.g. curved and irregular grooves, concoidal fractures, striations, fresh mechanical fracture faces etc. clearly pointed out that the grains are also subglacially modified at the basal ice zone. Reworking and reincorporation of grains with preweathered surfaces are also observed in some cases. Effects of other geomorphic agents are absent to very insignificant, except a few of the reworked aeolian grains.

x) **Clast macro fabric analyses**, lastly, confirm the principle flow direction of the ice in the study area which is parallel and transverse in orientations to the general long-axes of the drumlins in respective study sites; except at Sarchu 1 (i.e. Exposure 1) where the fabric pattern is near diffusive in nature, other fabric results are satisfactory. The surface lodged boulders also indicate near similar flow direction, especially at the Kunzum La. At the Chandra Tal area, the boulders do possess strong directionality but they are dominantly southerly and limited southeasterly. The S_3/S_1 comparison also indicates that deformation may account for such kind of fabric orientations. While it is quite common in literature that parallel and transverse positions of an elongated grain is the most stable position and most likely as well, the reasons for such orientation in the present area of interest is not clear from the present study, but it is clear that clast rolling within deforming till must have been the dominant subglacial process for the genesis and evolution of the drumlins in the study area.

On the basis of above inferences the palaeoenvironment of the region during the formation of drumlins, may be reconstructed. The detail study of these streamlined forms provide many of the key insight of the past glaciological and environmental condition, which otherwise may be difficult to infer. However, keeping in view the background of timing, extent, and nature of glaciation in the Lahul Himalaya, and Zanskar Valley along with the present study of drumlins and filed evidences, an attempt has been made to reconstruct the palaeoenvironment of the study region.

7.3. Reconstruction of palaeoenvironment during the formation of drumlins:

During the period of the formation of drumlins in the Chandra valley of Lahul Himalaya and Yunan Valley of Zanskar, the possible environmental condition must have been distinct enough to develop thick ice cover and extensive distribution of glaciers to aid the formation of these large baskets of egg topography. Possibly during the late glacial interstadial time (12 to 16 ka), an extended period of heavy precipitation in the form of snowfall might have occurred in this region. This substantial phase of continuous snowfall in the Lahul Himalaya (or Zanskar valley), thus, might developed thick ice cover along the Greater Himalayan range, with possible ice-divide being at or around the Baralacha La (4,900 m asl.). The likelihood of the strengthening of the Southwesterly Indian Summer Monsoon and heavy precipitation is most probably responsible for this extended period of pluvial activity in this part of the Himalaya. The literature review suggests that there were periods when the southwesterly monsoon becomes strengthen by more than 40% to 100% from the present, and resulted in phases of heavy precipitation (Shi et al., 2001 cf. Hedrick et al., 2011). The region is also dominated by mid-latitude westerlies. But studies indicate that although at present this climatic system is contributing on heavy snowfall during the winter months in this region, during the late glacial warming period or younger, no extensively long snowfall event is recorded in other parts of the mid-latitude westerly dominated regions of the Himalayas and Transhimalaya to produce extensive valley glaciation like that of Batal stage with glacier extension of > 100m. from the present glacial termini. The present understanding thus, suggest that Indian summer monsoon is largely accountable for this extended period of snowfall event in the Himalayas. This fact thus, increases the important of the present study, because the changes in the monsoon intensity has direct link to global climate and moreover on the socio-economy of the surrounding countries like, India, Pakistan, Nepal, Bhutan, China and others. The reason behind the strengthening of the Indian summer monsoon is still not known precisely, but given the time period it is more likely that during the interglacial warming events, the southwesterly monsoon may strengthen more than during the cool glacial periods (Owen et al., 2001). The present temperature regime of the study area also suggest that even at present (interglacial warming period) the region experiences extended months of subzero temperatures. With this condition even it is quite likely that heavy extended snowfall along with albedo and other negative feedback effect, glaciers may show positive mass balance and extensive valley glacial advance may not be surprising.

However, it is quietly likely that this extended period of snowfall and consequent advance of glaciers in the Lahul region has occurred much before 12 ka., because the CRN dates provided by Owen et al. (2001) from the lodged boulders of the drumlin surfaces in the Chandra Tal area and also from the morainic boulders at Batal constrained the Batal stage glaciation between 12 ka to 15.5 ka. Since CRN dates provide the minimum age distribution, it is thus believed that the possible extended snowfall event and extensive valley glaciation may be much older than this. Without more numerical dates this fact cannot be substantiated, but the possibility must be explored. The Batal stage glaciation was undoubtedly more extensive type and glaciers may have extended more than 100 km. from the present glacier margins in this area (Hedrick et al., 2011). During Batal stage glacier advance, thus, extensive snow accumulation might have taken place in the high reaches, especially at the Baralacha La (the ice-divide) and streams of ice might flow down valley into the Chandra basin, Bhaga basin (of Lahul Himalaya), and amy also be into the Yunan valley (of the Zanskar). However, in the Chandra valley it is likely that many of the supraglacial boulders are entrained within the glaciers (englacial subenvironment) owing to high snowfall accumulation at the accumulation zones and/or along shear planes during movement of the glaciers. These englacial (and also subglacial supplied) boulders were possibly the major source of the lodged boulders identified extensively at the surfaces of the drumlins.

However, the topographical configuration of the valley indicates that in the Chandra Tal area ice flew downstream and possibly accumulated in huge amount in the funnel shaped basin, and more likely that the funnel basin contains more ice than the up-valley sections. The opening of the broad shallow valley near Chandra Tal into this funnel shape basin thus indicates that ice possibly spread in this part of the valley creating conducive condition for the formation of subglacial streamlined landforms like drumlins. In the Chandra Tal area, however, the spreading of ice into the funnel basin might also be affected by the tributary Samundri glacier, emanating from the Mulkila peak. This tributary glacier initially confluence with the main valley glacier and might deflect the main valley ice. Together with the spreading affect and deflection, the main valley glacier-ice possibly took a southeasterly course. The ice might thicken to a certain extent that the funnel basin can contains and hence, overtops the Kunzum range at Kumzum La. The long-axes orientations of the drumlins clearly indicates the southeasterly flow direction of main valley ice and this is found in similar orientation to the angle at which Samindri glacier might confluence with the main valley ice. However, drumlins, striations, ice-molded rocks etc. at the Kunzum La and Upper Spiti valley, and clasts fabric from the drumlin surfaces further substantiate this explanation and confirmed that the main Chandra Valley ice during Batal stage of extensive glacial advance, also spread well into the Upper Spiti valley. The relatively narrow valley configuration further downstream might have retarded the favourable conditions for drumlin formation.

This is equally true in the Yunan valley where gradual widening of the valley into broad shallow valley is clearly visible. The main valley ice not only followed the main valley course but spreading also occurred downstream in the preset study site 2. Ice was thick enough during the formation of drumlins. The long-axes data of the drumlins in the Yunan valley clearly demonstrate this flow path of the ice during their formative period; possibly between late glacial interstadial to historical time. This time frame is important because during ~12 to 16 ka (late glacial interstadial event) the drumlins of the Himalaya may have formed whereas during ~4 ka. (Historical time) the drumlins of the Miyar basin have formed. This fact further limits the period of formation of the drumlins in the adjacent Yunan valley area (site 2). However, present evidences indicates that extensive valley glaciation during the late glacial interstadial or later period is largely absent in the main valley and even in most of the tributary valleys of the Zanskar. This signifies to the urgent need of the controlled numerical dates of drumlin formation in the study area. This can be furthermore interesting because the numerical dates will either corroborate the existing understanding or modify the glacial chronology of the region. Both have immense palaeo-climatic importance.

Not only the glaciological and topographical characteristics but subglacial rheological condition, as the internal sedimentology of the drumlins suggests, also favoures the sliding and movement of ice though deformation till at the glacier sole in this area. This kind of processes is also extensively cited from the drumlin fields of mid-latitudinal glaciated countries. Well developed deforming sandy till matrix, thus, favoured not only sliding of the glacier but also augment the extensive drumlin formation in this area. The internal structures of drumlins form the Chandra Tal area clearly indicates that the rheological behaviours under subglacial and submarginal condition was not uniform over the time but changes along with the change in the glaciological properties and porewater pressure. This also suggests that the glaciological behaviour was active all along up to the final drumlins formation. Hence glaciological, topographical and till rheological properties were together influenced the genesis and evolution of drumlin in the Chandra valley and Yunan valley during Batal stage glacial advance. Finding these aspects together in any other areas of the Himalayas is difficult and certainly explained the rarity of drumlin swarms in this high mountain realm.

7.4. Future Scope of the Present Study:

The present study tries to cover several morphological and sedimentological aspects of drumlins together. Even if they are not robust, but to a large extent this preliminary study solve many of the doubts and speculations regarding the drumlins of the Himalayas; although it equally raises some of the limitations of the present study and identifies the areas where future study must look into in order to come up with much better understanding of the Himalayan drumlins. The major scope for the future study may be pointed out as follows.

There is a greater requirement of numerical dates from the drumlins in the Lahul Himalaya. These dates not only improve the timing of Batal Stage glaciation and drumlin formation, but also will help in correlating between the drumlin's formation period in the Chandra Tal area and in the Yunan valley in the context of palaeo-climatic events. They will further enable correlation among other proxy data sets of climate, such as sea-core sediments, ice cores, and isotopic data etc. Whether the hypothesis which suggests strengthening of the monsoon is responsible for such extensive glaciation in the Lahul Himalaya and Zanskar region, can be verified with the newly age data sets. Since CRN dates are already given and is believed to be robust, OSL dates may solve the dilemma about the maximum age of the formation of drumlins and initiation of thick ice cover in this area.

More systematic study of the internal composition and structures of drumlins in both the Chandra Tal area and Yunan valley are required in order to further verify the theoretical model proposed in the present study. Since the present model explains the development of rock cored drumlins, genesis and evolution of the till cored drumlins are yet to provide, especially from the Yunan valley region where good road-cuts are available and drumlins are believed to be entirely submarginally formed.

Since at the macro-, most of the sections apparently look massive (Dmm type) with typical clast orientation pattern, thin section analysis may prove more satisfactory. Such kind of micro-scale analysis may further identify some of the key glacial characteristics or corroborate the already proposed inferences. More SEM analysis of surface textures of the samples from the Yunan valley area will also exhibit the genetic processes (including reworking) and energy regime at the time of deposition.

Besides, more systematic clast fabric analyses are also required, especially at the different depths of a drumlin and more form the Yunan valley area. Filed mapping in the low ridge section in the Chandra Tal area, bounded by the Chandra River in the east and Samundri Nala in the south, are also required to conduct to have more detail knowledge geographical distribution of drumlins in the study area. The Upper Spiti valley also needs careful attention in order to identify the extent of the main Chandra Valley glacier in this area during Batal stage.

It is therefore, clear from the above discussion that the ability to ask the right questions, unveil the unequivocal possibility to resolve them in right way and certainly encompass multiple aspects together. Such as in the present study both morphological, sedimentological aspects are given equal waitage and together they help in proposing a theory of drumlin formation. That means three aspects of the present paradigm in drumlin studies i.e. Morphological, Sedimentological and Theoretical, are sufficiently covered in the present study. The merit of these analyses will certainly depends upon how well they explain the characteristics of drumlins in the Himalayas.

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ANNEXURE

Annexure:1

SAMPLE IDENTITY :	**KG1/DPF**		
Grain Sizes			
COARSE SAND:	17.8%		
MEDIUM SAND:	18.3%		
FINE SAND:	12.9%		
V FINE SAND:	13.4%	SAND:	98.4%
V COARSE SILT:	1.5%	MUD:	1.6%
COARSE SILT:	0.0%		
MEDIUM SILT:	0.0%		
FINE SILT:	0.0%		
V FINE SILT:	0.0%		
CLAY:	0.0%		
	METHOD OF MOMENTS		
	Arithmetic	Geometric	Logarithmic
Statistics	mm	mm	ϕ
MEAN :	731.6	398.3	1.060
SORTING (s):	609.4	4.249	1.524
	FOLK & WARD METHOD		
	Geometric	Logarithmic	Description
Statistics	mm	φ	
MEAN :	490.5	1.028	Medium Sand
SORTING (s):	3.063	1.615	Poorly Sorted

SAMPLE IDENTITY :	**KG2/ DPF**		
Grain Sizes			
COARSE SAND:	17.6%		
MEDIUM SAND:	22.7%		
FINE SAND:	18.4%		
V FINE SAND:	10.2%		
V COARSE SILT:	1.0%	SAND:	98.9%
COARSE SILT:	0.0%	MUD:	1.1%
MEDIUM SILT:	0.0%		
FINE SILT:	0.0%		
V FINE SILT:	0.0%		
CLAY:	0.0%		
	METHOD OF MOMENTS		
	Arithmetic	Geometric	Logarithmic
Statistics	mm	mm	φ
MEAN :	677.2	430.7	1.159
SORTING (s):	561.7	2.908	1.395
	FOLK & WARD METHOD		
	Geometric	Logarithmic	Description
Statistics	mm	φ	
MEAN :	460.6	1.119	Medium Sand
SORTING (s):	2.759	1.464	Poorly Sorted

SAMPLE IDENTITY :	**DPF2**		
Grain Sizes			
COARSE SAND:	11.8%		
MEDIUM SAND:	12.0%		
FINE SAND:	9.7%	**Grain Size Distribution**	
V FINE SAND:	15.7%	SAND:	80.8%
V COARSE SILT:	12.5%	MUD:	19.2%

SAMPLE IDENTITY :	**IDPF1**		
Grain Sizes			
COARSE SAND:	9.5%		
MEDIUM SAND:	22.8%		
FINE SAND:	19.4%	**Grain Size Distribution**	
V FINE SAND:	27.7%	SAND:	84.6%
V COARSE SILT:	11.2%	MUD:	15.4%

COARSE SILT:	1.5%		
MEDIUM SILT:	1.3%		
FINE SILT:	1.3%		
V FINE SILT:	1.3%		
CLAY:	1.3%		
	METHOD OF MOMENTS		
	Arithmetic	Geometric	Logarithmic
Statistics	mm	mm	φ
MEAN :	433.5	96.25	2.014
SORTING (s):	556.5	10.42	2.278
	FOLK & WARD METHOD		
	Geometric	Logarithmic	Description
Statistics	mm	φ	
MEAN :	320.5	1.642	Medium Sand
SORTING (s):	4.858	2.280	Very Poorly Sorted
SAMPLE IDENTITY :	**KUN/07/50**		
Grain Sizes			
COARSE SAND:	14.1%		
MEDIUM SAND:	17.0%		
FINE SAND:	13.7%	**Grain Size Distribution**	
V FINE SAND:	26.3%	SAND:	90.8%
V COARSE SILT:	7.4%	MUD:	9.2%
COARSE SILT:	0.4%		
MEDIUM SILT:	0.4%		
FINE SILT:	0.4%		
V FINE SILT:	0.4%		
CLAY:	0.3%		
	METHOD OF MOMENTS		
	Arithmetic	Geometric	Logarithmic
Statistics	mm	mm	φ
MEAN :	502.0	250.9	1.984

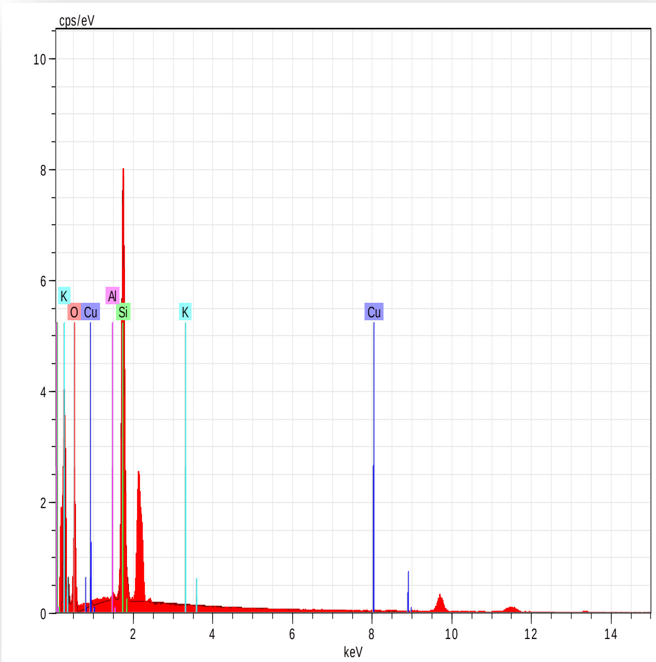
COARSE SILT:	0.9%		
MEDIUM SILT:	0.8%		
FINE SILT:	0.8%		
V FINE SILT:	0.8%		
CLAY:	0.8%		
	METHOD OF MOMENTS		
	Arithmetic	Geometric	Logarithmic
Statistics	mm	mm	φ
MEAN :	283.2	153.8	2.667
SORTING (s):	336.0	3.298	1.676
	FOLK & WARD METHOD		
	Geometric	Logarithmic	Description
Statistics	mm	φ	
MEAN :	168.5	2.570	Fine Sand
SORTING (s):	2.799	1.485	Poorly Sorted
SAMPLE IDENTITY :	**Sarchu1**		
Grain Sizes			
COARSE SAND:	15.3%		
MEDIUM SAND:	15.6%		
FINE SAND:	10.0%	**Grain Size Distribution**	
V FINE SAND:	16.2%	SAND:	94.1%
V COARSE SILT:	5.2%	MUD:	5.9%
COARSE SILT:	0.2%		
MEDIUM SILT:	0.1%		
FINE SILT:	0.1%		
V FINE SILT:	0.1%		
CLAY:	0.1%		
	METHOD OF MOMENTS		
	Arithmetic	Geometric	Logarithmic
Statistics	mm	mm	φ
MEAN :	754.4	394.6	1.219

SORTING (s):	541.2	3.578	1.821
	FOLK & WARD METHOD		
	Geometric	Logarithmic	Description
Statistics	mm	φ	
MEAN :	278.1	1.846	Medium Sand
SORTING (s):	3.517	1.814	Poorly Sorted

SORTING (s):	646.4	4.063	1.784
	FOLK & WARD METHOD		
	Geometric	Logarithmic	Description
Statistics	mm	φ	
MEAN :	421.0	1.248	Medium Sand
SORTING (s):	3.562	1.832	Poorly Sorted

Annexure: 2

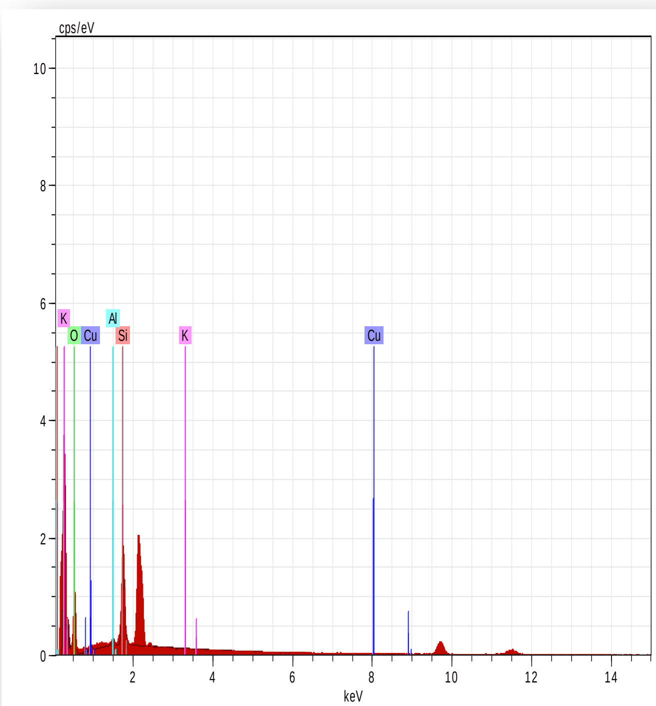
KG1: Randomly Selected Single Grain



Spectrum: Sourav Saha CSRD * S1, 24/ 2013

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]	Error [%]
Silicon	K-series	8.77	8.77	5.20	0.4
Copper	K-series	0.13	0.13	0.04	0.0
Potassium	K-series	0.00	0.00	0.00	0.0
Aluminium	K-series	0.16	0.16	0.10	0.0
Oxygen	K-series	90.93	90.93	94.66	0.4
	Total:	100.00	100.00	100.00	

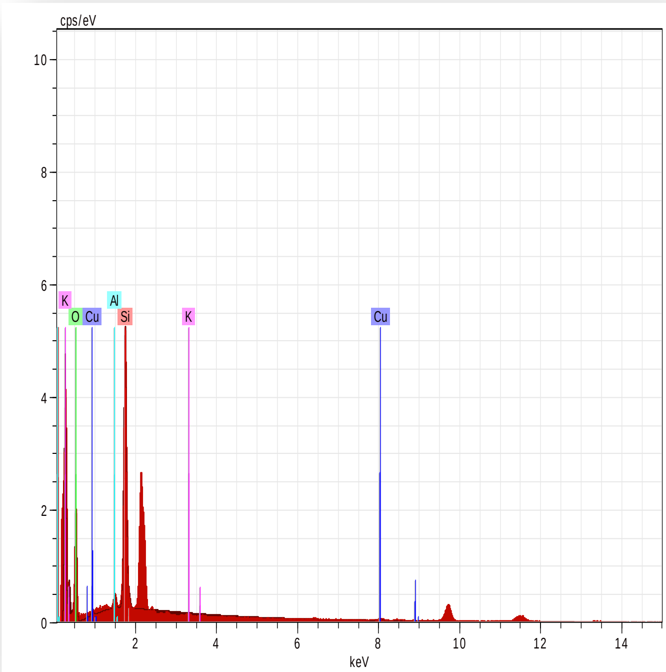
KG1: Selected Total Grains



Spectrum: Sourav Saha CSRD * S1, 24/2013

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]	Error [%]
Silicon	K-series	2.52	2.52	1.45	0.1
Copper	K-series	0.10	0.10	0.03	0.0
Aluminium	K-series	0.22	0.22	0.13	0.0
Potassium	K-series	0.00	0.00	0.00	0.0
Oxygen	K-series	97.16	97.16	98.39	0.1
	Total:	100.00	100.00	100.00	

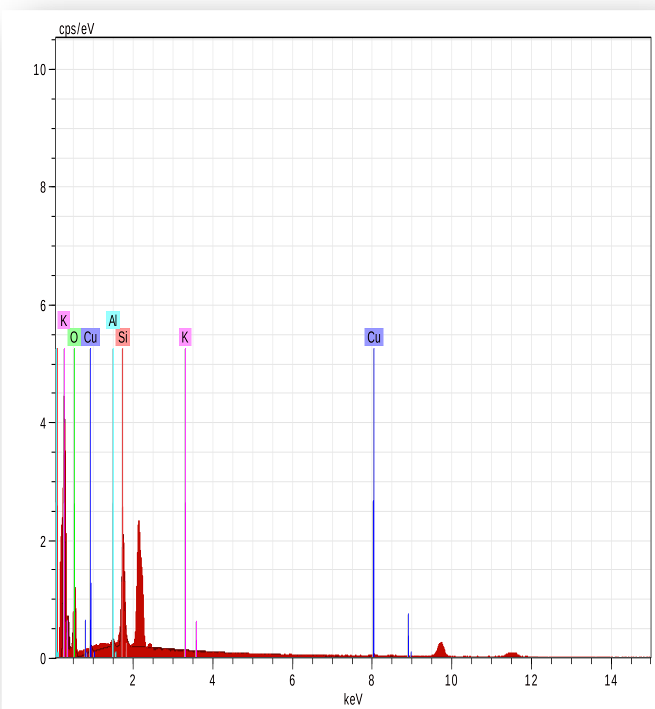
DPF2: Randomly Selected Single Grain



Spectrum: Sourav Saha CSRD *S3, 24/2013

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]	Error [%]
Silicon	K-series	5.19	5.19	3.03	0.2
Copper	K-series	0.31	0.31	0.08	0.0
Aluminium	K-series	0.34	0.34	0.21	0.0
Potassium	K-series	0.00	0.00	0.00	0.0
Oxygen	K-series	94.16	94.17	96.68	0.3
	Total:	100.00	100.00	100.00	

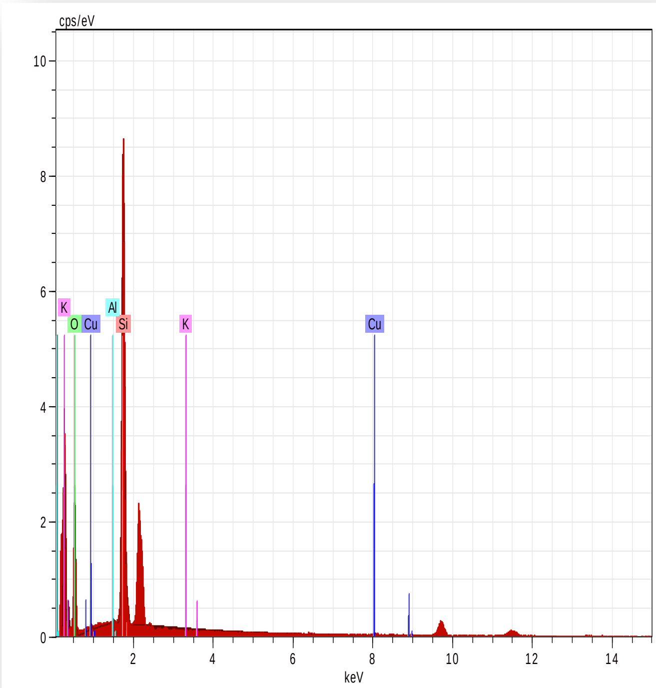
DPF2: Selected Total Grains



Spectrum: Sourav Saha CSRD *S3, 24/2013

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]	Error [%]
Silicon	K-series	2.50	2.50	1.45	0.1
Copper	K-series	0.46	0.46	0.12	0.0
Aluminium	K-series	0.21	0.21	0.12	0.0
Potassium	K-series	0.00	0.00	0.00	0.0
Oxygen	K-series	96.83	96.83	98.31	0.2
	Total:	100.00	100.00	100.00	

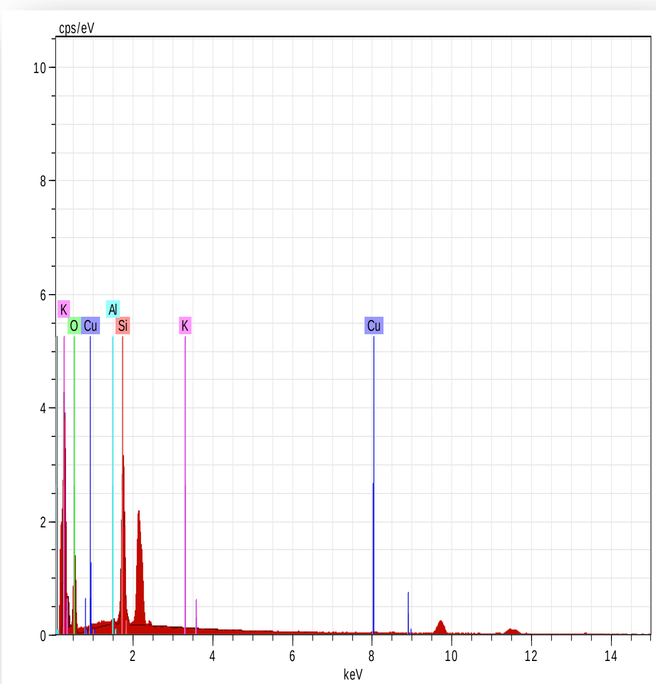
KG2: Randomly Selected Single Grain



Spectrum: Sourav Saha CSRD *S2, 24/2013

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]	Error [%]
Silicon	K-series	9.70	9.70	5.79	0.4
Copper	K-series	0.37	0.37	0.10	0.0
Aluminium	K-series	0.08	0.08	0.05	0.0
Potassium	K-series	0.00	0.00	0.00	0.0
Oxygen	K-series	89.84	89.84	94.06	0.5
	Total:	100.00	100.00	100.00	

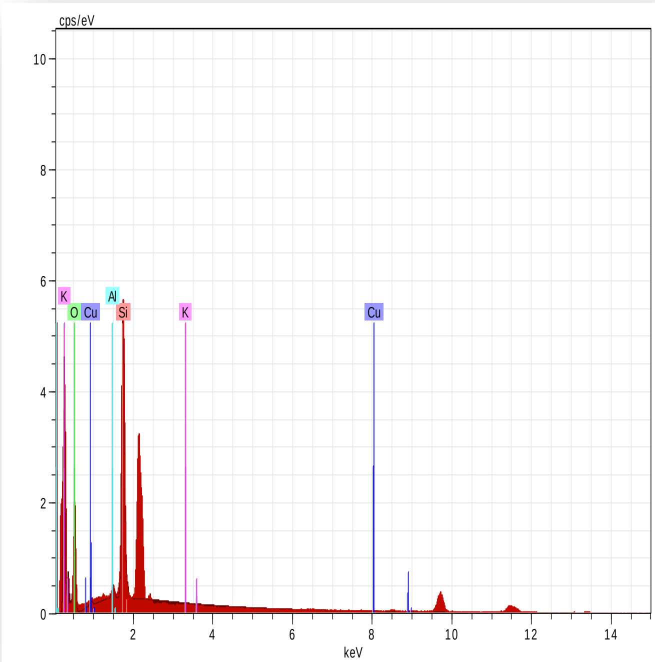
KG2: Selected Total Grains



Spectrum: Sourav Saha CSRD *S2, 24/2013

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]	Error [%]
Silicon	K-series	4.16	4.16	2.42	0.2
Copper	K-series	0.45	0.45	0.11	0.0
Aluminium	K-series	0.17	0.17	0.11	0.0
Potassium	K-series	0.00	0.00	0.00	0.0
Oxygen	K-series	95.22	95.22	97.36	0.2
	Total:	100.00	100.00	100.00	

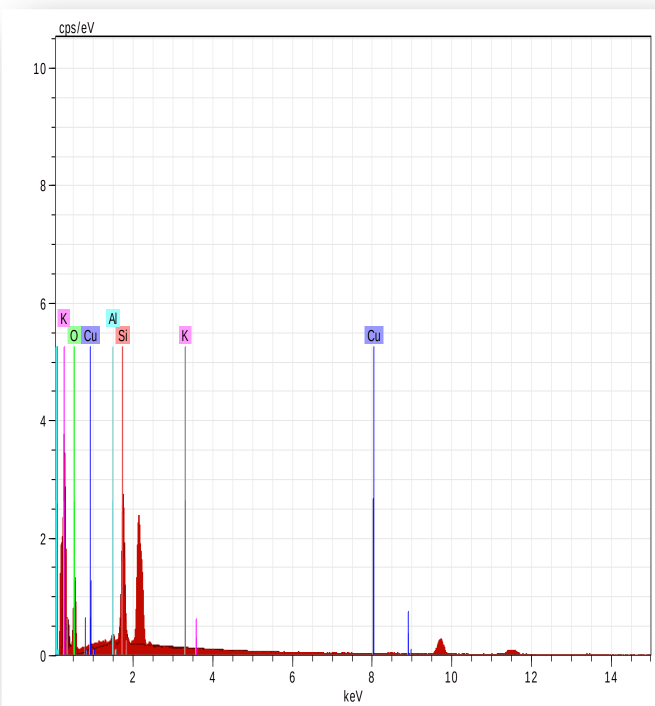
KUN: Randomly Selected Single Grain



Spectrum: Sourav Saha CSRD *S4, 24/2013

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]	Error [%]
Silicon	K-series	5.01	5.01	2.92	0.2
Copper	K-series	0.08	0.08	0.02	0.0
Aluminium	K-series	0.26	0.26	0.16	0.0
Potassium	K-series	0.00	0.00	0.00	0.0
Oxygen	K-series	94.65	94.65	96.90	0.3
	Total:	100.00	100.00	100.00	

KUN: Selected Total Grains



Spectrum: Sourav Saha CSRD *S4, 24/2013

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]	Error [%]
Silicon	K-series	3.35	3.35	1.94	0.2
Copper	K-series	0.10	0.10	0.03	0.0
Aluminium	K-series	0.29	0.29	0.17	0.0
Potassium	K-series	0.00	0.00	0.00	0.0
Oxygen	K-series	96.26	96.26	97.86	0.2
	Total:	100.00	100.00	100.00	

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