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Provenance, Depositional and Diagenetic Reconstruction of the Early Palaeozoic Succession in Kupwara District, Kashmir, North-western Himalaya

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Abstract

Early Palaeozoic succession in Kupwara district of Jammu and Kashmir, North-western Himalaya comprise of sandstone, shale, carbonates and slate. The petrological properties of these rocks were used to work out the provenance, depositional environment and their diagenetic history. The siliciclastic sediments with interbedded carbonate rocks indicate shifts in sea level and consequent changes in energy conditions of the basin as well as biogenic interferences leading to carbonate precipitation in a shallow marine depositional environment. Provenance of these rocks has been of mixed nature with monocrystalline quartz dominant in sandstones indicating greater contribution from igneous sources.

Keywords: Early Palaeozoic, Kupwara, North-western Himalaya, Depositional environment

INTRODUCTION

The Tethyan sedimentary belt of Himalaya extends from Nanga Parbat in the west to Namcha Barwa in the east overlying the central crystalline basement known as Salkhalas in Kashmir Himalaya (Wadia, 1934). The deposition of marine sediments of Phanerozoic Eon has been restricted to the Tethyan realm of Himalaya (Parcha, 2021). Among the Tethyan strata, the Palaeozoic-Mesozoic rock formations along the northern margin of the Indian plate are essentially a shelf sequence (Shah, 1991). These nearly uninterrupted sedimentary successions were deposited in four sub-basins i.e., Kashmir, Zanskar, Spiti-Kinnaur and Garhwal-Kumaon during Proterozoic to Eocene with varying thickness from 5000 to 16000m. The early and late Palaeozoic Tethyan strata are widely distributed in north-western and south-eastern parts of Kashmir basin respectively.

The majority of physico-chemical processes involved in sedimentation history of a basin are weathering in the source area, transportation, sorting, deposition and diagenesis (Roser and Korsch, 1986, 1988; McLennan et al., 1990; Eriksson et al., 1992; Weltje and Eynatten, 2004). These major processes involved during sedimentation are controlled by nature of sedimentary provenance, processes dominating in the depositional basin and sediment dispersal from provenance to basin that affects the mineralogical composition of clastic rocks. Facies and petrographic analysis of sandstones is an organized discipline in depositional and diagenetic studies.

The sandstone petrography is governed by the combined impact of provenance of the detrital input, the distance between the depositional basin and the provenance, the mode of transport of the sediments, and the prevalent environment. Plate tectonics-controlled geometry of provenance with respect to basin defines the type of sandstone deposited (Dickinson & Suczek, 1979). Quartz content in sediments has varied with the tectonic settings (Crook, 1974 and Schwab 1975). Quartz-rich rocks have been associated with passive continental margins whereas quartz-poor rocks as volcanogenic derivatives from magmatic island arcs. The rocks of intermediate quartz content are associated typically with active continental margins. Since inter-granular cement and matrix are the function of diagenesis and deposition, provenance studies focus on proportions of detrital framework grains (Dickinson, 1970). Diagenesis controls porosity of the sediments which in turn is controlled largely by framework composition of the rocks (Dickinson and Suczek, 1979).

The early Palaeozoic rocks in the north-western Kashmir have been substantially addressed for stratigraphy and palaeontology (Shah, 1968, 1972, 1982; Shah and Sudan, 1983, 1987; Shah, 1991), but a research gap exists as to the provenance, depositional and diagenetic environment of these rocks. This preliminary study is the first attempt to address that gap by carrying out facies, petrographic and diagenetic investigations in this area.

Geological Setting

The Palaeozoic-Mesozoic rocks of the “Himalayan Tethys belt” are exposed along a series of structural basins which constituted a continuous sea, separated as a result of collision tectonics of the Himalayan Range (Shah, 1991). Sedimentation in structural sub-basin of Kashmir, between the Pir Panjal Range in the southwest and Zanskar Range in northeast, has been deposited in subtidal shoreface to tidal flats (Bhargava, 2011). In the north-western Kashmir, the early Palaeozoic succession has been assigned to Pohru Group in Kupwara district, and predominantly comprises of argillaceous rocks with sub-ordinate calcareous and arenaceous bands. These successions are Cambro-Silurian with Precambrian basement referred as Salkhalas (Wadia, 1934). Wadia (1934) during mapping of the north-western sector of Kashmir recorded Trilobite-bearing Cambrian sediments and unconformities between the Silurian and middle Carboniferous, besides, an apparent gradation between Salkhala Crystallines and the 'Dogra Slate'. Lithologically, these rocks comprise of interbedded sequence of slate, shale, greywacke, sandstone and thin-bedded limestone. Strike is due NE-SW with average dips varying from 15º-25º to 40º-50º. In the early Palaeozoic, the basal Lolab Formation is conformably overlain by Nutnus Formation comprising of thin bedded, pale to deep green shale, with the sporadic occurrence of sandy and cherty fabric and few beds of limestones. The Trehgam Formation represents green shale or siltstone alternating with limestone interbedded with minor arenaceous bands (Table 1).

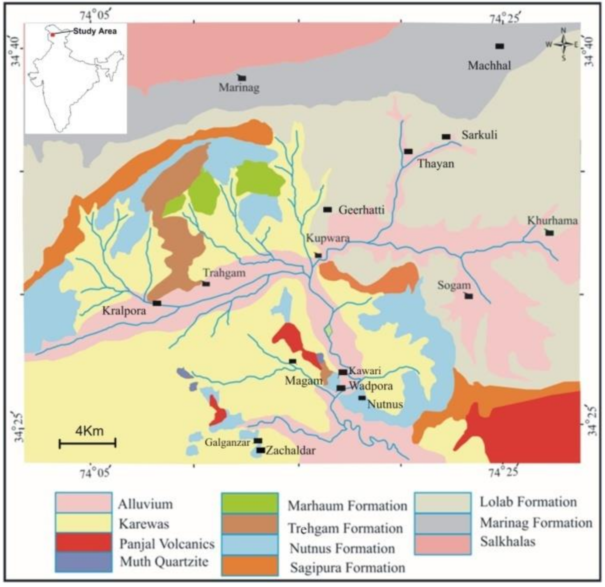

Fig-1: Geological map of study area in Kupwara district, North-western Kashmir (after Shah, 1968)

The early Palaeozoic rocks in Pohru valley are exposed in a folded sequence of Cambrian, Ordovician and Silurian rocks. These are overlain by Muth Quartzite of Middle Silurian to Early Devonian (Reed, 1912 and Goel et al., 1987) and Panjal Volcanics of Permo-Carboniferous age with a discrete angular unconformity. The age of Muth Quartzite has often remained contentious due to lack of fauna (Talent et al., 1988). However, Goel et al., 1987, Webster et al., 1993, Draganits et al., 1998; suggest Middle Silurian to Early Devonian (?) age for these rocks. Larger extent of outcrops of the early Palaeozoic comprises of the Cambrian rocks, whereas the Ordovician and Silurian rocks are exposed within the Marhaum syncline and the Shamsabari syncline (Shah, 1982). Cambrian strata directly overlie Precambrian and the complete sequence rests on a schistose basement, the Salkhala Formation. Stratigraphically, Salkhalas are overlain by Marinag Formation along a faulted contact (Wadia, 1934). The dominance of Lolab Formation exposures in the Lolab Valley is due to repetition of beds by tight and often isoclinal folding (Shah, 1982). The stratigraphic nomenclature (Table-1) adopted in this work is after Shah (1968) for lucid reading. Marinag Formation has also been referred to as Dogra Slates (Wadia, 1934) and Machhal Formation (Raina and Razdan, 1975).

Table 1: Litho-stratigraphic succession of early Palaeozoics of North-western Kashmir (After Shah, 1968)

Formation			**Lithology**	**Age**
Late Palaeozoic	Panjal Volcanics		Mafic and silicic volcanic rocks	Late Carboniferous - Early Permian
	-------------------------**NONCONFORMITY**---			
	Muth Quartzite		Quartzite and quartzitic sandstone	Middle Silurian-Early Devonian
	-------------------------**DISCONFORMITY**----			
	Marhaum		Greywacke and dark sandy Shale	Early Silurian-Middle Ordovician
Early Palaeozoic	**POHRU GROUP**	Trehgam	Green shale with alternating massive and oolitic limestone with carbonate component increasing towards top	Early Ordovician-Late middle Cambrian
		Nutnus	Thin bedded, pale to deep green shale, occasionally sandy and cherty	Middle Cambrian
		Lolab/ Sagipora	Thin bedded green to bluish grey shale alternating with sandstone/grey slaty shale alternating with sandstone	Early middle Cambrian – early Cambrian
Marinag/ Machhal/ Dogra Slates			Grey to dark grey phyllite and slate with bands of greywacke	Early Cambrian -- Precambrian
Salkhala			Schistose basement	Precambrian

Field Samples and Micropetrography

The field investigations resulted to map the lateral and vertical facies variations at Sarkuli and Geerhatti localities representing lower and upper parts of Lolab Formation, Zachaldar-Galganzar and Wadpora-Kawari of Nutnus Formation, and Kralpora representing Trehgam Formation. Oriented stratigraphic samples and thin sections of sandstones and limestones of the early Palaeozoic succession of Kupwara district are studied. The modal analyses of sandstones were addressed by following point counting method of Dickinson and Suczek (1979), with minimum of 300 frame work grains/thin section. Matrix contents were resolved during counting by tabulating only masses of the matrix having clear grain boundaries besides, rock fragments and reworked grains.

In this study, five different lithofacies have been identified on the basis of petrographic characters. The spatial and temporal interrelationship of different facies is helpful in interpretation of sedimentary history. With sedimentary processes through time, the boundaries between facies migrate laterally in response to transgressive-regressive events and geographically contiguous facies form temporal associations (Prothero and Schwab, 1996).

Facies

1. Lolab Formation (Thayan-Machhal Road Section)

The Lolab Formation along Thayan-Machhal Road has been studied at two localities namely Sarkuli and Geerhatti and is comprised of shale, siltstone, sandstone and low grade silty-slate or phyllite to siltstone or silty sandstone.

1A. SARKULI SECTION

Sandstone Facies

The lower part of Lolab Formation at Sarkuli section (34.61ºN, 74.37ºE) is characterised by bimodal sandstone facies (Fig 4a) at the lower part of the lithosection followed by boudinaged sandstone with tectonic fishes (Fig 4b) and shale/silty shale. This formation is composed of thin-bedded bluish green to grey shale with alternating sandstone/grey slaty shale interbedded with sandstone in its lower part and partly bimodal in its upper part at Geerhatti. These subfacies have gradational contacts and are seen laterally continuous for about 800m showing grain size and thickness variations. Some argillaceous beds in this lithosection being incompetent have yielded to sediment load giving subtle foliation to such rock beds, hence slate or slaty prefixes have been used here.

The sandstone of bimodal fabric is made up of quartz grains of two size populations floating in fine grained matrix of silica and clay minerals (Fig 4a). The quartz grains show high angularity indicating transportation from the nearby source, and fractured and corroded grains are attributes due to compaction. The diagenetic response of sandstone during progressive burial is specific to a complex set of boundary conditions (Dickinson and Suckzek, 1979). The bimodal sandstone is supposed to have a high natural tendency to hygric swelling and shrinking and, therefore, moisture-induced degradation (Blöchl et al., 1998). Bimodal distribution has been reported in sands of varied origin like fluvial, beach and desert (Folk, 1968). Such textural properties are common to sandstones from the lower Palaeozoics across different continents (Folk 1968).

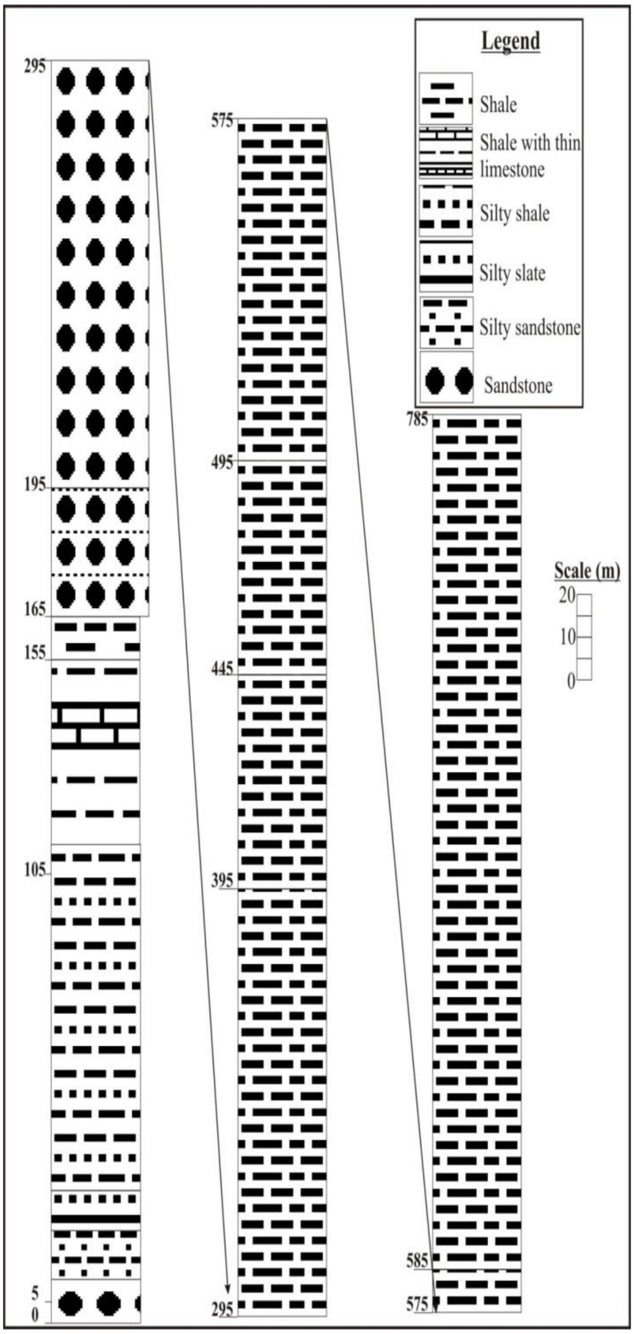

Fig-2: Litholog of lower part of Lolab Formation at Sarkuli along Thayan-Machhal Road indicating coarsening upward towards middle of the section followed by fining upward top of the section.

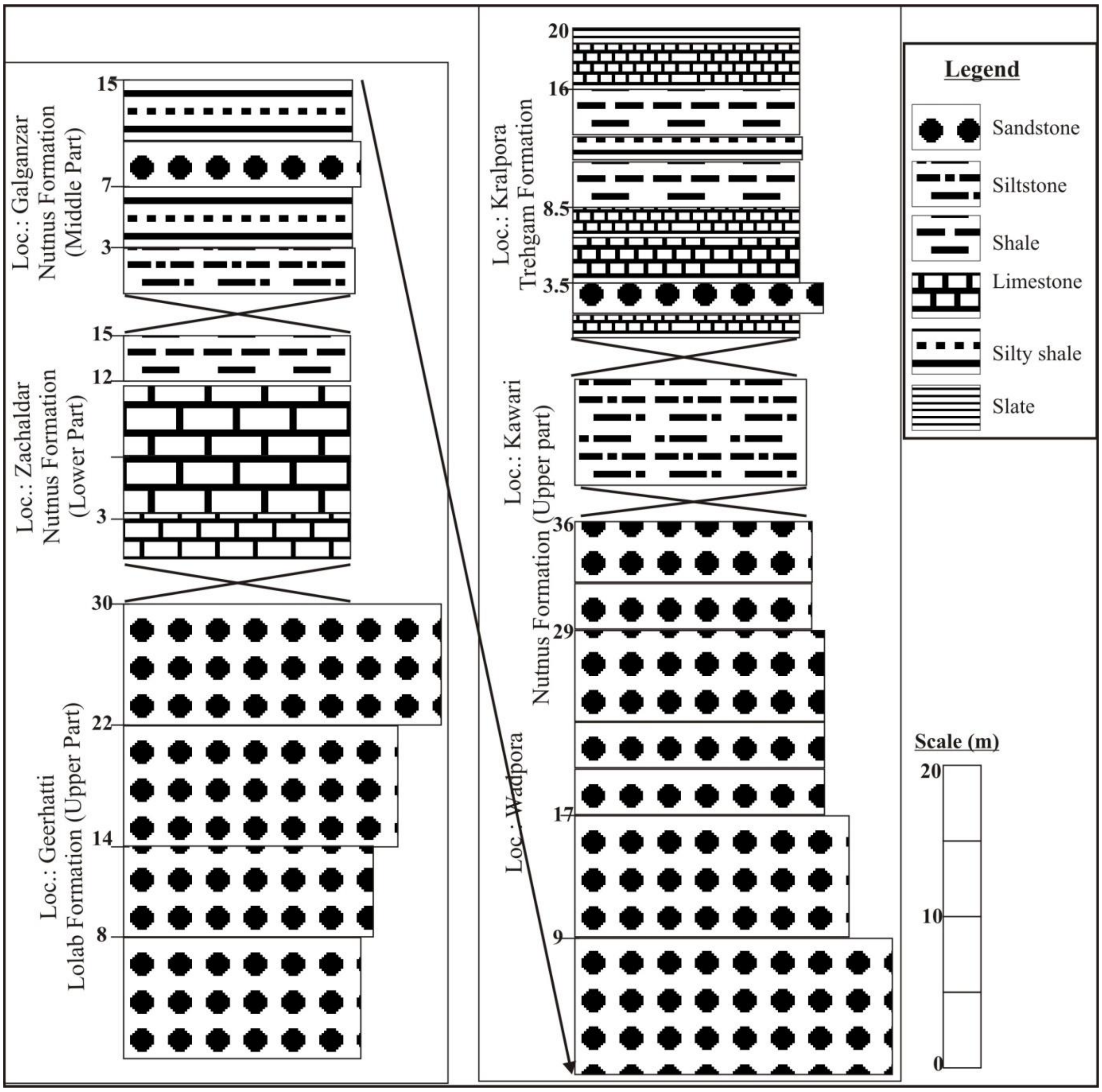

Fig-3: Litholog of Lolab Formation (upper-part), Nutnus Formation and carbonate-dominated Trehgam Formation

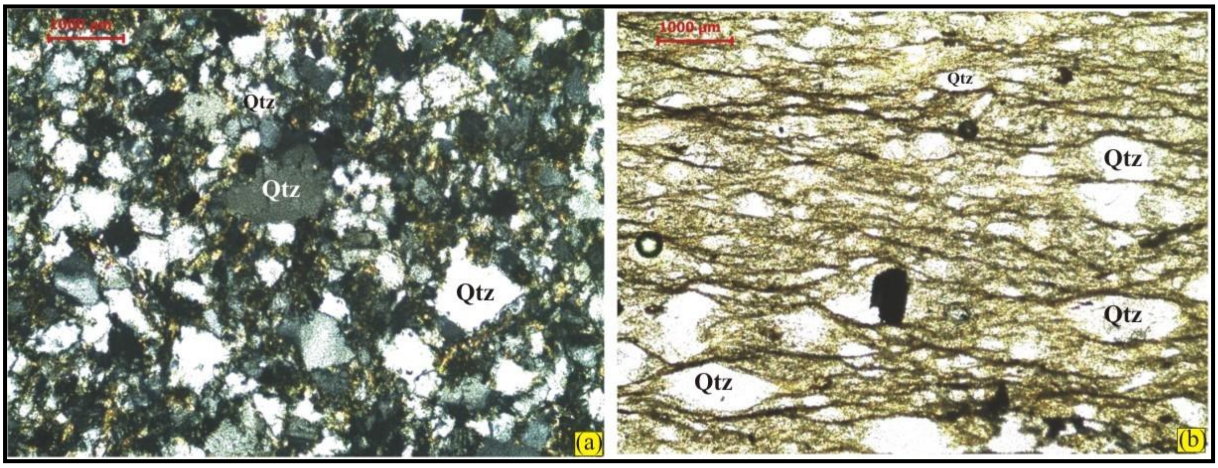

Fig: 4. Photomicrographs showing (a) Sandstone with bimodal fabric. Quart (Qtz) grains of two sizes floating in fine grained matrix of silica and clay minerals. (b) Tectonic fishes floating in fine grained ground mass of clay and silt size sediments. Boudinaged sandstone beds interbedded within the mudstone layers are indicative of extensional setup.

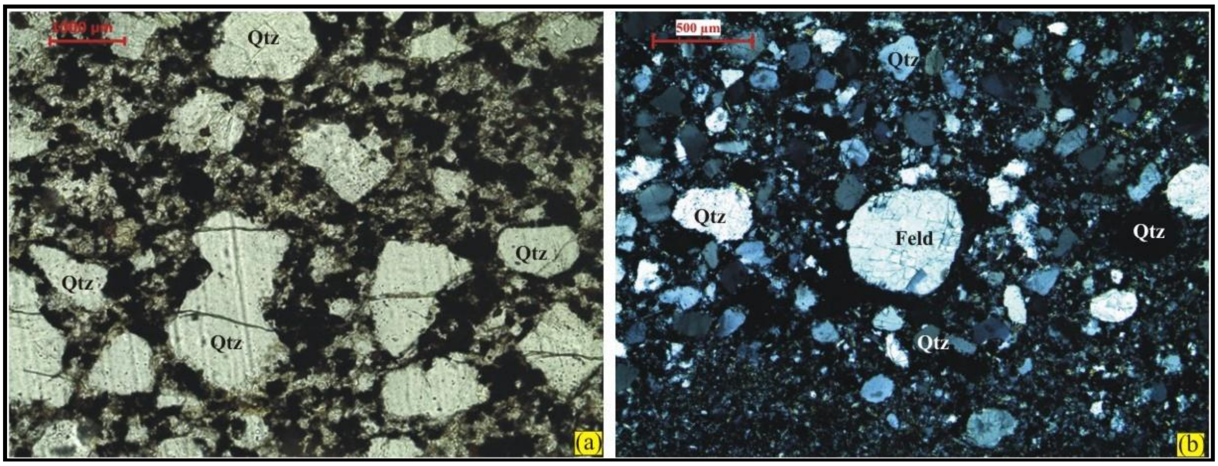

Fig: 5. Photomicrographs showing (a) Fine grained sandstone with round to subround quartz grains along with prominent quartz vein (Qv) with euhedral grains. (b) Compressional evidence where quartz vein is sheared. Recrystallization of quartz in vein due to pressure solution process in the surrounding quartz and the ground mass

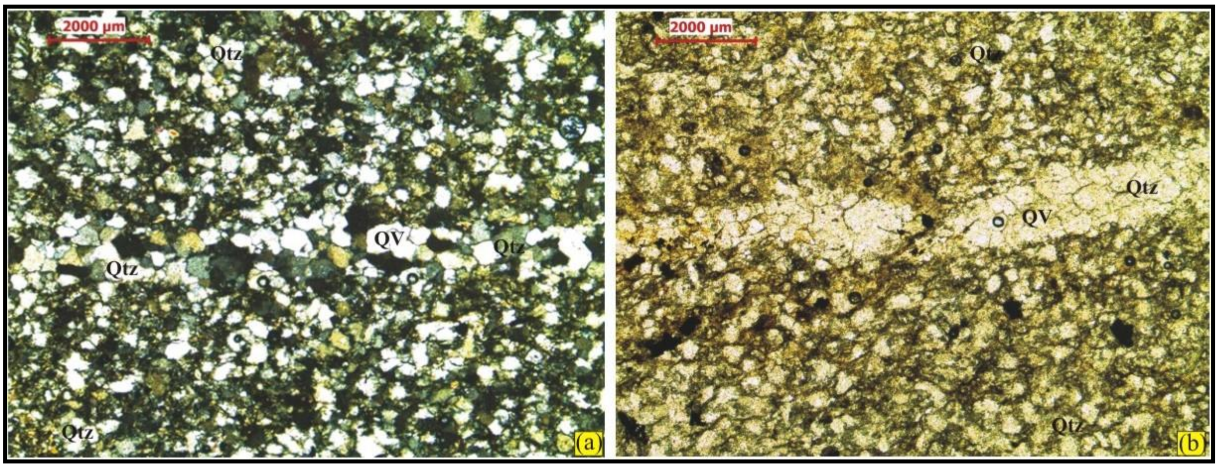

Fig: 6. Photomicrographs showing (a) Bimodal sandstone floating in fine grained ground mass. Evidences of dissolution process is reflected in residual quartz grains and fractures in larger quartz grains (b) Large feldspar (Field) grain with stress induced fractures within bimodal sandstone.

Silty Sandstone Facies

The overlying silty sandstone at lower part of the section is on an average composed of 70 - 80% monocrystalline, sub angular to sub round quartz grains with low sphericity along with 10-15% mica, characterised by tectonic fishes of muscovite floating in fine grained ground mass of clay and silt size sediments.

Besides the rock is characterised by boudinage of detrital quartz bands (Fig 4b) interbedded within the mudstone layers indicating extensional stress setup. This boudinage is reflective of limb-parallel stretching of the competent sandstone band within an incompetent mudstone. The boudinages are consistent at the limb of the fold in multilayered sequence (Ghosh and Sengupta, 1999). The extension in massive quartz result in periodic necking of the layer, giving a prominent "pinch and swell" structure followed by separation of the layer into discrete rhombic or lens-shaped boudins (Paterson & Weiss, 1968). Quartz is dominantly monocrystalline which is typically derived from volcanic source (Basu, et al; 1975) as well as from the disintegration of polycrystalline quartz in transit for long distance from a magmatic or metamorphic source (Dabbagh and Rogers, 1983), and the low sphericity indicates lower transport distance. In the middle of the Sarkuli section, the grain size grades to fine or medium sandstone characterised with quartz veins (Fig 5a, b). Moreover, the quartz veins along with the host rock have been cut across by later fractures which appear to be compressional in nature (Fig 5b). The quartz grains are round to subround in nature. Recrystallization of quartz in vein has been as a consequence of pressure solution process in the surrounding quartz of the ground mass.

The offset in quartz veins appear to be compressional as the part of vein on the left side of the fracture appears to be riding over the right hand side (Fig 5b) with bulging on either side of the fracture. However, there has been alteration of mineral where silica along the fracture zone has given rise to chlorite with free ions which are present in clay minerals. The sandstone samples (SRK1 and TM7) from lower part of Lolab Formation got plotted in lithic arenite field in QFL diagram (Fig. 12).

1B. GEERHATTI SECTION

Fine – Coarse Sandstone Facies

The Geerhatti section (N 34.50º E 74.30º) represents upper part of Lolab Formation and is dominated by range of fine to coarse sandstones and silty sandstone followed by massive coarse sandstone towards the top. This facies also shows lateral variations in grain size and thickness. The difference in silty-shale to shale-dominated lithology at Sarkuli and coarse sandstone-dominated section at Geerhatti with sandstone beds showing bimodality gives indication of depositional shift from a low energy environment suitable for fine sediments to an estuarine environment where coarse and fine sediments mix.

The coarse sandstone continues to dominate the section at Geerhatti. Bimodal sandstone is followed by sandstone with uniform grain size and is subround to round in nature (Fig 7b). The contact between siltstone and bimodal sandstone (Fig 7a) shows sharp change in the sediment size. Quartz shows evidences of compaction in the form of undulatory/wavy extinction. Quartz grains show overgrowth and compaction resulting in breakage of the grains. The contacts are sutured owing to compression and resultant pressure solution. Due to continuous compaction, the ductile grains have been squeezed out from quartz clasts. The amount of plastic deformation and framework collapse is dependent upon the amount of lithic fragments and on the time of initiation and quantity of cementation (Lander & Walderhaug, 1999). In case of more rigid grains, the mechanical compaction has caused floating and point contacts to become long as well as fracturing of rigid framework grains

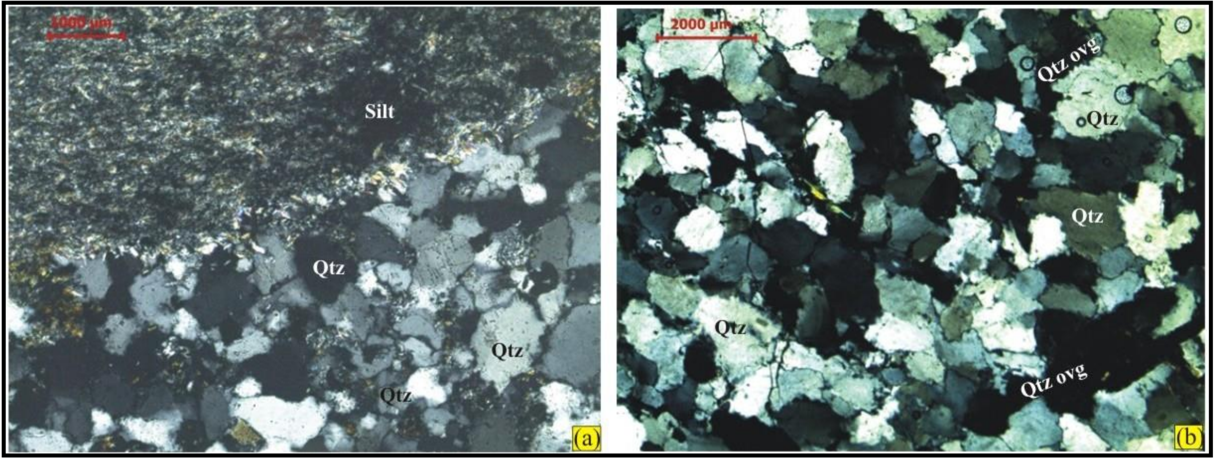

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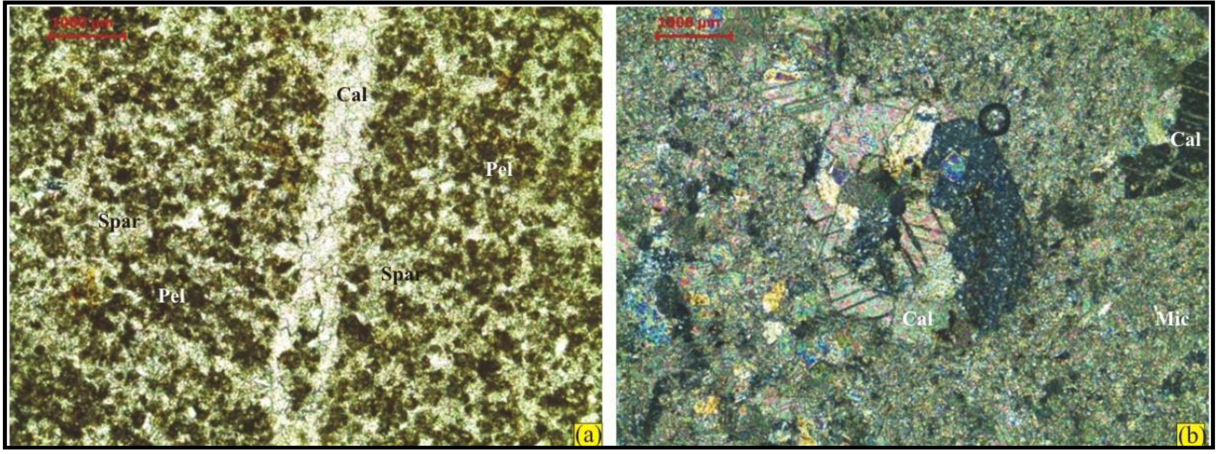
Fig: 7. Photomicrographs showing (a) Contact between sandstone and siltstone (Silt) beds (b) Sandstone with uniform grain size and sub round to round in nature. Some quartz grains show overgrowth (Qtz ovg)) and compaction resulting in breakage of the grains.

The studied section at Geerhatti shows variation in textural properties from bottom to top with bimodal silty sandstone (Fig 6a) in the lower part to low-matrix coarse grained sandstone (Fig 7b) towards the top. Undulose extinction in quartz is typical of low rank metamorphic rocks (Basu et al., 1975, Pandita and Bhat, 1995; Pandita et al., 2014). The grain contacts are predominantly sutured with few concavo–convex and pore spaces are recognizable. In sandstones, long axis grain contacts are suggestive of intermediate burial depth and concavo-convex and sutured contacts as a result of intense compaction and pressure dissolution processes during deep progressive burial diagenesis (Chima et al., 2018). Intensity of compaction is directly proportional to the overburden which results in bed thinning, expelling of intergrannular fluids (dewatering), closer packing of the grains, and reduction of porosity with advance-stage compaction transforming the concavo-convex contacts into sutured contacts (Baiyegunhi et al., 2017). The sandstone samples from the lower part of Lolab Formation are lithic arenites in nature whereas, those from upper part of the Lolab Formation belong to subarkose and sublitharenite category (Fig 12). The limited presence of sandstones in lower part of Lolab Formation with dominance of argillaceous part represented by shale implies dominance of deep and low-energy environment in comparison to sandstone dominated upper part of the formation.

2. NUTNUS FORMATION

Mixed Carbonate - Clastic Facies:

Nutnus Formation conformably overlies the Lolab Formation and is exposed in parts at Zachaldar-Galganzar locality with limestone followed by siltstone or silty sandstone and at Wadpora locality with siltstone as dominant facies and fine sandstone, whereas at Kawari it is exclusively composed of siltstone. Four exposed lithosections of Nutnus Formation were studied at Zachaldar, Galganzar, Wadpora and Kawari. A 10m lithosection at Zachaldar composed of carbonates is characterised by pelsparite facies followed by recrystallized limestone. The degree of calcite recrystallization varies between the lower and upper parts of the section. Following the dip direction to younger beds, the lithosection towards top of Nutnus Formation at Galganzar is cropping out with fine grained sandstone dominated by subround quartz grains with feldspar in fine grained ground mass followed by fine grained sandstone with uniformly distributed sub round quartz grains floating in matrix. Both sandstones are having prevalent elongated mica grains. The lower part is composed of pellet bearing carbonate (Fig 8a) containing scattered peloids cemented within calcite (Pelsparite of Folk, 1959). The overlying part of the lithosection comprises of limestone recrystallized from micritic matrix in which about 60% of matrix has got recrystallized into calcite with distinct cleavage sets (Fig 8b). Moreover, prior to recrystallization the veins of calcite have been developed. After the deposition of carbonate-rich part in calm and warm environment, the depositional environment has shifted to fluvial low energy condition leading to deposition of fine sandstone both at Zachaldar as well as at Wadpora. The three sandstone samples (from Galganzar and Wadpora lithosections) of the Nutnus Formation plotted in subarkose field in QFL diagram (Fig 12).



Figs: 8. Photomicrographs showing (a) Limestone beds marked by calcite (Cal) veins filled with sparry calcite. The thin section shows pelsparite having well distributed sparite (Spar) and, partially replaced pellets (Pel) due to compaction and pressure solution processes. (b) Recrystallized limestone showing well developed crystals of calcite (Neomorphism) with prominent cleavage sets. Calcitization of micrite (Mic) is prevalent uniformly throughout the thin section.

The limestone at bottom of Zachaldar section is marked by calcite veins filled with sparry calcite. The section shows pelsparite having well distributed sparite which partially replaces pellets due to compaction and pressure solution process. Variations in the intensity of the calcification being controlled by the level of calcium carbonate saturation give rise to homogeneous micrite and peloid-like bodies, producing a pelmicrite fabric. Disintegration of such fabric gives way to formation of individual peloids and reworking by currents result in a pelsparite texture (Flugel & Flügel, 2004). The comparison between lower and upper part of Zachaldar lithosection and the continuous calcite veins with recrystallization of calcite along veins and in host mass in the lower section and the upper part of the section indicates a break in diagenetic progression as it is still partially micritic in nature. This is attributed to tectonic exhumation of the section during the middle Cambrian. Since, it is difficult to differentiate between solution-precipitates and recrystallization in polarising microscope (Boggs, 1995), a term neomorphism was introduced (Folk, 1965) which includes all transformations between one mineral itself or its polymorph. This process involves all transformations between polymorphs of carbonate minerals and their recrystallization to stable forms within a given set of physico-chemical parameters of the basin.

Towards northwest of Zachaldar lithosection at a distance of about 200m, Galganzar lithosection is composed of mudstone followed by non fissile siltstone and fine sandstone with remarkable amounts of muscovite flakes (Fig 9a) which have been bent and have high order blue and green colour. Individual detrital minerals which are flexible or brittle are indicators of deformation (Adams and Mackenzie, 1998). The preferred orientation difference in different minerals is due to differential response of minerals to diagenetic stress (Reed, 1962). The siltstone is overlain by fine grained sandstone with uniformly distributed subround quartz grains floating in matrix along with prevalent elongated mica grains (Fig 9b).

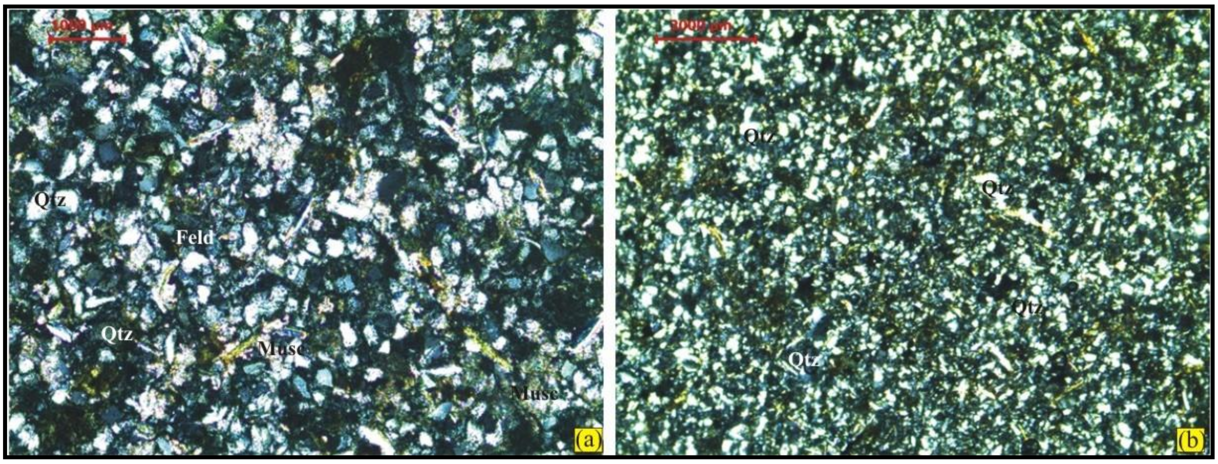


Fig: 9. Photomicrographs showing (a) Fine grained sandstone dominated by sub round quartz grains, feldspar, elongated micas (Muscovite) and fine grained ground mass. (b) Fine grained sandstone with uniformly distributed sub round quartz grains floating in matrix with elongated mica grains.

Nutnus Formation at Wadpora and abandoned quarry at Kawari is composed of siltstone, and medium to coarse sandstone with occasional alternating mudstone laminations. This attributes to as facies variant of Zachaldar-Galganzar section in vertical extension as the carbonate beds are absent. However, like interrupted diagenesis indicated by partially recrystallized calcite from carbonates in Zachaldar section, this part shows diagenetic immaturity of detrital siltstones and sandstones from their low degree of sorting and presence of clayey matrix of chlorite appearing in first order yellow interference colour in most of the samples apart from iron oxide-filled pores. The grain-coating of chlorite, inhibits quartz overgrowth in sandstone and reflects the original porosity in deeply buried sandstones (Worden, et al., 2020). The upper part of lithosection at Wadpora is represented by siltstone with dispersed quartz grains (Fig 10a). The quartz grains are comparatively large in size. The small quartz grains are aligned in one direction giving rise to subtle foliated fabric of the rock.

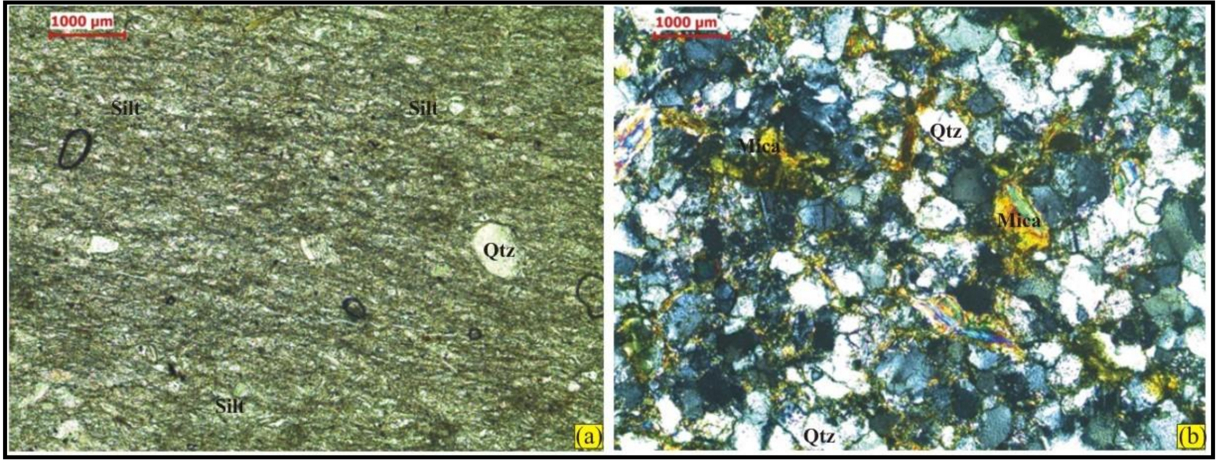


Fig: 10. Photomicrographs showing (a) Siltstone with scattered quartz grains (b) Sandstone with subround to round quartz grains and elongated micas

Kawari section is dominantly composed of sandstone (Fig 10b) with sub round to round quartz grains and elongated micas, loosely packed fine grains of feldspar and muscovite floating in matrix supported material (>15%), with interbedded mud laminations. Bent mica flakes indicate mechanical compaction. The quartz grains are corroded which enhances the porosity of the rock (Lin et al., 2019). The indurated nonfissile siltstone has moderate to poor orientation of clay minerals and a predominance of silt over clay-sized material. The original lamination appears to have been destroyed with apparent difference in orientation of detrital quartz grains. Quartz with abundant fluid inclusions or vacuoles is usually derived from a source of low-temperature origin, like hydrothermal vein (Adams and Mackenzie, 1998).

3. TREHGAM FORMATION-KRALPORA SECTION

Mixed Carbonate –clastic Facies

Trehgam Formation has one of its best outcrops at Kralpora which represents a lithosection dominated by limestone with interbedded sandstone or siltstone. Limestones dominate bedding at Kralpora section from micritic bottom layer with interbedded siltstone or fine sandstone towards top of the section. This is followed by meter-thick fine sandstone with calcite cement. Towards upper part, the section is again dominated by carbonates with prominent recrystallized limestone showing well developed crystals of calcite (neomorphism) along with pseudo pellets. Trehgam Formation is characterised by pelsparite (Fig 11a) with uniformly distributed sparry calcite, corroded pellets with patches of algae also discernible in the micro sections. Calcitization of micrite is prevalent uniformly throughout the section.

From the lateral and vertical facies variations it can be deduced that the lithosection at Kralpora demonstrates the formation of carbonate part within warmer, sub-tropical conditions. Moreover the silty or sandy beds can be inferred as a result of fall in sea level giving rise to shallow and higher energy siliciclastic sediments. The deposition of sandstone and shale beds indicates shift from deep-water and low energy to shallow-water high energy environment and vice-versa that has given rise to alternate areno-argillaceous beds with carbonate-dominated deposition within Kralpora section of Trehgam Formation.

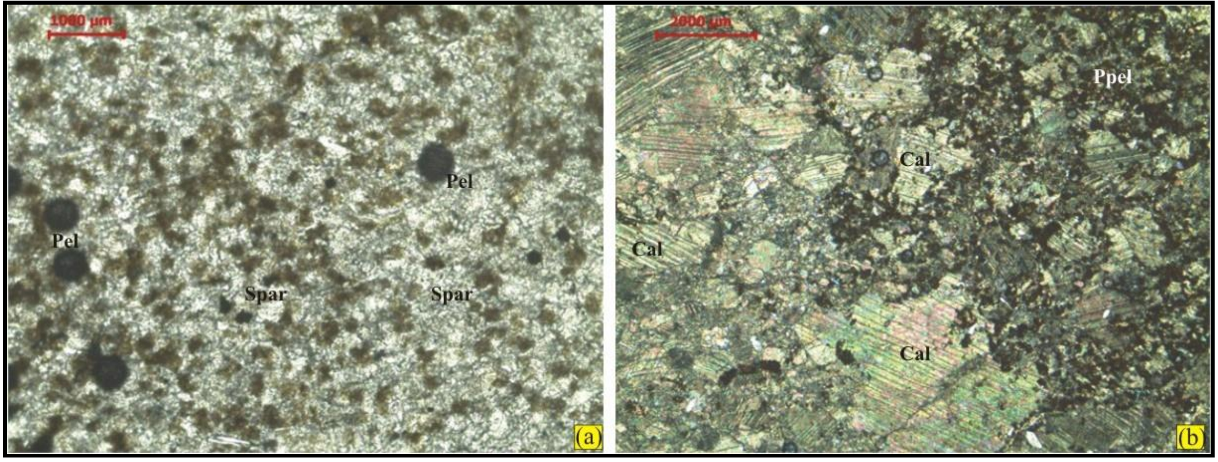


Fig: 11. Photomicrographs showing (a) Pelsparite with uniformly distributed sparry calcite and corroded pellets. Patches of algae are also discernible in the thin sections. (b) Recrystallized limestone showing well developed crystals of calcite (neomorphism) along with pseudo pellets (Ppel). Calcitization of micrite is prevalent uniformly throughout the thin sections.

The patches of algae discernible in pelsparite, and recrystallized limestone (Fig 11b) show well developed crystals of calcite (neomorphism) along with pseudo pellets. Calcitization of micrite is prevalent uniformly. The neomorphic features apart from pseudopellets (Fig 11b) are similar to recrystallized limestone (Fig 8b) of Zachaldar section. In Kralpora section intergrannular spaces are characterised with carbonate cement as evident from high interference colours under crossed nicols. The limestone (Fig 11a) is composed of pelsparite with uniformly distributed sparry calcite and corroded pellets. Recrystallization and neomorphism are processes involved in transformation of minerals in situ into their polymorphs (Dickson, 2003). However, the gap exists with respect to the term recrystallization as it is restricted to strain induced transformation (Bathurst, 1958) but it has been used for any change in form without a change in mineral species. The carbonate cement in fine sandstone is typical indication of regressive environment that led to the deposition of sandy layer with available in situ carbonate that was incorporated as cement. However, regression has remained short-lived as the bed is followed by alternate limestone and shale beds towards the top of the section. The only sandstone sample (KRL2) from this formation got plotted in subarkose field in QFL diagram (Fig 12).

RESULTS AND DISCUSSION

The Lolab Formation has shown alternating phases of regression and transgression environments. The deposition of lower part of Lolab Formation has taken place in high energy environment with indications of mixing as reflected by bimodal sandstone (Fig 5a). It is followed by rise in sea level (transgression) as is indicated by low energy silty and shale-dominated lithologies. Towards middle part of lithosection the regression has given way to deposition of sandstone characterised by diagenetic quartz veins followed again by transgression and resultant fining of sediments upward. The environment of deposition for lower part of Lolab Formation has largely been deep water that provides low-energy environment favourable for argillaceous deposition. Shales form under environmental conditions in which fine sediments are abundant and energy is sufficiently low to allow settling of suspended fine particles. Such favourable conditions for shale deposition are particularly available below the wave base (Boggs, 1995). In sandstones of upper part of Lolab Formation, the strain is reflected by quartz with undulose extinction. Chemical compaction has resulted in the formation of concavo-convex and sutured grain contacts, both caused by pressure solution. The sandstones at Geerhatti display point to sutured grain contacts developed as a result of progressive burial. The grain-to-grain contacts are suggesting that the grains were mechanically compacted.

Table 2: Modal composition of sandstones from early Palaeozoic succession in Kupwara District of North-western Kashmir in the study area.

Formation	Sample No.	Quartz %	Feldspar %	Lithic fragments / others %
TREHGAM FORMATION	KRL2	70	20	10
NUTNUS FORMATION	GG1	80	15	5
	ZB1C	75	15	10
	ZBT3	70	20	10
LOLAB FORMATION	GH1	75	20	5
	GH2	80	15	5
	GH3	75	10	15
	GH4	65	10	25
	SRK1	60	10	30
	TM7	65	10	25

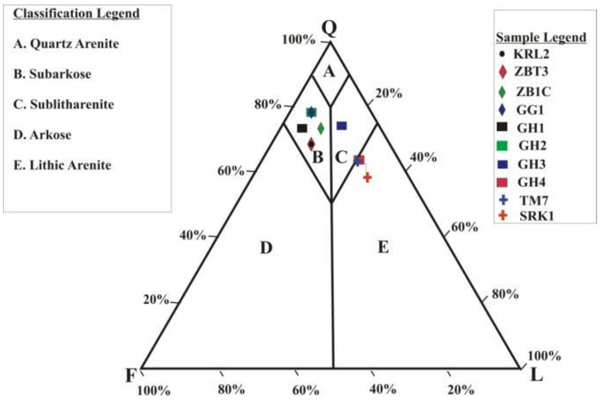


Fig-12: Classification of sandstones from early Palaeozoic succession of north-western Kashmir in the study area.

In Lolab Formation, the difference in response to diagenetic compaction between lower and upper parts is recognised by development of subtle foliated fabric in incompetent argillaceous beds of lower part and sutured contact development with fracturing in competent quartz- rich upper part. Moreover, the overlying sediment load warrants a greater diagenetic stress for bottom beds. The coarsening of sediments towards middle of the section is evidence of seaward shift of shoreline followed by transgression as indicated by fining upwards. However, upper part of Lolab Formation in the study area has got low-matrix coarse sandstone at Geerhatti indicating higher energy conditions in comparison to lower part with indications of estuarine sedimentation. Quartz overgrowths in upper part (Geerhatti section) of Lolab Formation reduce porosity of these sedimentary rocks. Sands respond differently to processes involved for porosity reduction with changes in basin tectonics. The sorting depends on the range of the sediment sizes, deposition rate, the strength and variation in energy of the agent of deposition (Amaral and Pryor, 1977). The poorly sorted silty-sandstone towards top of the section indicates low textural maturity. The fractured grains of K-feldspar with high relief appear to be deformed post deposition otherwise being fractured and cleavable would have preferably disintegrated during the course of transit due to attrition. The petrographic signatures show a gradual shift from a bimodal sedimentation in estuaries at bottom of the section where both silt-size and coarse-size sand have mixed to deep water sedimentation followed by very coarse grained sandstones indicating shallowing of the basin towards top of the section. Moreover, such a sharp shift in grain size from deep water fine shaly sediments to coarse sandstone can be attributed to fast basin-uplift during the process of sedimentation. The difference in silty-shale to shale-dominated bottom part and coarse sandstone-dominated upper part showing bimodality brings forth two different depositional settings with respect to depth and energy conditions of the basin.

The lower part of Nutnus Formation (overlying Lolab Formation) at Zachaldar has carbonate beds within siliciclastics indicating a shift in sea level from shallow shelf to deep shelf or slope as well as temperature change necessary for carbonate deposition.

Depositional margins have a low relief from platform to slope and basins; by-pass margins have a characteristic steeper relief shifting the deposition of platform-sourced sediment on lower slopes and adjacent basinal plains. This means that during the deposition of the lower part of Nutnus Formation, the basinal setup was possibly between deep basinal part and shelf favourable for carbonate precipitation within the warm photic zone. The upper part of Nutnus Formation is dominated by siliciclastic sedimentation with silts and sands reflecting change in sea level giving way to shelf deposition. The Kawari section in continuity of Wadpora section seems to represent a deep slope to continental rise environments. The effect of water-rock interaction has been time dependent as well as variable with alkalinity or acidity of water. In terms of hydrophysical effects, the dissolution of rocks results in reduction of the physical and mechanical properties by reducing the interconnection between the mineral particles and the effectiveness of lithostatic pressure. These effects deteriorate the physical and mechanical properties of rocks by altering the mineral components and microstructure of rocks, such as the particle size, represented by micritic texture towards the top with onset of calcitization (Sparry calcite). The formation of sparry calcite from micrite involves a set of intermediate processes including genesis of dense liquid phases inside the aqueous solution in organized (meta)stable clusters that serve as precursors to the formation of amorphous calcium carbonate (ACC) micro crystals (Cartwright et al., 2012). This ACC can either be hydrated or anhydrous (Ihli et al., 2014). Its aging gives rise to formation of calcium carbonate polymorphs like vaterite, aragonite, calcite depending on the physicochemical conditions (Gebauer et al., 2008; Rodriguez-Blanco et al., 2011; Sun et al., 2015), e.g. temperature, depth or hydrostatic pressure, chemical composition of the solution, including pH, salinity, Mg content, etc. (Tai and Chen, 1998; Wolthers et al., 2012; Blue et al., 2017). Dehydration of ACC in turn provides another driving force (i.e. an energetic contribution) to give orientation to the crystallization process towards a particular polymorph (Ihli et al., 2014). The stable crystalline phase may also nucleate directly from the solution, without the genesis of cluster precursors (Nielsen et al., 2014). In view of the classic nucleation theory, surface tension plays an important role in the evolution of a nucleus. However, published data on surface energies of calcium carbonate polymorphs are scattered and inconsistent (Aquilano et al., 1997; Sun et al., 2015). The dominance of carbonates in the section indicates a warm sub-tropical climate as most modern carbonate deposition demonstrates a positive correlation between such deposition and the equatorial belt as well as areas of warm ocean currents (Wilson, 1975).

Chilingar et al., (1967) has graphically presented that neritic carbonates exist mainly to north and south of the equator within latitudes of 30°. However, biogenic elements are rarely seen in Trehgam pore geometry, and crack morphology. The physical and chemical water–rock reactions result in the generation of secondary porosity of the rock followed by slowing down of the process of porosity enhancement. This finally moves to a state of equilibrium after many associated processes of hydrolysis, corrosion, oxidation, and reduction along with ionic exchange giving interim stability to the rock (Qiao et al., 2017). It has been established that round and well round grains which are unfractured are least affected by surface corrosion, whereas round grains which are fractured are more prone to embayments and surface corrosion. The constituent grains are cemented by iron oxide (isotropic in X-polars) and partly by chlorite having first order yellow. Chlorite being readily recognized by its birefringence and morphology, commonly grows in sedimentary regime and has a tendency to form within the entire range of temperatures and pressures from moderate diagenetic burial through green-schist grade of metamorphism. The Trehgam Formation has significant representation of carbonates at Kralpora section. The carbonate beds occur around middle of the section and are Formation which indicates absence of sustenance-temperature and/or nutrients for biogenic agents. This warrants a possibility of deep environment necessary for micritic precipitation rather than a biogenic contribution or lime mud formation by the erosion and abrasion of micritized grains (Reid et al., 1992). Micritic limestones form by CaCO3 'rain' triggered by inorganic precipitation in the water column (Kazmierczak et al., 1996).

The line between metamorphism-induced recrystallization and diagenesis in carbonates of both basal part of Nutnus Formation and carbonates of Kralpora section is drawn by the degree of transformation of micrite into calcite. The degree of calcite crystallization has been higher in Zachaldar section representing lower part of Nutnus Formation in comparison to that of Kralpora section of Trehgam Formation. Bathurst (1966) employed the term "micritization" to describe alteration or grain-diminution (Wolf, 1965) of original skeletal grains to a cryptocrystalline nature by repeated algal micro-borings and subsequent filling of these borings by micritic precipitate. Micrite is formed by several processes including destructive micritization by the micro boring organisms, positive development of micrite, related to epilithic organisms, and inequitable dissolution and recrystallization (Flügel, 2004). The carbonate-dominated section of Trehgam Formation without any traces of biogenic imprints and micritic nature at Kralpora indicates shifts in temperature of the basin as well as the depth of sedimentation in an environment adverse to biota but favourable for micrite precipitation. This is referred to as inequitable dissolution and recrystallization (Flügel, 2004), the recrystallization has not been able to keep pace with the precipitate deposition to poly-phase transformation of micrite or ACC to calcite owing to unfavourable conditions.

CONCLUSION

The facies and petrographic evidences of the early Palaeozoic successions from Lolab Formation through Nutnus Formation to Trehgam Formation suggest varying depositional environments. Provenance of these rocks has been of mixed nature with monocrystalline quartz dominant in sandstones indicating greater contribution from igneous sources.

The diagenetic responses have varied between argillaceous lower part of Lolab Formation and its arenaceous upper part in the study area. These responses to mechanical compaction and cementation are in harmony with difference in their composition as well as their depth of burial and/or position in stratigraphic column. The transgression-regression cycles have continued through Nutnus Formation well up to Trehgam Formation. The Nutnus Formation shows warm and deep environment represented by biogenic traces-rich carbonates in its basal part followed by shallower argillaceous to arenaceous sediments towards its upper part. The change from carbonate to siliciclastic deposition is due to temperature changes as well as depth of the basin that might have shifted carbonate deposition further north of study area in the Tethyan realm making way for non-carbonate deposition. Diagenetic evidences are suggestive of higher burial-residence time for carbonates of Nutnus Formation (lower part with higher degree of calcite recrystallization) than those of the Trehgam Formation. This is in harmony with the stratigraphic position of these formations as geothermal gradient warrants higher diagenetic temperatures for deeper formations in comparison to their shallower counterparts. With fine argillaceous deep-water sediments in lower part of Lolab Formation, coarsening in its middle part followed again by alternate fining and coarsening towards top, along with carbonate alternations with siliciclastic sedimentation in Nutnus and Trehgam formations, it is concluded that there are five transgressive-regressive cycles that have shaped the formations of early Palaeozoic of the north-western Kashmir in the study area.

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References

Adams, A., & MacKenzie, I. (1998). Carbonate Sediments and Rocks under the Microscope: a colour atlas. CRC Press.

Amaral, E. J., & Pryor, W. A. (1977). Depositional environment of the St. Peter sandstone deduced by textural analysis. *Journal of Sedimentary Research*, *47*(1), 32-52.

Aquilano, D., Rubbo, M., Catti, M. and Pavese, A. (1997) Theoretical equilibrium and growth morphology of CaCO3 polymorphs I. Aragonite. *J. Cryst. Growth,* 182, 168–184.

Baiyegunhi, C., Liu, K., & Gwavava, O. (2017). Diagenesis and reservoir properties of the permian Ecca Group sandstones and mudrocks in the Eastern Cape Province, South Africa. *Minerals*, *7*(6), 88.

Basu, A., Young, S.W., Suttner, L.J., James, W.C., Mack, G.H., (1975). Re-evaluation of the use of undulatory extinction and polycrystallinity in detrital quartz for provenance interpretation. *Journal of Sedimentary Petrology*, 45, 873-882.

Bathurst, R. G. (1961). Diagenetic fabrics in some British Dinantian limestones. *Geological Journal*, *2*(1), 11-36.

Bathurst, R. G. C. (1966). Boring algae, micrite envelopes and lithification of molluscan biosparites. *Geological Journal*, *5*(1), 15-32.

Bhargava, O. N. (2011). Early Palaeozoic palaeogeography, basin configuration, palaeoclimate and tectonics in the Indian Plate. *Facets of Phanerozoic. Mem. Geol. Soc. India*, 78, 69-99.

Blöchl, B., Kirchner, D., & Stadlbauer, E. (1998). Die hygrische Dehnung von Baumberger Kalksanstein–tonmineralogische und gesteinsphysikalische Aspekte. *Arbeitshefte zur Denkmalpflege in Niedersachsen*, *15*, 46-53.

Blue C. R., Giuffre A., Mergelsberg S., Han N., De Yoreo J. J. and Dove P. M. (2017). Chemical and physical controls on the transformation of amorphous calcium carbonate into crystalline CaCO3 polymorphs. *Geochimica et Cosmochimica Acta*, 196, 179–196.

Boggs, S. (1995). Principles of Sedimentology and Stratigraphy (Vol. 774). New Jersey: Prentice Hall.

Cartwright, J. H., Checa, A. G., Gale, J. D., Gebauer, D., & Sainz-Díaz, C. I. (2012). Calcium carbonate polyamorphism and its role in biomineralization: how many amorphous calcium carbonates are there?. *Angewandte Chemie International Edition*, *51*(48), 11960-11970.

Chilingar, G. V., Bissell, H. J., & Wolf, K. H. (1967). Diagenesis of carbonate rocks. In *Developments in sedimentology* (Vol. 8, pp. 179-322). Elsevier.

Chima, P., Baiyegunhi, C., Liu, K., & Gwavava, O. (2018). Diagenesis and rock properties of sandstones from the Stormberg Group, Karoo Supergroup in the Eastern Cape Province of South Africa. *Open Geosciences,* 10(1), 740-771.

Crook, K. A. (1974). Lithogenesis and geotectonics: the significance of compositional variation in flysch arenites (graywackes).

Dabbagh, M. E., Rogers, J. W. (1983). Depositional environments and tectonic significance of the Wajid Sandstone of southern Saudi Arabia. *Journal of African Earth Sciences*, 1, 47-57.

Dickinson, W. R. (1970). Interpreting detrital modes of graywacke and arkose. *Journal of Sedimentary Research*, *40*(2), 695-707.

Dickinson, W. R. and Suczek, C. A. (1979). Plate tectonics and sandstone compositions; *Am. Assoc. Pet. Geol. Bull.* **63** 2164–2182.

Dickson, J. A. D. (2003). Neomorphism and Recrystallization. *Encyclopedia of Sediments and Sedimentary Rocks (ed. Middleton GV).* Kluwer Academic Publishers, Boston, 460-462.

Draganits, E., Grasemann, B., & Braddy, S. J. (1998). Discovery of abundant arthropod trackways in the ?Lower Devonian Muth Quartzite (Spiti, India): implications for the depositional environment. *Journal of Asian Earth Sciences*, *16*(2-3), 109-118.

Eriksson, K. A., Taylor, S. R., & Korsch, R. J. (1992). Geochemistry of 1.8-1.67 Ga mudstones and siltstones from the Mount Isa Inlier, Queensland Australia: Provenance and tectonic implications. *Geochimica et Cosmochimica Acta*, *56*(3), 899-909.

Flugel, E., & Flügel, E. (2004). Microfacies of Carbonate Rocks: Analysis, Interpretation and Application. Springer Science & Business Media.

Folk, R. L. (1959). Practical petrographic classification of limestones. *AAPG bulletin*, *43*(1), 1-38.

Folk, R. L. (1965). Some aspects of recrystallization in ancient limestones.

Folk, R. L., (1968). Bimodal supermature sandstones of the Desert floor, pp. 9-32, Int. Geo/.Congo Report, 23rd. Session, Czechoslavakia, Proc. Sec. 8.

Gebauer, D., Völkel, A., & Cölfen, H. (2008). Stable prenucleation calcium carbonate clusters. *Science*, *322*(5909), 1819-1822.

Ghosh, S. K., & Sengupta, S. (1999). Boudinage and composite boudinage in superposed deformations and syntectonic migmatization. *Journal of Structural Geology*, *21*(1), 97-110.

Goel, R. K., Kato, M., Jain, A. K., & Srivastava, S. S. (1987). Fauna from the" Muth Quartzite", Garhwal Himalaya, India. *北海道大学理学部紀要*, *22*(2), 247-257.

Ihli J., Wong W. C., Noel E. H., Kim Y.-Y., Kulak A. N., Christenson H. K., Duer M. J. and Meldrum F. C. (2014). Dehydration and crystallization of amorphous calcium carbonate in solution and in air. *Nat. Commun*. 5.

Kazmierczak, J., Coleman, M. L., Gruszczynski, M., & Kempe, S. (1996). Cyanobacterial key to the genesis of micritic and peloidal limestones in ancient seas. *Acta Palaeontologica Polonica*, *41*(4), 319-338.

Lander, R. H., & Walderhaug, O. (1999). Predicting porosity through simulating sandstone compaction and quartz cementation. *AAPG bulletin*, *83*(3), 433-449.

Lin, Y., Zhou, K., Gao, R., Li, J., & Zhang, J. (2019). Influence of chemical corrosion on pore structure and mechanical properties of sandstone. *Geofluids*, *2019*.

McLennan, S. M., Taylor, S. R., McCulloch, M. T., & Maynard, J. B. (1990). Geochemical and Nd□ Sr isotopic composition of deep-sea turbidites: crustal evolution and plate tectonic associations. *Geochimica et Cosmochimica Acta*, *54*(7), 2015-2050.

Nielsen, M. H., Aloni, S. and De Yoreo, J. J. (2014). In situ TEM imaging of CaCO3 nucleation reveals coexistence of direct and indirect pathways. *Science* 345, 1158–1162.

Pandita, S. K. & Bhat, G. M. (1995). Petrographic and facies evaluation of Middle Siwalik Subgroup Jammu, Himalaya. *Journal of Geological Society of India*, 46: 369–374.

Pandita, S. K., Bhat, S. K., Kotwal, S. S., Singh, Y. And Thakur, K. K. (2014). Provenance and tectonic settings of the Lower Siwalik Subgroup, Jammu, Northwest Himalaya. *The Palaeobotanist*, 63, 17-23.

Parcha, S. K. (2021). Stratigraphy and the Fossil record of the Palaeozoic and Mesozoic Tethyan sequences of North-western Himalaya. *Himalayan Geology*, *42*(1), 1-68.

Paterson, M. S., & Weiss, L. E. (1968). Folding and boudinage of quartz-rich layers in experimentally deformed phyllite. *Geological Society of America Bulletin*, *79*(7), 795-812.

Prothero, D. R., & Schwab, F. (1996). An Introduction to Sedimentary Rocks and Stratigraphy. *Sedimentary Geology, New York, WH Freeman and Company*, 575.

Qiao, L., Wang, Z., & Huang, A. (2017). Alteration of mesoscopic properties and mechanical behavior of sandstone due to hydro-physical and hydro-chemical effects. *Rock Mechanics and Rock Engineering*, *50*(2), 255-267.

Raina, B. K. & Razdan, M. L., (1975). Geology of parts of Machhal, Lolab and Kandi-Shiu areas of Kupwara, Hundwara and Sopore tehsils, Baramulla Distt, J & K State *(Unpub. GSI Report)*

Reed, F.R.C., (1912). Ordovician and Silurian fossils of central Himalayas. *Palaeont. Indica, Geol. Surv. India.* Ser. 15,7 (2): 1-168.

Reed, J. J. (1962). The importance of lithology in determining response to metamorphism and tectonic forces. *New Zealand Journal of Geology and Geophysics*, *5*(1), 86-91.

Reid, R. P., Macintyre, I. G., & Post, J. E. (1992). Micritized skeletal grains in northern Belize Lagoon; a major source of Mg-calcite mud. *Journal of Sedimentary Research*, *62*(1), 145-156.

Rodriguez-Blanco, J. D., Shaw, S., & Benning, L. G. (2011). The kinetics and mechanisms of amorphous calcium carbonate (ACC) crystallization to calcite, via vaterite. *Nanoscale*, *3*(1), 265-271.

Roser, B. P., & Korsch, R. J. (1986). Determination of tectonic setting of sandstone mudstone suites using SiO2 content and K2O/Na2O ratio. Journal of Geology, 94, 635–650.

Roser, B. P., & Korsch, R. J. (1988). Provenance signatures of sandstone mudstone suite determined using discrimination function analysis of major element data. Chemical Geology, 67, 119–139.

Schwab, F. L.,(1975). Framework mineralogy and chemical composition of continental margin-type sandstone: Geology, v. 3, p. 487-490.

Shah, S. K., (1968). A lithostratigraphic classification of Lower Palaeozoic slate group of Pohru Valley of North Western Kashmir. *University Review*, *2*, 10-17.

Shah, S.K., (1972). Palaeo-ecological studies of the Cambrian--Ordovician formation of north-western Kashmir. University Review, Jammu, 4: 1--7.

Shah, S. K. (1982). Cambrian stratigraphy of Kashmir and its boundary problems. *Precambrian Research*, *17*(2), 87-98.

Shah, S. K., & Sudan, C. S., (1983). Trace fossils from the Cambrian of Kashmir and their stratigraphic significance.

Shah, S. K., & Sudan, C. S. (1987). Damesellidae from the Cambrian of Kashmir. *Journal of the Geological Society of India*, *29*(5), 503-509.

Shah, S. K. (1991). Stratigraphic setting of the Phanerozoic rocks along the northern boundary of the Indian plate. *Physics and Chemistry of the Earth*, *18*, 317-328.

Sun, W., Jayaraman, S., Chen, W., Persson, K. A., & Ceder, G. (2015). Nucleation of metastable aragonite CaCO3 in seawater. *Proceedings of the National Academy of Sciences*, *112*(11), 3199-3204.

Tai, C. Y., and Chen, F. B. (1998). Polymorphism of CaCO3, precipitated in a constant-composition environment. AIChE J. 44, 1790–1798.

Talent, J. A., Goel, R. K., Jain A. K. and Pickett J. W. (1988) Silurian and Devonian of India, Nepal and Bhutan: Biostratigraphic and Palaeobiogeographic Anomalies. *Cour. Forsch.-Inst. Senckenberg* **106**, 1-57.

Wadia, D. N. (1934). The Cambrian-Trias sequence of north-western Kashmir (parts of Muzaffarabad and Baramula districts). *Records of the Geological Survey of India*, *68*(2), 121-176.

Webster, G. D., Rexroad, C. B., & Talent, J. A. (1993). An evaluation of the VJ Gupta conodont papers. *Journal of Paleontology*, *67*(3), 486-493.

Weltje, G. J., & Eynatten, H. V. (2004). Quantitative provenance analysis of sediments: Review and outlook. Sedimentary Geology, 171, 1–11.

Wilson, J. L. (1975). Principles of carbonate sedimentation. In *Carbonate Facies in Geologic History* (pp. 1-19). Springer, New York, NY.

Wolf, K. H. (1965). 'Grain-diminution'of algal colonies to micrite. *Journal of Sedimentary Research*, *35*(2), 420-427.

Wolthers, M., Nehrke, G., Gustafsson, J. P. and Van Cappellen P. (2012). Calcite growth kinetics: modeling the effect of solution stoichiometry. Geochimica et Cosmochimica Acta 77, 121–134.

Worden, R. H., Griffiths, J., Wooldridge, L. J., Utley, J. E. P., Lawan, A. Y., Muhammed, D. D., ... & Armitage, P. J. (2020). Chlorite in sandstones. *Earth-Science Reviews*, *204*, 103105.

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