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Early Permian Siliciclastic System of the North-Gondwanaland: A Comparison between Nilawahan Group of North Pakistan and Haushi Group of Oman.

Iftikhar Ahmed Abbasi [1], Mohammad Haneef [2] and Mohammad Asif Khan [3]

ABSTRACT

The early Permian siliciclastic system of the north Gondwanaland is represented by the rocks of the Haushi Group in the Oman Interior Basin and the Nilawahan Group in the Salt Ranges of the northern Pakistan. The rocks of the two, time-equivalent groups, though exposed ~2500 kilometers apart, share great similarities in their lithofacies association, composition and depositional systems. The upper Paleozoic sediments of the Haushi Group host major hydrocarbon reservoirs in Oman Interior Basin. This clastic sequence represents 3rd episode of Gondwanan glaciation in the Arabian Peninsula and is composed of glacial and glacio-fluvial deposits of the Al-Khlata Formation, overlain by fluvial dominated Gharif Formation. This clastic sequence is widely distributed in subsurface of the Oman Interior Basin and surrounding parts of the Arabian Peninsula such as in Saudi Arabia and U.A.E. The siliciclastic rocks of the late Paleozoic Nilawahan Group in the Salt Ranges in north Pakistan are comprised of glacial and glaciofluvial Tobra Formation, deltaic to estuarine Dandot Formation overlain by the fluvial Warchha Formation, and near-shore, coastal-marine Sardhai Formation. This study describes and compares the lithofacies association of the two groups to interpret the depositional system and tectonic context of the two widely-apart sedimentary sequences.

INTRODUCTION

The north Gondwanaland including the western margin of the Indian Plate and Arabian Peninsula was under the influence of late Paleozoic glaciation that lasted for over 100 million years (Hambrey and Harland 1981; Eyles et al., 1993). These areas were covered with several small and isolated ice caps (Crowell 1983) depositing glaciogenic rocks over large part of the north Gondwanaland. Along the western margin of the Indian Plate, the Salt and Trans Indus Ranges in north Pakistan constitute the southernmost part of the Himalayan orogenic belt, and form the leading thrust front of the Kohat-Potwar fold-thrust-belt in the outer Himalayas (Yeats and Lawrence 1984)(Figure 1a). Precambrian to Neogene rocks are exposed in various parts of these ranges (Figure 1a). Late Paleozoic (Late Carboniferous to Early Permian) rock sequence is on average 670m thick in the area, and is divided into two major groups on the basis of their lithological variation; i.e. a basal continental to marginal marine siliciclastic sequence known as the Nilawahan Group, and an upper marine carbonate sequence called the Zaluch Group (Teichert 1967). This sequence rests unconformably on Cambrian and possibly Precambrian strata (Kummel and Teichert 1970) (Figure 2a). The late Paleozoic succession of the Salt and Trans Indus ranges is famous for its rich fauna and attracted attention from many workers since late nineteenth century to deliberate on biostratigraphy and Permo-Triassic boundary issues (Kummel and Teichert 1970; Waagen 1878-79; Noethling 1901; Diener 1912; Balme 1970; Grant 1970; Wardlaw and Pogue 1995)

The Sultanate of Oman is situated on the southeastern margin of the Arabian Plate (Figure 1b). It is bounded to the south by the Gulf of Aden spreading zone, to the east by the Masirah Transform Fault and Owen Fracture Zone, and to the north by the complex Zagros-Makran convergent plate margin overriding the active Makran subduction zone in Gulf of Oman, which in its earlier history resulted in the building of the Oman Mountains (Loosveld et al., 1996). The Oman Interior Basin comprising Oman Salt Basin (Early Cambrian Ara Salt) is located to the west of Oman mountains and is bounded on the east-southeast by the Huqf-Haushi outcrops, to the north by the Oman Mountains, to the northwest by the Central Oman Platform, and to the south and southwest by the Central Oman High (Loosveld et al., 1996; Robertson et al., 1990)(Figure 1b). The upper Paleozoic siliciclastic sediments of the Haushi Group are distributed throughout the basin and host major hydrocarbon reservoirs in the Sultanate of Oman. Isolated outcrops of the Haushi Group sediments are accessible in different parts of the Oman desert along Haushi-Huqf High (Figure 1b). The Haushi Group rests unconformably on Cambrian-Precambrian sedimentary sequence of the Haima and Huqf groups in Oman Interior Basin (Hughes Clarke 1988)(Figure 2b). This study aims to describe major lithofacies of the two groups, i.e., the Nilawahan Group in Salt Ranges of Pakistan and the Haushi Group in Central Oman area, to interpret their depositional setting when these areas were still part of the Gondwanaland during Late Carboniferous-Early Permian time. Special emphasis will be on the study of the glacial and fluvial deposits of the two groups.

STRATIGRAPHY

Nilawahan Group: The Nilawahan Group comprises 300-400m thick clastic sequence of interbedded conglomerates (tillites in lower part), sandstone and shale of Asselian and Sakmarian stages (Kazmi and Abbasi 2008). Thickness of the group increases westward and its maximum thickness is encountered in the western and Trans Indus Salt Ranges (Fatmi 1973). The Nilawahan Group rests unconformably over the Early Cambrian siliciclastic Jehlum Group, and Precambrian evaporite sequence of the Salt Range Formation (Figure 2a). The Nilawahan Group has a conformable upper contact with the carbonate sequence of

[1]Earth Science Department, Sultan Qaboos University, Al-Khod, Muscat, Oman
[2]Department of Geology, University of Peshawar, Pakistan
[3]National Center of Excellence in Geology, University of Peshawar, Pakistan

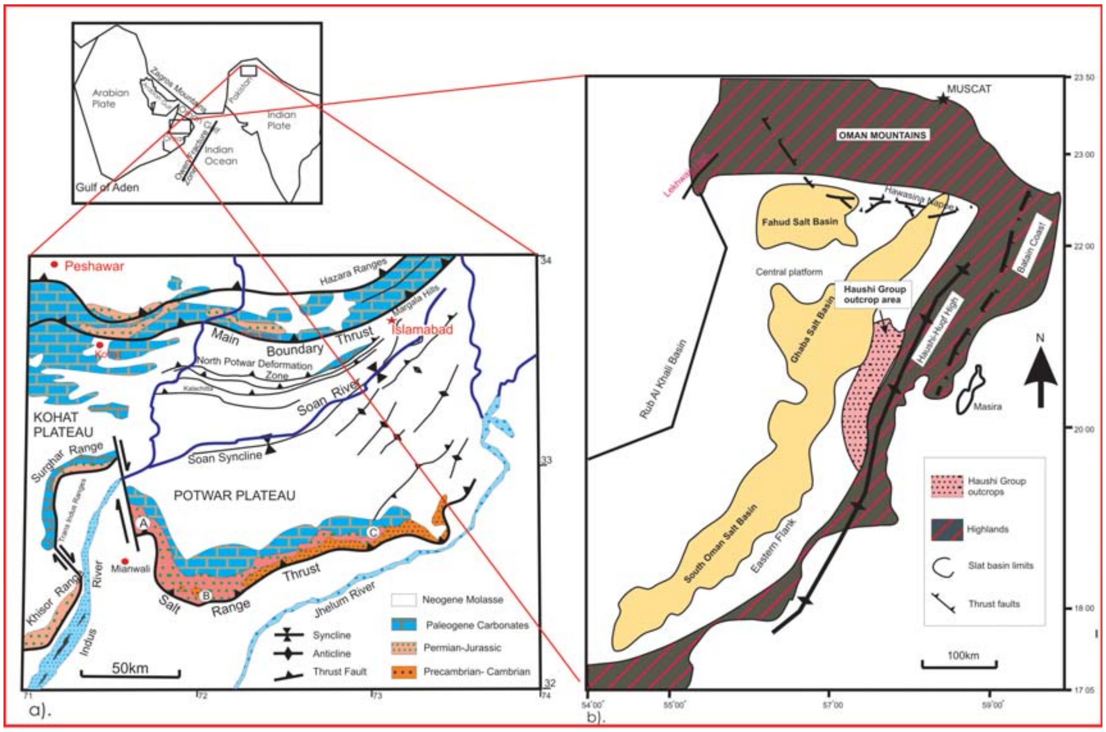

Figure 1 - Location map of a) north Pakistan and b) Oman. In Figure 1a, the Nilawahan Group rocks are exposed in A-western Salt Range; B-Central Salt Range; C-Eastern Salt Range. The Haushi Group outcrops are shown in Figure 1b.

the Zaluch Group (Fatmi 1973). The group is divided into four different formations on the basis of lithostratigraphy, namely Tobra, Dandot, Warchha and Sardhai formations (Figure 2a and 3b). These formations are known for terrestrial fauna (Reed 1936; Pascoe 1959), and show thickness and lithofacies variations in different parts of the Salt and Trans Indus Ranges. The Tobra Formation is named after Tobra village in eastern Salt Range (Gee 1945) and is comprised of striated pebbles and boulders in mud matrix (diamictite), conglomerate, sandstone and mudstone. Its lower contact with the Cambrian Baghanwala Formation in the eastern Salt Range and the Early Cambrian-Late Proterozoic Salt Range Formation in central and western Salt Ranges marks a major disconformity in the area. The overlying Dandot Formation is named after Dandot village in eastern Salt Range (Noethling 1901), and comprises dark greenish gray splintery shale and siltstone with intercalated sandstone. The Warchha Formation is named after Warchha ravine in central Salt Range, and is a sandstone dominant unit previously known as “Speckled Sandstone” (Waagen 1878-79). The Sardhai Formation named after Sardhai ravine in eastern Salt Range (Gee 1945), earlier known as “lavender clays” (Wynne 1878) is dominated with dark violet to black, bluish gray, purple and red clays. Its upper contact with carbonate succession of the Zaluch Group is considered a disconformity (Nakazawa and Dickins 1985).

Haushi Group: The late Paleozoic siliciclastic Haushi Group is widely distributed in the Oman Interior Basin and is exposed along Haushi-Huqf High in central Oman (Figure 1b). The Haushi Group disconformably overlies upper Proterozoic and lower Paleozoic rocks of the Haima/Huqf Supergroups, while conformably passes up-section into the carbonate sequence of the Akhdar Group (Forbes et al., 2010)(Figure 2b). The Haushi Group is divided into a basal glaciogenic and paralic deposits of the Al-Khlata Formation conformably overlain by the fluvitile Gharif Formation (Figure 3a) (Hughes Clarke 1988). The group is dated as Late Sakmarian (stage wise age not provided for Pakistan) in age on the basis of marine fauna in carbonate strata found in the lower part of the Gharif Formation (Angiolini et al., 2004). The Al-Khlata Formation is named after the outcrops in wadi Al-Khlata in southern Huqf region (Hughes Clarke 1988; Levell et al., 1988.]. The formation comprises of diamictites of glacial and glacio-fluvial origin related to Late Carboniferous-Early Permian glaciation in the Arabian Peninsula (Al-Belushi et al., 1996; Sharland et al., 2001; Osterloff et al., 2004b). Thickness of the formation is highly variable ranging from 100-800m in south and central Oman basins but much thinner in north Oman (Levell et al., 1988). This thickness variation is attributed to (a) erosional paleorelief on pre Al-Khlata unconformity, and (b) halokenesis and differential subsidence due to salt removal in subsurface.

The Al-Khlata Formation disconformably overlies the Lower Paleozoic sediments of the Haima Group, whereas its upper boundary with the Gharif Formation is considered transitional (Forbes et al., 2010). The Ghraif Formation is named after wadi Gharif in Haushi-Huqf area (Hughes Clarke 1988). The formation is informally divided into lower, middle and upper Gharif members. The Gharif Formation is a sequence of sandstone, shale and a limestone unit in its basal part, interbedded shale and sandstone in its upper part, and sandstone with subordinate shale in the upper part. The

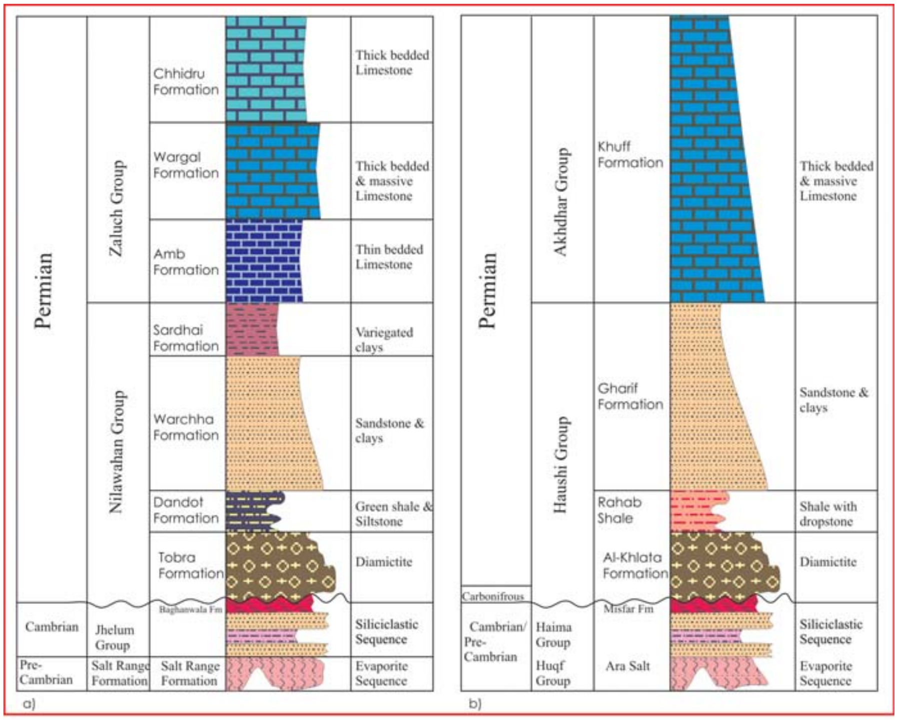

Figure 2 - Generalized upper Paleozoic stratigraphy and its relationship with the lower Paloezoic stratigraphy in the Salt Ranges (Figure 2a) and Huqf area (2b). Major unconformities mark the contact between the upper Paleozoic and lower Paleozoic sequences in the Salt Ranges and the Huqf area.

formation has a transitional upper contact with carbonate rocks of the Khuff Formation belonging to the Akhdhar Group. The Gharif Formation on the basis of fauna and flora is dated as Early-Middle Permian (Sakmarian-Wordian age; ca.292-267Ma) (Angiolini et al., 2004; Berthelin et al., 2003; Stephenson et al., 2008).

In section below, we will describe various lithostratigraphic units of the two groups with special emphasis on the lithofacies association of these units to interpret depositional setting in their respective tectonic context.

LITHOFACIES ASSOCIATION

Nilawahan Group: The Nilawahan Group is comprised of glacial- to glaciofluvial Tobra Formation, coastal marine Dandot Formation, fluviatile Warchha Formation and lagoonal Sardhai Formation (Figure 3b). These formations are studied from central and western Salt Range area and are described below:

Tobra Formation: The Tobra Formation is comprised of distinct lithofacies association of diamictites, conglomerates, pebbly sandstone and mudstone. Diamictite is a mixture of dark gray to black clays, facetted, smoothed, pitted, polished and striated pebbles and boulders of pink granite, volcanics slates and quartzite (Figure 4a), and is described as tillite lithofacies (Teichert 1967) . This lithofacies generally occurs in the lower part of the association and is common in the western Salt Range such as in Zaluch nala section (Figure 1a) where the formation has a maximum thickness of 120m (Figure 3b). The conglomerate lithofacies is associated with the diamictite lithofacies and consists of pebble to gravel size poor to moderately sorted clasts of granite, volcanics and quartzite in cream to reddish brown colour sandstone matrix (Figure 4b). The conglomerate lithofacies fines upward into pebbly sandstone lithofacies, which is laterally discontinuous at the outcrop scale as it is eroded by subsequent flows. Inverse grading is common in this lithofacies. The mudstone lithofacies is a monotonous sequence of dark gray to black mudstone, laminated at places. The laminated mudstone at places also exhibits varve-bedding with drop-stones (Figure 4c). This lithofacies association is best developed in Zaluch nala in western Salt Range and is repeated many times but is not traceable everywhere. In eastern Salt Range, at the type-locality, the Tobra Formation is 20m thick and consists dominantly of polymictic conglomerates with pebbles and boulders of igneous, metamorphic and sedimentary rocks. Along Choa-Khewra road section, it is about 5m thick, unconformably overlying the Lower Cambrian Baghanwala Formation (Figure 4d). In central Salt Range, the formation is about 5m thick and consists of fresh water facies comprising siltstone and shale with rare boulder size clasts. Plant fossils such as Glossopteris and Gangamopteris, and several species of fresh water bivalves and ostracods are reported from this area (Reed 1936).

Interpretation: The facies association of the Tobra Formation dominated with diamictite and tillites, polymictic conglomerate and mudstone with drop-stones indicate deposition under glacial, glacio-fluvial and glacio-lacustrine environments (Kummel and Teichert 1970; Kummel and Teichert, 1970). Thick diamictite lithofacies in the western Salt

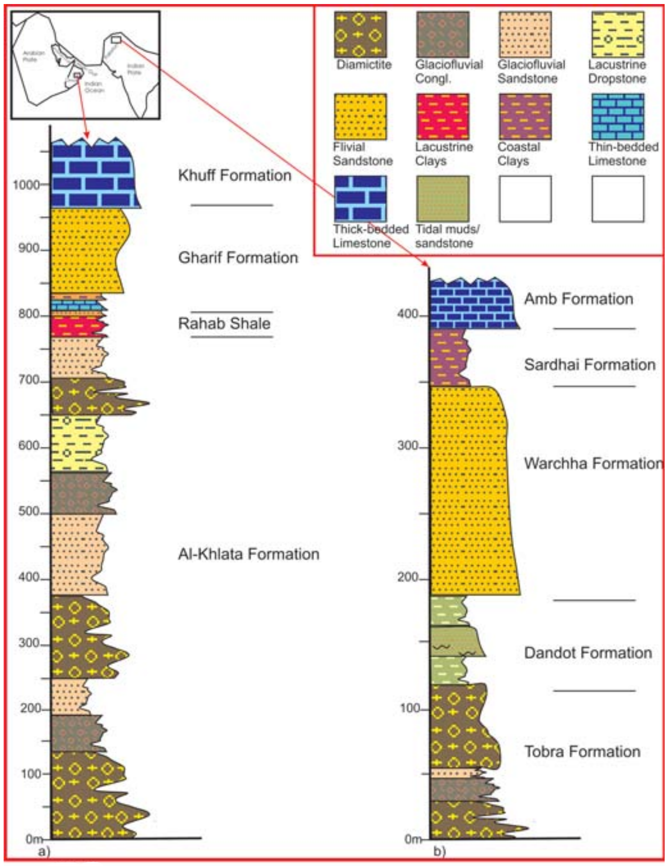

Figure 3 - Lithostratigraphy of the Haushi Group (a), and the Nilawahan Group (b) from the Huqf and Salt Range areas. Thickness of the Nilawahan section is two times exaggerated as compared to the Haushi Group. Maximum thicknesses of various formations are plotted as reported from the Huqf and Salt Range areas. These thicknesses are highly variable across the study areas and some formations laterally pinch-out also. Only characteristic depositional facies are shown in the figure.

Range area was due to repeated intense ice-rafting of glacial material. Polymictic conglomerates were deposited as glacio-fluvial deposits during glacial melt phase. In central Salt Range, the fresh-water facies are associated with lacustrine environment with occasional drop-stones. Occasional varve-bedding in mudstone lithofacies in western Salt Range also indicate presence of periodic glacio-lacustrine environments.

Dandot Formation: The Dandot Formation is exposed in eastern and central Salt Ranges and missing from western Salt Range. The Dandot Formation consists of rather simple lithofacies association of dark green-gray splintery shale and siltstone interbedded with thin, green colour, cross-bedded and flaser-bedded sandstone (Figure 4e,f). The shale/siltstone lithofacies appears massive to faintly laminated, while cross-bedded sandstone intercalated in shale/siltstone is fine-grained exhibiting small cross-beds and wave-ripple lamination. It grades into flaser-bedded lithofacies. Marine fauna such as brachiopods, bivalves, bryozoans, pteropods are reported from the formation (Reed, 1936; Pascoe 1959).

Interpretation: On the basis of its lithofacies association, transitional marine environments are proposed for the formation. Presence of wave-ripples, normal marine fauna mixed with brackish fauna, calcareous/ carbonaceous clays, heterolithic and flaser bedding indicate tidal flat and estuarine conditions prevailing at the time of deposition of the Dandot Formation (Kazmi and Abbasi 2008).

Warchha Formation: The Warchha Formation in central and western Salt Ranges represents an overall fining-upward sequence comprising a generalized lithofacies assemblage of conglomerate-pebbly sandstone lithofacies in the lower part, interbedded sandstone and red siltstone in the middle part, and red siltstone/claystone with sandstone intercalations in the uppermost part. Carbonaceous clays are also found in the upper part of the formation. The sedimentological, compositional and provenance details of Warchha Formation have recently been studied along the eastern and central Salt Ranges (Ghazi and Mountney 2009; Ghazi and Mountney 2011). Lithofacies assemblage in the western Salt Range is not very different from that of the eastern and central Salt Ranges except some local variations. The conglomerate lithofacies is localized and usually occurs in the lower part of the formation containing abundant clasts of pink granite, grey and green volcanic, quartzite and slate. This clast association is fairly similar to that of the Tobra Formation which conformably underlies the Warchha Formation in the western Salt Range (Figure 4g). In the western Salt Range, the formation dominantly comprises of coarse grained, white to reddish white (speckled) in colour, arkosic in composition, and loosely cemented sandstone which can be divided into a number of lithofacies including; i) trough cross-bedded pebbly sandstone lithofacies (St), ii) horizontally-bedded sandstone lithofacies (Sh), iii) planar cross-bedded sandstone (Sp), and iv) ripple-laminated sandstone (Sr). The sandstone is thick-bedded and multistoreyed (Figure 4h), individual storeys being on average about 2m thick, separated from each other either by thin shale or lag layers. The cross-bedded sandstone lithofacies (planar and trough cross-bed) are common in coarse-grained sandstone (Figure 4i), and are present in all sections. Horizontally-bedded sandstone lithofacies (Sh) and ripple-laminated sandstone (Sr) are found in medium to fine-grained sandstone as fining-upward sequences (Figure 4j). Fine grained lithofacies of red-purple colour siltstone and shale appear in the middle and upper part of the formation (Figure 4k) and constitute tens of metres thick sequences in western Salt Range, however, less significant in the eastern and central Salt Ranges. These fine-grained sediments are generally massive due to intense mottling and are interbedded with thin, laterally discontinuous sandstone. Dark gray to black colour carbonaceous clays are also developed in the upper part of the formation.

Interpretation: The lithofacies association of the Warchha Formation is characterized by conglomerate and pebbly sandstone lithofacies grading up-section into cross-bedded sandstone and siltstone indicate deposition by fluvial system (Kummel and Teichert 1970). Coarser lithofacies of conglomerate and pebble sandstone with well-developed planar cross-sets in lower part of the formation in western Salt Range were deposited on braid-bars associated with low-sinuosity river system. Multistoreyed sandstone interbedded with red clays was deposited as the river system was changing into high-sinuosity meandering system (Ghazi and Mountney 2009). Red and purple colour siltstone and clays

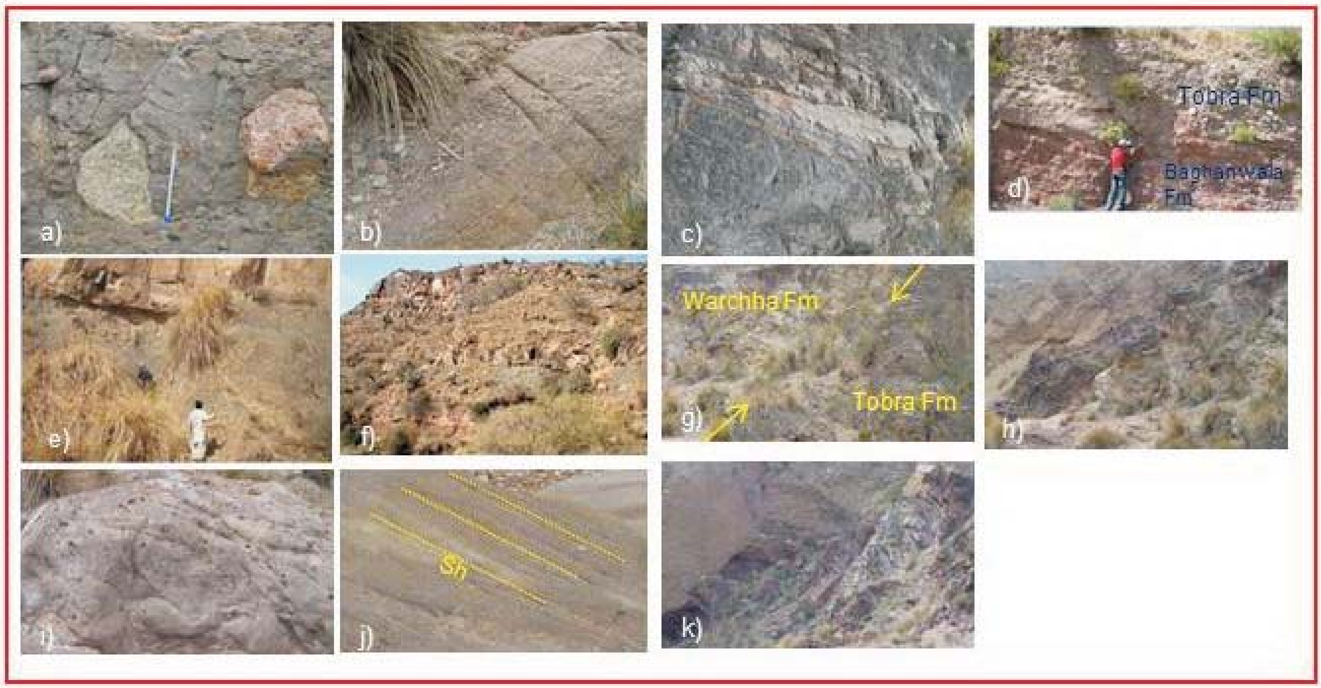

Figure 4 - Field photograph of the Nilawahan Group; a) Tobra Formation diamictite; b) coarsening upward glaciofluvial conglomerate of the Tobra Formation; c) thick dark gray to black colour mudstone of the Tobra Formation; d) lower contact of the Tobra Formation tillite with the Cambrian age Baghanwala Formation in eastern Salt Range; e) green colour shale of the Dandot Formation overlain by the Warchhah Formation sandstone f) general view of Nilawahan Group in eastern Salt Range g) conformable contact of the Warchha and Tobra formations in western Salt Range; h) multistoreyed sandstone of the Warchha Formation in western Salt Range; i) cross-bedded pebbly sandstone facies of the Warchha Formation; j) cross-bedded medium-grain sandstone of the Warchha Formation; k) red clays with sandstone interbeds in the upper part of the Warchha Formation.

were deposited as overbank fines on flood-plains. Fine-grained sandstone interbeds resulted due to crevasse-splay deposition on flood-plains. High proportion of flood-plain deposits in western Salt Range as compared to the central and eastern Salt Ranges indicates that this area is less frequented by the active channels. The channel-belt deposition in the central and eastern Salt Ranges resulted in higher proportion of coarse-grained lithofacies with thick multistoreyed sandstone bodies. The river system therefore, changed from low-sinuosity braided river in the lower-most part to high-sinuosity meandering system in the middle and upper part of the formation. Carbonaceous clays and localized coal beds developed along abandon channels, oxbow-lakes and other swampy parts on the flood plain. These facies may also develop as coastal-plain facies as the river system was approaching coast-line.

Sardhai Formation: The Sardhai Formation previously called as “lavender clays” (Wynne 1878) in eastern and central Salt Range is composed of bluish-gray to greenish-grey, purple to reddish claystone, which becomes dark-violet to black in the western Salt Range. The claystone contains subordinate sandstone and siltstone interbeds and is also reported to contain minor carbonaceous clays. This clay-rich sequence is fairly monotonous and is difficult to divide in predictable facies association. Plant remains and fish scales have occasionally been found (Kazmi and Abbasi 2008; Jackson 1978).

Interpretation: The formation is interpreted as being deposited in terrestrial to coastal marine setting (Shah 1977).

Haushi Group: The Haushi Group (Hughes Clarke 1988) in the Oman Interior Basin is a siliciclastic succession represented by glaciogenic Al-Khlata Formation in the lower part and fluviatile Gharif Formation in the upper part (Figure 2b and 3a). These formations are discussed below from Al-Khlata wadi in eastern and central Huqf area along Haushi-Huqf High (Figure 1b).

Al-Khlata Formation: The Al-Khlata Formation in outcrops is characterized by a distinct lithofacies assemblage of: i) diamictite, ii) polymictic conglomerate iii) sandstone, iv) siltstone v) varved clays and drop-stones, and vi) Shale and mudstone (Rahab Shale) (Figure 5a). The diamictite lithofacies is the most dominant one in outcrop and also in subsurface, defined by pebble to boulder size clasts of red and pink granite, volcanics and quartzite floating in grey to buff colour clay matrix (Figure 5b). Some of these boulder clasts are up to 1m in diameter. This lithofacies is found to occur on top of lower Paleozoic-upper Proterozoic rocks producing well-defined striation marks (Figure 5c). At places the diamictite beds are differentially compacted due to sediment load and also dewatering of clay matrix (Figure 5d). Polymictic conglomerate lithofacies is characterized by pebble to cobble size sub-angular to sub-rounded clasts of red and pink granites, volcanics, porphyries and quartzite clasts in a sandy matrix (Figure 5e). Striated and faceted cobble and boulders are also found in the lithofacies. The lithofacies occurs as many metres thick beds with intercalated sandstone and exhibit large scale cross-beds and low-angle plane beds (Figure 5e). This lithofacies is repeated many times on the outcrops scale and is also commonly interbedded with the sandstone lithofacies. The lithofacies has a sharp erosional contact usually defined by boulder size clasts with the underlying diamictite facies (Figure 5e). It exhibits large size (>1m thick), high angle cross-sets (Figure 5e). These high angle cross-bedded conglomerates exhibit coarsening-upward trend at places. The sandstone lithofacies comprises both medium to coarse-grained sandstone and pebbly sandstone units. The pebbly sandstone units are characterized by as much as 50% of sub-rounded to well-rounded pebble clasts. The sandstones are compositionally lithic to feldspathic litharenite, loosely cemented and friable. The sandstone lithofacies exhibit well-developed cross-bedding, common liquefaction structures, microfaulting and syndepositional deformation structures (Figure 5f,g). Cross-sets at places are 1m or more thick. This lithofacies occurs as very thick (10s of metres thick) continuous sandy successions and is major reservoir in Oman Interior Basin (Levell et al., 1988). Associated with the sandstone lithofacies are siltstone lithofacies which constitutes many meters thick sequences. The siltstone is usually blue-gray in colour, appears massive and is found as thick, massive siltstone sequences and as interbeds in sandstone lithofacies. The varved clays and drop-stones lithofacies is comprised of finely laminated clays displaying distinct rhythmic varves containing pebble to cobble size clasts (Figure 5h). The varved clays at places grade into siltstone with distinct light and dark colour laminations, and constitute 1-10m thick sequences. The upper part of the formation in the area is covered with 10-20m thick, laterally extensive clays known as Rahab Shale.

Interpretation: The lithofacies association of the Al-Khlata Formation indicates that the formation was deposited under glacial and associated depositional environments [25;28]. The lithofacies diamictite was deposited during glacier-rafting as tillites. The glacial melt-out phase resulted in deposition of polymictic conglomerates by glacio-fluvial process. Large size cross-beds (>1m thick) at places indicate possibility of sub-aqueous delta-lobes. Thick sandstone lithofacies was deposited by glacio-fluvial processes. Some of these sands were probably deposited as glacial-deltaic deposits due to their association with coarsening-upward conglomerate. Siltstones lithofacies is interpreted as sub-aqueous deposits formed by settling from suspension of glacial melt water. The varved-clays and dropstone lithofacies were deposited in glacial-lacustrine setting. Thick clay deposits (Rahab Shale) in the upper part of the formation formed due to settling of suspended load in vast lakes formed during deglaciation phase.

Gharif Formation: The Gharif Formation in the subsurface of Oman Interior Basin is divided into three members by Petroleum Development Oman (PDO) and other petroleum companies, the lower, middle and upper members are defined on their lithofacies distribution and reservoir characteristics **(**Hughes Clarke 1988; Forbes et al., 2010). The Lower Gharif member consists of transitional marine sandstone overlain by the marine Haushi Limestone containing brachiopods, bryozoa, crinoids and fusilinids confirming a late Sakmarian age (Angiolini et al., 2004). The middle Gharif member consists of thick red siltstone beds interbedded with thin sandstone, and has limited outcrop exposures. The upper Gharif member is comprised of thick multistoreyed sandstone sequences interbedded with red siltstone, shale and localized carbonaceous clay in the upper part. In Haushi-Huqf outcrops, the upper Gharif member is characterized by lithofacies association of i) pebbly sandstone, ii) sandstone, iii) red siltstone and claystone, and iv) carbonaceous clays. The pebbly sandstone is characterized by clasts of pink granite, volcanics and metamorphic rocks in coarse-grained sandstone matrix. The sandstone lithofacies is the most prominent one making low ridges in the area (Figure 5i) and comprises of pebbly sandstone and coarse-grained sandstone in the lowermost part, and medium to fine grained sandstone in the upper part of the section. The sandstone lithofacies on average constitutes 10m thick multistoreyed sequences, comprising of several amalgamated sandstone bodies, on average about three meters thick. Individual sandstone bodies are identified by the presence of lag deposits or laterally pinching thin clay beds. The sandstone is both planar and trough cross-bedded with cross-sets on average 30cm thick exhibiting a dominant paleoflow direction towards northwest (Figure 5j). The sandstone is white to buff in colour, loosely cemented and is arkosic in composition. Silicified tree trunks are preserved in the sandstone (Figure 5k). The sandstone lithofacies in the upper part of the formation is medium to fine-grained, brown in colour and is interbedded with thick red siltstone and clay units. The sandstone in this part is trough cross-bedded and exhibit well-developed lateral accretion surfaces (Figure 5l). Silicified plant fragments are commonly distributed in sandstone in its upper part. The red siltstone and clay lithofacies is composed of dark red to maroon colour, mottled siltstone and claystone. Root burrows (rhizoliths) and mature vertisols (paleosole) with vertic features (pseudo-anticlines) are common with minor amount of preserved calcrete (Figure 5m). Most of calcretes might have been eroded by channel scouring and redeposited as channel lag deposits. The lithofacies carbonaceous clays occur in the upper part of the formation. It is 0.5-3 metre thick, laminated to thin bedded and contains occasional gypsum layers. The carbonaceous clays are partially changed to coal (Figure 5n).

Interpretation: The lithofacies assemblage of the Gharif Formation indicates deposition by fluvial process. The sandstone lithofacies was deposited as in-channel deposit while fine-grained lithofacies of siltstone and claystone was deposited as flood-plain deposits. The cross-bedded sandstones were deposited as both in-channel and side-channel river bars. Predominance of coarse-grained sandstone facies (pebbly to coarse-grained sandstone), characterized by thick (> 1m thick) planar cross-beds in the lower part of the upper member of the formation shows deposition along mid-channel braid bars associated with a low-sinuosity river system. Fine to medium-grained sandstone interbedded with red siltstone and clay, and characterized by lateral accretion surfaces show deposition along lateral bars in the upper part of the formation. Red siltstone and claystone lithofacies was deposited on broad

Figure 5 - Field photographs of the Haushi Group rocks; a) various lithofacies of the Al-Khlata Formation in wadi Al-Khlata outcrops, Huqf area; b) large size boulder clasts of pink granite in diamictite lithofacies; c) striated surface at the base of the Al-Khlata Formation. The striations (marked by arrows) are produced due to glacial transport on bed rock; d) syn-depositional compaction of diamictite facies due to load of overlying sandstone facies; e) over 1m thick high angle foresets in polymictic conglomerate facies deposited probably as glacio-deltaic facies; f) sandstone lithofacies exhibiting syn-sedimentary deformation due to high rat of sedimentation; g) microfaults due to syn-depositional deformation in polymictic conglomerate lithofacies; h) dropstones in lacustrine clays of the Al-Khlata Formation; i) multistoreyed sandstone-bodies in the Gharif Formation. Individual sandstone-body is on average 2m thick; j) cross-bedded sandstone lithofacies in the Gharif Formation; k) petrified wood-logs in upper part of the Gharif Formation representing conifer trees many meters in height during early Permian time in Huqf area; l) lateral accretion surfaces passing into channelized flow associated with meandering river system in the upper part of the Gharif Formation (scale 50cm); m) red to maroon highly oxidized root burrowed clays interbedded with sandstone, Gharif Formation; n) carbonaceous clays in the upper-most part of the Gharif Formation.

flood-plains during active channel migration. The lithofacies carbonaceous clays was deposited under swampy conditions with abundant vegetation cover on flood-plain or in coastal-plain setting (Jackson 1978).

DEPOSITIONAL SYSTEM OF NILAWAHAN AND HAUSHI GROUPS

The Upper Carboniferous-Lower Permian siliciclastic sediments of the Nilawahan Group in north Pakistan and the Haushi Group in Oman Interior Basin formed by terrestrial processes in two different basins. Both groups disconformably overlie upper Proterozoic-lower Paleozoic evaporite and mixed siliciclastics rock sequences of the Jehlum Group in north Pakistan and Haima Group in Oman Interior Basin (Kummel and Teichert 1970; Hughes Clarke 1988). This major disconformity is related to Hercynian orogeny that eroded most of Paleozoic sequences (Silurian-Late Carboniferous) from the two basins. Anomalously well rounded clasts in some sediments of the Nilawahan and Haushi groups (Angiolini et al., 2004; Ghazi and Mountney 2011) are derived from the lower Paleozoic formations by fluvial and aeolian reworking. Sedimentation commenced in both basins from glaciers activity depositing diamictites and representing tillites on top of the basal unconformity. As the glacier sheets moved in these areas, the rock salt deposits of the Salt Range Formation in north Pakistan and the Ara Salt (Huqf Group) in Oman basins moved diapirically to form series of broad synclinal valleys filled with glacial sediments of the Tobra and Al-Khlata formations respectively. Glacial deposits may also create their own base level by imposing new slopes and not necessarily controlled by already existing topography in the area. The abundance of diamictite facies in both formations and its recurrence at various levels indicates repeated ice activity in both areas with deposition taking place from grounded ice (Figure 6). Melting of ice sheets resulted in glaciofluvial processes depositing polymictic conglomerate and pebbly sandstone in the proximal and distal reaches. Very large, high-angle foresets in some conglomerate sequences, especially in the Al-Khlata Formation may probably be due to glaciofluvio-deltaic processes, possibly associated with deposition in large glacial lakes (Figure 6). Following glaciofluvial processes and topography created by the ice-sheet movement, large lacustrine conditions developed in the area. Enormous thickness of lacustrine deposits in the Al-Khlata Formation compared to the Tobra Formation is due to formation of extensive lakes in Oman basins as compared to north Pakistan. These lakes were influenced by the advance and retreat of ice-lobes as reflected by common occurrence

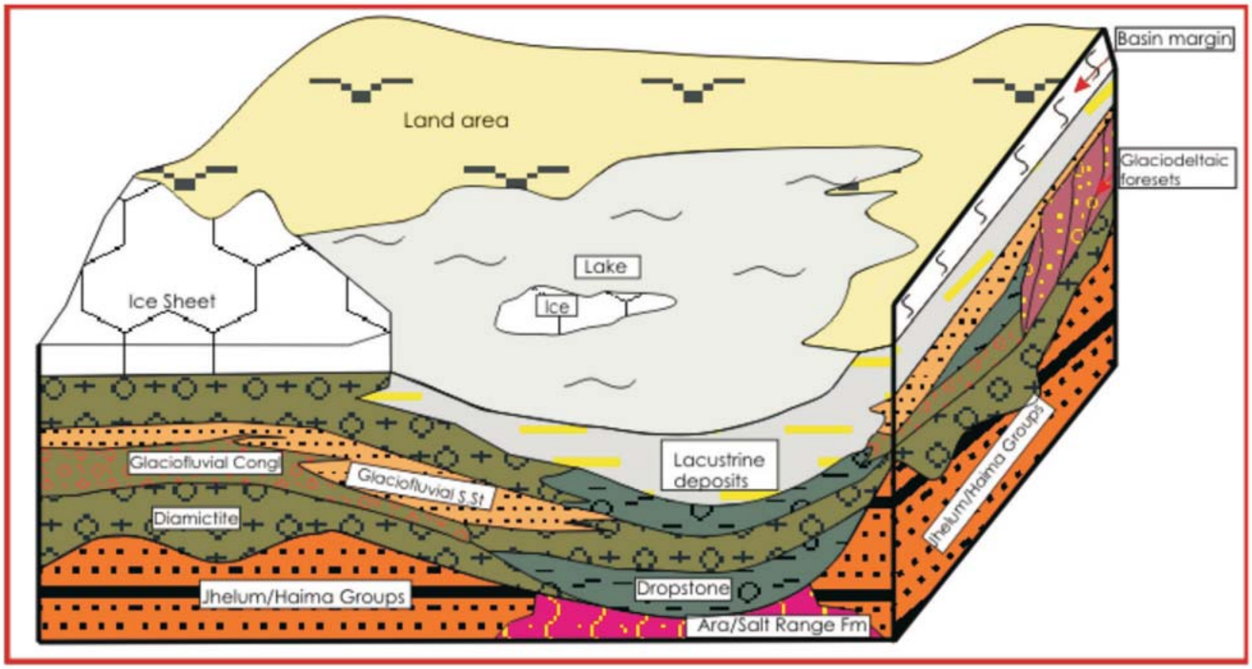

Figure 6 - Depositional model for the glacial and associated deposits of the Al-Khlata and Tobra formations. The basal contact of both formations mark a major unconformity with the underlying Lower Cambrian sediments.

of drop-stones in the Al-Khlata Formation. Such lakes were either localized or less extensive during Tobra deposition as lacustrine deposits are either thin or absent in north Pakistan. Glacial melt lakes covered almost whole of Oman basin by the end of the Al-Khlata time when 10-20m thick lacustrine deposits of the Rahab Shale were deposited. In north Pakistan stratigraphically equivalent to the Rahab Shale is the Dandot Formation comprising sandstone and shale with abundant marine fauna. The olive green sandstone and shale of the Dandot Formation was deposited by marginal marine processes such as tidal channels and mud-flats. The sea incursion during Dandot time was short-lived and confined to the central and eastern Salt Ranges, whereas in the western and Trans Indus Ranges terrestrial conditions prevailed during this time (Kazmi and Abbasi 2008). Onset of fluvial deposits of the Warchha and Gharif formations in north Pakistan and Oman Interior Basin respectively mark the end of marine and lacustrine conditions from the two areas. The two formations are time-equivalent and are characteristically similar in their lithofacies association. The abundance of coarse-grained clast size associated with large size planar and trough cross-bedding, plane and low-angle plane bedding and broad shallow channel margins suggests deposition by multichannel, low sinuosity braided river system (Bluck 1976; Miall 1992; Bridge 1993) in the lower part of the Warchha and Gharif formations (Figure 7a) (Angiolini et al., 2004; Ghazi and Mountney 2009; Osterloff et al., 2004a). The braid bars laterally and vertically coalesced to form amalgamated multistoreyed sandstone sequences. The bar dimensions usually scale with bank-full channel dimensions but are frequently modified by erosion and deposition by subsequent flows (Cant and Walker 1978; Church and Jones 1982). The middle and upper parts of both formations are characterized by intraformational channel lag at the base of the sandstone bodies, scoured channel margins, common lateral accretion surfaces and fining upward sequences suggesting deposition by high sinuosity meandering streams (Ghazi and Mountney 2009) (Figure 7b). High angle lateral accretion surfaces are possibly due to good vegetation cover increasing bank cohesion and resulting in ribbon shape sandstone body geometry. Abundant petrified wood fragments in the sandstone also indicate good vegetation cover over the surrounding flood plain. The red colour siltstone and claystone lithofacies was deposited from suspension on floodplain and also as abandoned channels and pools. Extensive mottling and development of vertisole and localized calcrete horizons suggest subaerial soil formation in semi-arid climate. The carbonaceous clay and localized coal beds in the upper part of the formations indicate onset of coastal setting before major marine flooding in these areas. The coastal marine setting in north Pakistan is represented by the “lavender clays” of the Sardhai Formation which is stratigraphically equivalent to the upper most part of the Gharif Formation transitionally passing up-section into thick carbonate sequence of the Khuff Formation (Jan et al., 2009). Most part of the Salt Range and Oman Interior Basin was flooded by a major marine transgression depositing carbonate sequences of the Amb and Khuff formations respectively (Angiolini et al., 2004; Shah 1977).

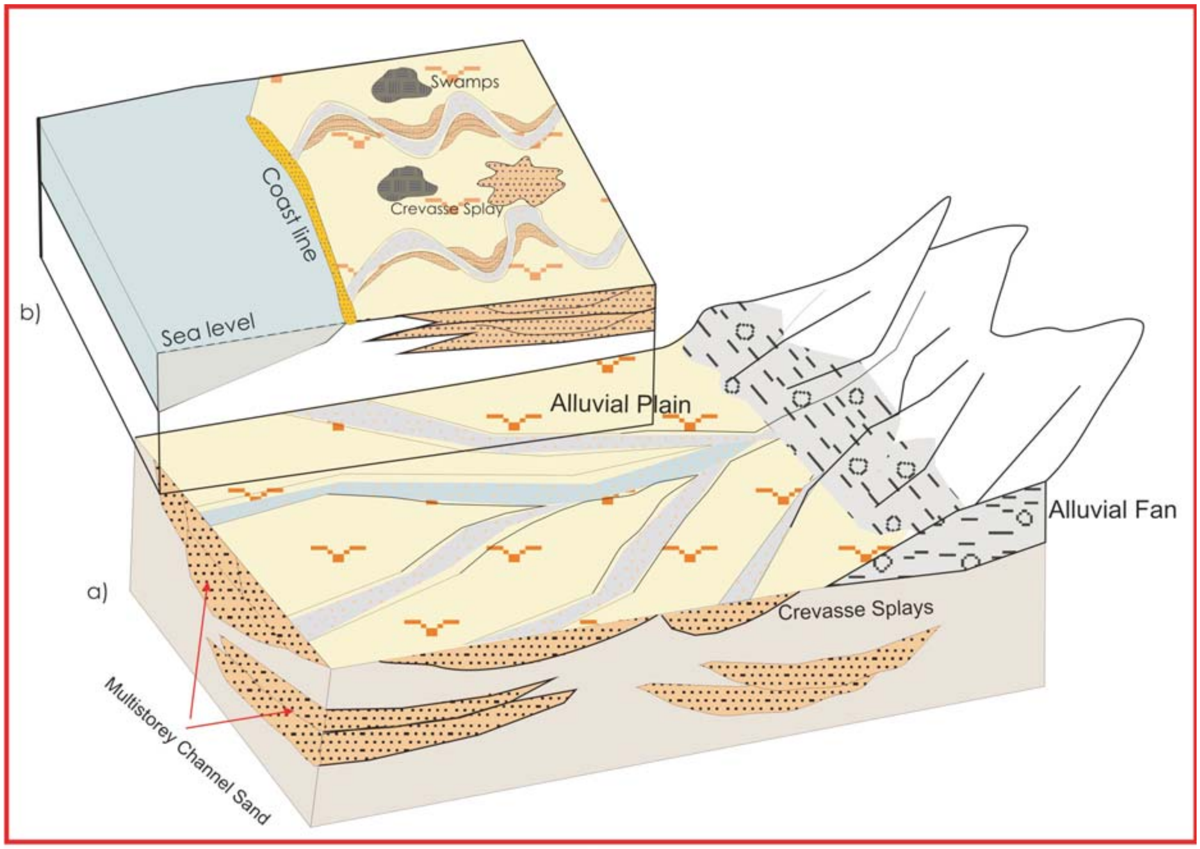

Figure 7 - Depositional system of the Gharif and Warchha formations. The lower and middle parts of these formations was deposited by high energy low sinuosity flows, whereas the upper part was deposited by the high sinuosity meandering river systems. The coastal facies appear in the uppermost parts of these formations.

DISCUSSION

The Late Carboniferous-Early Permian period in north Pakistan and Arabian Peninsula is associated with major glacial episode along the northern margin of the Gondwanaland (Sharland et al., 2001; Zeigler et al., 1979; Konert et al., 2001). The plate reconstruction (Scottese and Langford1995) shows that the north Gondwanaland comprising the western margin of the Indian plate and the Arabian Peninsula was located close to South Pole at about 45°S (Figure 8) and was going through a phase of ice sheet retreat depositing a series of tillites (Tobra Formation in north Pakistan and Al-Khlata Formation in Arabian Peninsula) at the base of the Gondwana sequence (Kummel and Teichert 1970; Sharland et al., 2001). The base of the Gondwanan sequence underlying the lower Paleozoic-upper Proterozoic evaporites and siliciclastic rocks is marked by a regional unconformity related to widespread Late Carboniferous Hercynian uplift and erosion (Levell et al., 1988; Faqira et al 2009). The Hercynian orogeny was followed by regional doming and rifting of the north Gondwanaland eventually leading to the opening of the Neo-Tethys ocean (Konert et al., 2001) (Konert et al., 2001). The deglaciation initiated due to doming of the north Gondwanaland lead to retreat of ice-sheets depositing glaciogenic sediments. The ice-sheet advance and retreat was controlled by regional factors resulting in deposition of variable thicknesses and lithofacies assemblages in the two areas. In north Pakistan the maximum recorded thickness of the glacial deposits is 120m in western Salt Range (Kazmi and Abbasi, 2008) as compared to over 800m in the Oman Interior Basin (Osterloff et al., 2004a). Along the western margin of the Indian Plate in the Salt Range areas the Tobra Glaciation was not part of an extensive inland ice-sheet but a local glaciation that extended only up to the eastern Salt Range (Kummel and Teichert 1970). The glaciation in the Oman Interior Basin and also in other parts of the Arabian Peninsula such as in Saudi Arabia and UAE (Unayzah Formation) known as the Arabian Plate Glaciation 3 (AP G3) was much wide spread and related to extensive inland ice-sheets (Levell et al., 1988; Sharland et al., 2001; Al-Hussseini 2004). The clast composition and petrographic studies indicate that the source of sediments were basement rocks exposed in Oman interior such as Precambrian Ghuba Granites and basement rocks in Marbat and Yemen (Levell et al., 1988). Subordinate amount of detritus may also have been contributed from underlying Lower Paleozoic Haima Group and Precambrian limestone of the Huqf Group along the intrabasinal palaeohighs. The northeast-ward decrease in the clast size and thickness of the glacial sediments indicates ice-sheet movement from southwest towards northeast (Osterloff et al., 2004b), however based on striation direction and

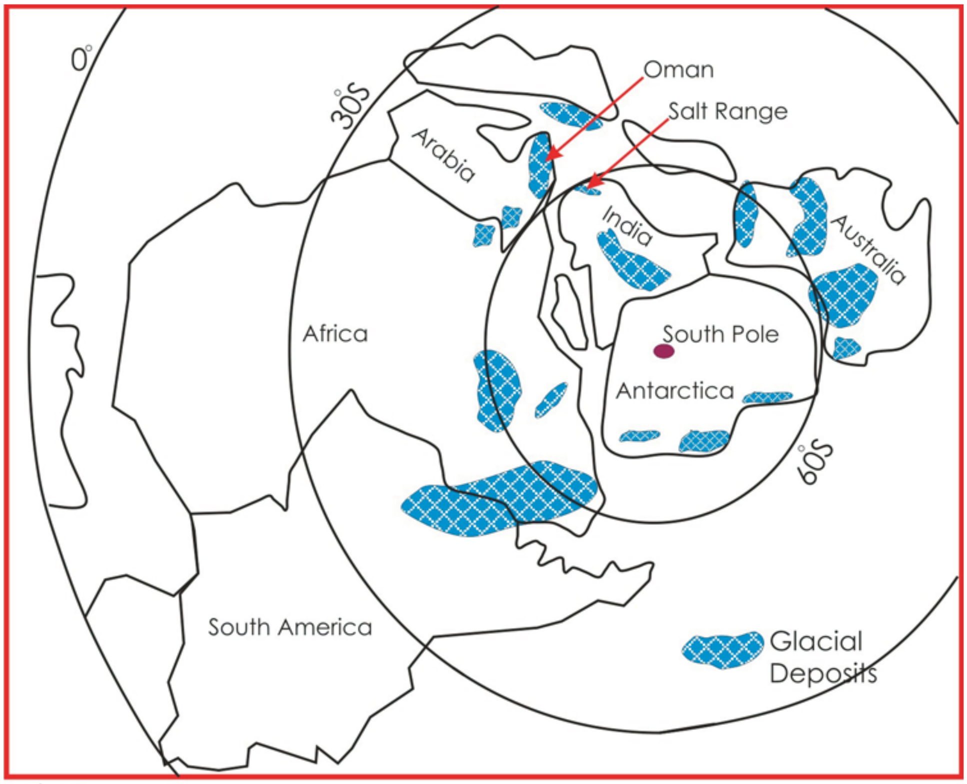

Figure 8 - Paleogeography of Gondwanaland with special reference to Oman and western part of the Indian plate (Salt Range) during Late Carboniferous-Early Permian glaciation in southern hemisphere (Scottese et al., 1979; Lovell et al., 1988). Both areas were located at about 50° S.

position of Arabian Peninsula at the Al-Khlata time, (Al-Belushi et al., 1996) proposed an opposite direction of ice sheet rafting. According to (Al-Belushi et al., 1996), the proposed triple junction along which the Neo-Tethys Ocean later opened, was a site of sufficient thermal uplift to become a centre of mountain glaciation and moved from northeast to southwest. In the Salt Ranges of north Pakistan, the glacial sediments of the Tobra Formation also become thinner to the eastern Salt Range as compared to the western Salt Range. The probable source terrain for coarse clasts is Precambrian granite and basement rocks in Nagar Parkar and adjacent Indian basement rocks, along with some material been derived from the underlying Cambrian and Precambrian Jhelum Group, Salt Range Formation and Kirana Group. This area was site of localized marine incursion as the continents drifted northward and climate became warmer that deposited marginal marine Dandot Formation in north Pakistan, whereas large scale deglaciation in the Oman Interior Basin resulted in deposition of thick lacustrine deposits of the Rahab Shale.

Northward drift of the Gondwanaland towards lower latitudes resulted in warmer climates and onset of fluvial conditions in both areas. These areas had shifted to about 20°S by Early-Middle Permian time (Kazmi and Abbasi 2008) when deposition of fluviatile Warchha and Gharif formations commenced in Salt Range and Oman Interior Basin respectively (Figure 9). The deposition of these rocks corresponds with initiation of active rifting in north Gondwanaland and clast was contributed from the uplifted rift margins too. Clast composition and provenance study of the Warchha and Gharif shows that the sediments were derived mainly from continental blocks (Dickinson et al.,1983) during early rifting phase which uplifted basement and cover sequence rocks in the source area (Ghazi, et al., 2011). Such provenances usually provide quartzo-feldspathic rich sands with high ratios of alkali feldspar to plagioclase (Dickinson et al., 1983). The clasts composition of the sandstone of the Warchha and Gharif formations is fairly similar to that of the glaciogenic Tobra and Al-Khlata formations, and there is strong possibility that much of the detritus was derived from the same source area and some of it may have been reworked Tobra and Al-Khlata material. The source area for some of the clast may also be located along the topographic highs developed during early phase of rifting around these areas.

Stratigraphically equivalent fluviatile rocks (Unayzah Formation member B and C) are widely distributed in other parts of the Arabian Peninsula such as in Saudi Arabia, Kuwait and UAE, and are major reservoir rocks (Al-Hussseini 2004; Tanoli et al., 2008). The depositional conditions are fairly similar in all these areas; however, variable thickness in different areas is due to varied basin configuration in different basins. Climatic warming and opening of the Neo-Tethys Ocean by mid-Permian lead to marine incursion in the area depositing coastal marine Sardhai clays in Salt Range area of north Pakistan. These

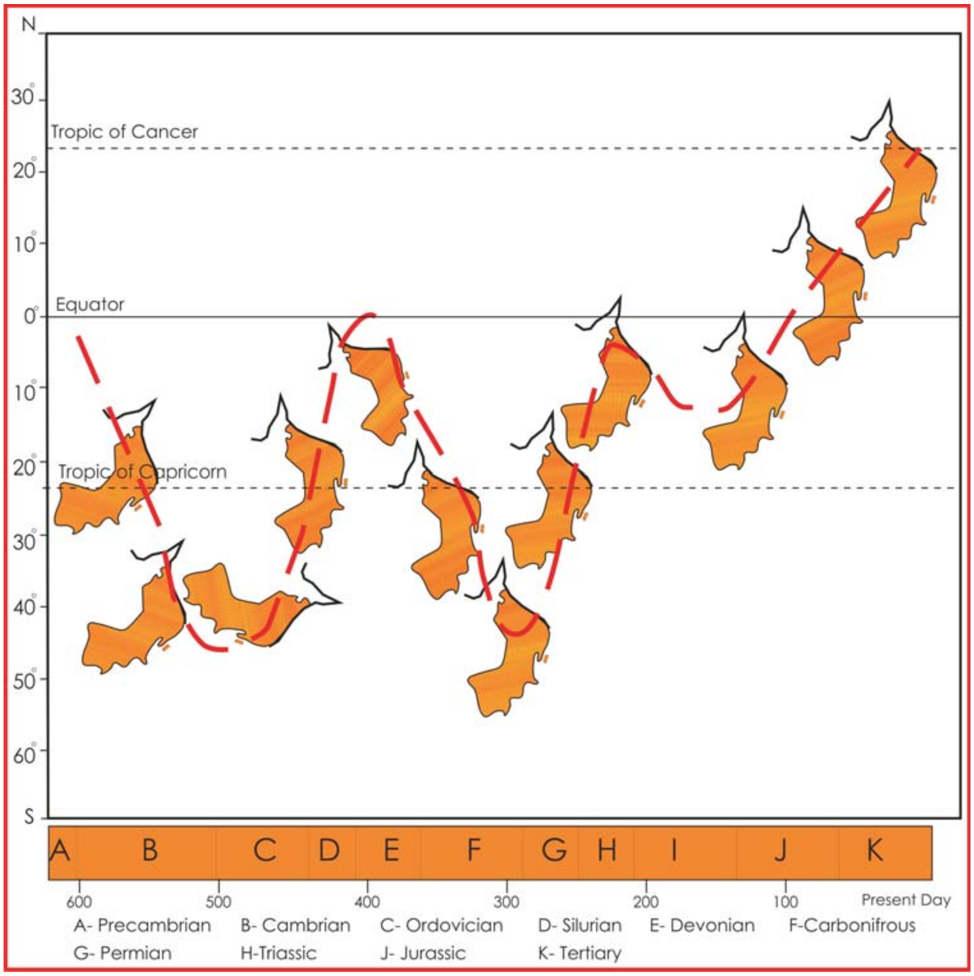

Figure 9 - Proposed latitudinal positions of Oman from Precambrian to Recent (Konert et al., 2001). Oman was located at about 50° S at the time of deposition of the Al-Khlata Formation, while drifted to 20° S by the Gharif time.

clays stratigraphically correlate with the upper-most part of the Gharif Formation in Oman basin (Jan et al., 2009). Large scale sea-level rise in both areas corresponds to thick carbonate deposits of the Zaluch Group in Salt Ranges of north Pakistan (Kummel and Teichert 1970) and the Khuff Formation in Oman Interior Basin (Hughes Clarke 1988).

CONCLUSIONS

1. The upper Paleozoic siliciclastic rocks of the Nilawahan and Haushi groups despite being deposited in different basins share great similarity in their lithofacies assemblages and depositional system due to their similar tectonic setting in north Gondwanaland.
2. The glacial and associated sediments were deposited during thermal doming of the north Gondwanaland when it was located near South Pole.
3. The fluviatile deposits formed as these areas drifted northward and rifting of the north Gondwanaland started leading to the opening of the Neo-Tethys Ocean.

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