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THE SEDIMENTOLOGY OF THE LOWER PERMIAN DANDOT FORMATION: A COMPONENT OF THE GONDWANA DEGLACIATION SEQUENCE OF THE SALT RANGE, PAKISTAN

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Abstract. The Dandot Formation is a part of the Lower Permian, dominantly continental, Gondwanan Nilawahan Group in the Salt Range, Pakistan. The formation conformably overlies the glacio-fluvial Tobra Formation and has a sharp conformable contact with the overlying fluvio-continental Warchha Sandstone. Sedimentary analyses show that the Dandot Formation consists of 1: bioturbated sandstone lithofacies (L1), 2: dark green mudstone/shale lithofacies (L2), 3: flaser bedded sandstone lithofacies (L3), 4: rippled sandstone lithofacies (L4), 5: cross-bedded sandstone lithofacies (L5), and 6: planar sandstone lithofacies (L6). These can be grouped into shoreface, inner shelf, and tidal flat and estuarine facies associations, deposited in shallow marine to intertidal environments. The upper part of the Tobra Formation at the Choa-Khewra road section, where it conformably underlies the Dandot Formation, contains palynomorphs assignable to the earliest Permian 2141B Biozone. In south Oman, the 2141B Biozone is closely associated with the Rahab Shale Member, a widespread shale unit which is considered to represent part of a Permian deglaciation sequence which culminates in the marine beds of the Lower Gharif Member, interpreted as due to post glacial marine transgression. Thus, the Tobra Formation and the overlying marine Dandot Formation may form part of a similar deglaciation sequence.

Introduction

The stratigraphic committee of Pakistan formalized the name Dandot Formation for the lithostratigraphic unit formerly known as the Dandot Group by Noetling (1901). The formation includes the former "Olive Series", "Eurydesma Beds" and "Conularia Beds" of Wynne (1878), and the "Speckled Sandstone" of Waagen (1879). The maximum thickness of the formation is 50 m at the Makrach Nala in the eastern Salt Range (Fatmi 1973; Shah 2009; Fig. 1).

Striking variation in the lithology and thickness of the unit is observed in the eastern and central Salt Range. In the eastern Salt Range, the Dandot Formation is comprised of dark greenish and grey splintery shales and sandstone. Weathered surfaces of the sandstones are reddish and the fresh surfaces show green coloration. In the central Salt Range, i.e. in the Nilawahan Gorge section, the formation comprises green and reddish sandstone alternating with shale and siltstone. The sandstone is fine-grained, micaceous, and thoroughly burrowed in the upper parts. Sedimentary structures include flaser bedding, lenticular bedding, ripple cross laminations and bioturbation. Abundant glaucony has been reported in some horizons at the Nilawahan Gorge and Pail-Khushab road sections (Shah 1977; Fig. 1).

Reed (1936) described *Eurydesma* and *Conularia* from the Dandot Formation and asserted that the fauna co-occurred between the Salt Range, Pakistan and Carboniferous-Permian of Australia. Reed (1939) described various non-marine lamellibranchs in the form of casts and impressions, and correlated them with age-equivalent lamellibranchs from Europe, Africa, China and Burma.

The stratigraphic position of the Dandot Formation is crucial to understand Permian deglaciation in Pakistan, as the formation overlies the

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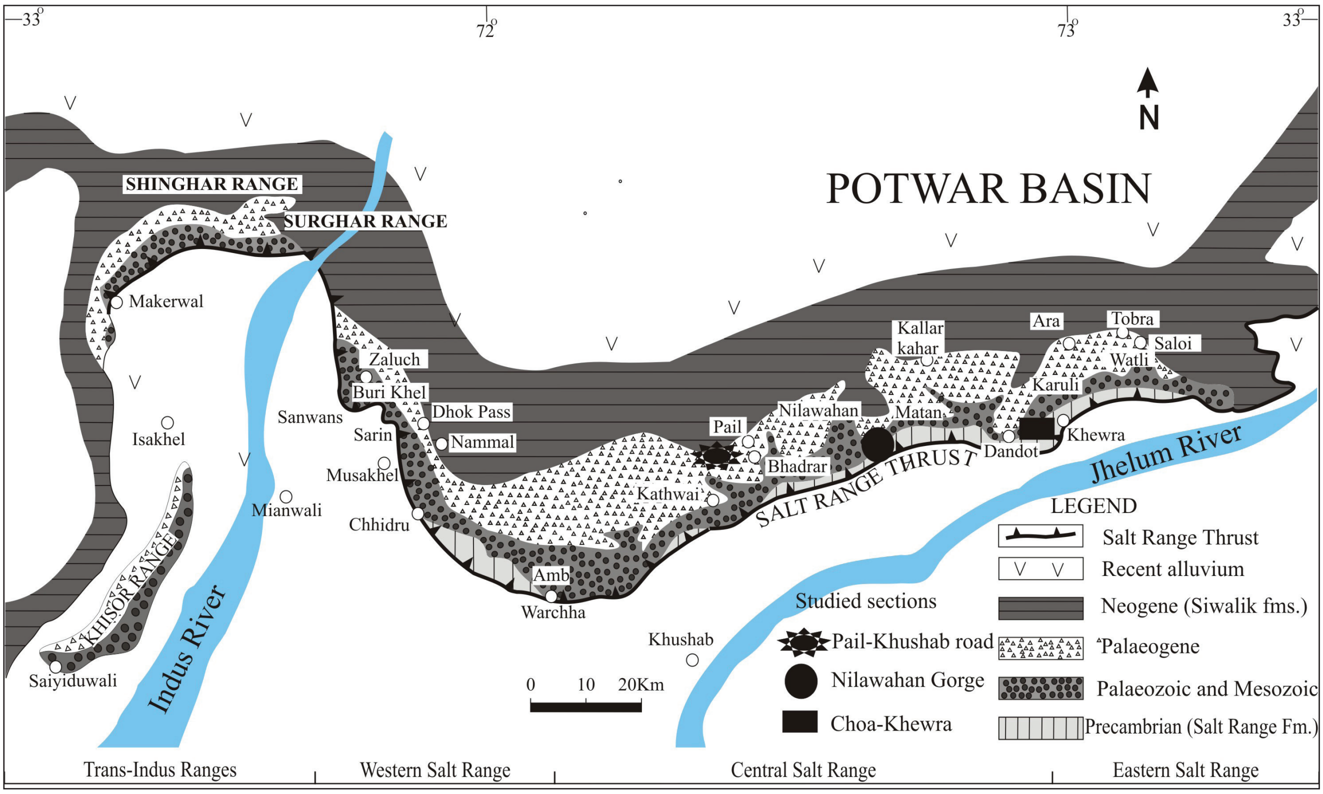

Fig. 1 - Location map of the Salt Range and Trans Indus ranges, showing Choa-Khewra road, Nilawahan Gorge and Pail-Khushab road sections, Pakistan (After Jan & Stephenson 2011).

glacio-fluvial Tobra Formation and underlies the fluvio-continental Warchha Sandstone (Fig. 2). The aim of this paper is to describe the sedimentology of the Dandot Formation in the context of deglaciation on the northwestern margin of the Indian Plate and correlate the Dandot Formation with other age-equivalent units of Gondwana basins (Fig. 3).

Geological settings

The Northern margin of the Indian Plate is occupied by an active fold and thrust belt of the Salt Range formed in response to the collision between Indian and Eurasian plates (Jaumé & Lillie, 1988; Fig. 4). This ongoing collision between the Indian and Eurasian plates started ~55 million years ago, as a result of northwards drift of the Indian Plate (Tahirkheli 1979; Yeats et al. 1984; Baker et al. 1988).

The Salt Range Thrust represents the southernmost fault and is considered the youngest compressional structure of the Himalayan foreland system (Grelaud et al. 2003). The syn-orogenic alluvium and fan material at the range front are overridden by the Precambrian evaporites and overlying strata (Yeats et al. 1984). The Precambrian Salt Range Formation is thrust on top of the younger strata in the eastern Salt Range (Fig. 1), while the oldest rocks exposed in the western Salt Range are represented by the Carboniferous-Permian Nilawahan Group (Gee & Gee 1989).

The Salt Range represents rocks ranging from Pre-Cambrian to Tertiary (Shah 1977; Gee & Gee 1989). These rocks units are distributed in the eastern, central and western part of the Salt Range. The Carboniferous-Permian succession of the Salt Range Pakistan is subdivided into the dominantly continental Lower Permian Nilawahan Group of the Gondwanan realm and the overlying shallow marine Middle to Upper Permian Tethyan Zaluch Group (Wardlaw & Pogue 1995; Jan et al. 2009; Jan & Stephenson 2011; Stephenson et al. 2013; Fig. 2). The Upper Pennsylvanian-Asselian Tobra Formation represents the lowermost formation of the Nilawahan Group deposited periglacially (Shah et al. 2010; Fig. 2). It displays palaeontological and sedimentological similarities with the middle part of the Al Khlata Formation of Oman and Unayzah B member of Saudi Arabia and has been correlated with Al Khlata reservoir production units AK P5 to AK P1 of Petroleum Development Oman (PDO)

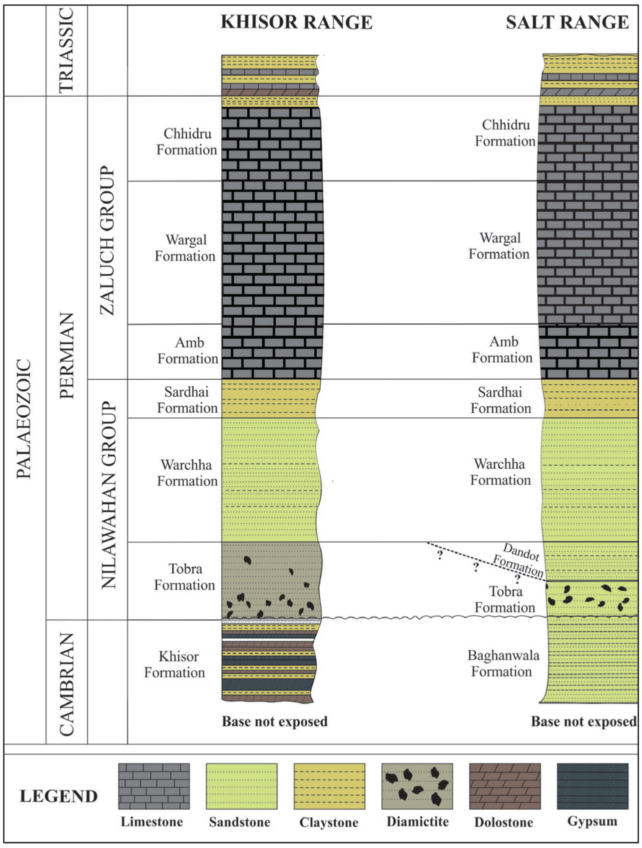

Fig. 2 - Carboniferous–Permian stratigraphy of the Salt Range and Trans Indus ranges, Pakistan. The Gondwana succession, i.e. Nilawahan Group is represented by the Tobra, Dandot, Warchha and Sardhai formations. The Dandot Formation is not developed in the Trans Indus ranges. The overlying Zaluch Group is represented by Amb, Wargal and Chhidru formations (After Jan et al. 2009).

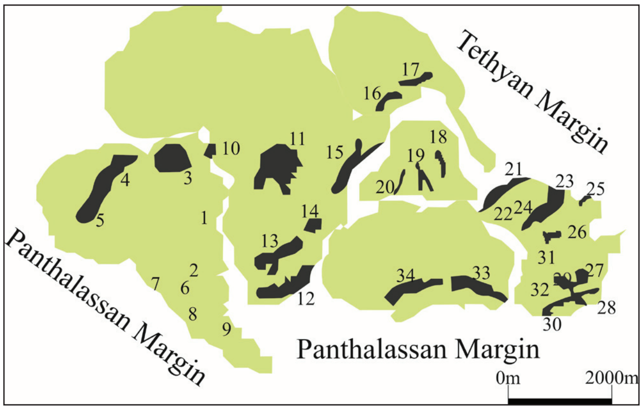

Fig. 3 - Chief Carboniferous-Permian basins of Gondwana, 1-9: South American basins, 10-15: South African basins, 16: Yemen, 17: Oman, 18: Himalayan zone, 19-20: Indian basins, 21- 32: Australian basins, 33- 34: Antarctic basins (After Stephenson 2008; Jan 2014).

and south Oman 2165B Biozone (Jan & Stephenson 2011).

The Tobra Formation is overlain by the Dandot Formation in the eastern Salt Range; however it is absent in the western Salt Range and Khisor Range where the Warchha Sandstone directly overlies the Tobra Formation (Fig. 2). The lower contact of the Dandot Formation is gradational with the Tobra Formation (Ahmad 1970; Shah & Sastry 1973; Dickins 1996; Fig. 2). The upper contact is sharp with the Warchha Sandstone and is marked by an abrupt change in the lithology and sedimentary structures (Fig. 2). The Warchha Sandstone consists of medium- to coarse-grained, purple, arkosic sandstone, conglomeratic in places, with interbeds of reddish shale, and represents an arid paleoclimate (Ghazi & Mountney 2009; 2011). The unit is barren of palynomorphs (Jan 2012), however an Artinskian age has been assigned to it based on plant megafossils, including *Glossopteris*, *Gangamopteris*, *Samaropsis* and *Ottokaria* (Virkki 1939).

The overlying Sardhai Formation (Fig. 2) represents deposition in lacustrine to shallow-marine settings and has been correlated with the "Khuff transition section" of Oman and the "basal Khuff clastics" of Saudi Arabia within the Gharif Formation (Jan et al. 2009). The overlying Zaluch Group represents a dominantly carbonate succession (i.e. the Amb, Wargal and Chiddru formations), developed on a carbonate platform on the north-western Tethyan margin of the Indian Plate representing shallow marine to inter-tidal deposition (Mertmann 2003; Jan et al. 2009; Jan & Stephenson 2011).

Methodology

Sedimentological analyses of the Dandot Formation were carried out at the Choa-Khewra road section (eastern Salt Range; N 32° 39' 59.3" E 72° 59' 12.8"; Figs 1 and 5), the Pail-Khushab road section (central Salt Range; N 32° 35' 49.42" E 72° 27' 15.7"; Figs 1 and 6) and the Nilawahan Gorge section (central Salt Range; N 32° 58' 32.0", E 72° 45' 56.5"; Figs 1 and 7). The locations are accessible and represent various intervals within the succession. Field observations, samples for petrography and grain size analysis from the formation were collected (Figs 5, 6 and 7). Proportions of the framework grains were counted using traditional methods. A Nikon polarizing LV 100ND microscope with DS-Fi2 Nikon digital camera was used for counting and photomicroscopy.

Sedimentological investigation

The Dandot Formation (Fig. 1) shows lateral and vertical changes in the lithology with the following lithofacies and facies associations:

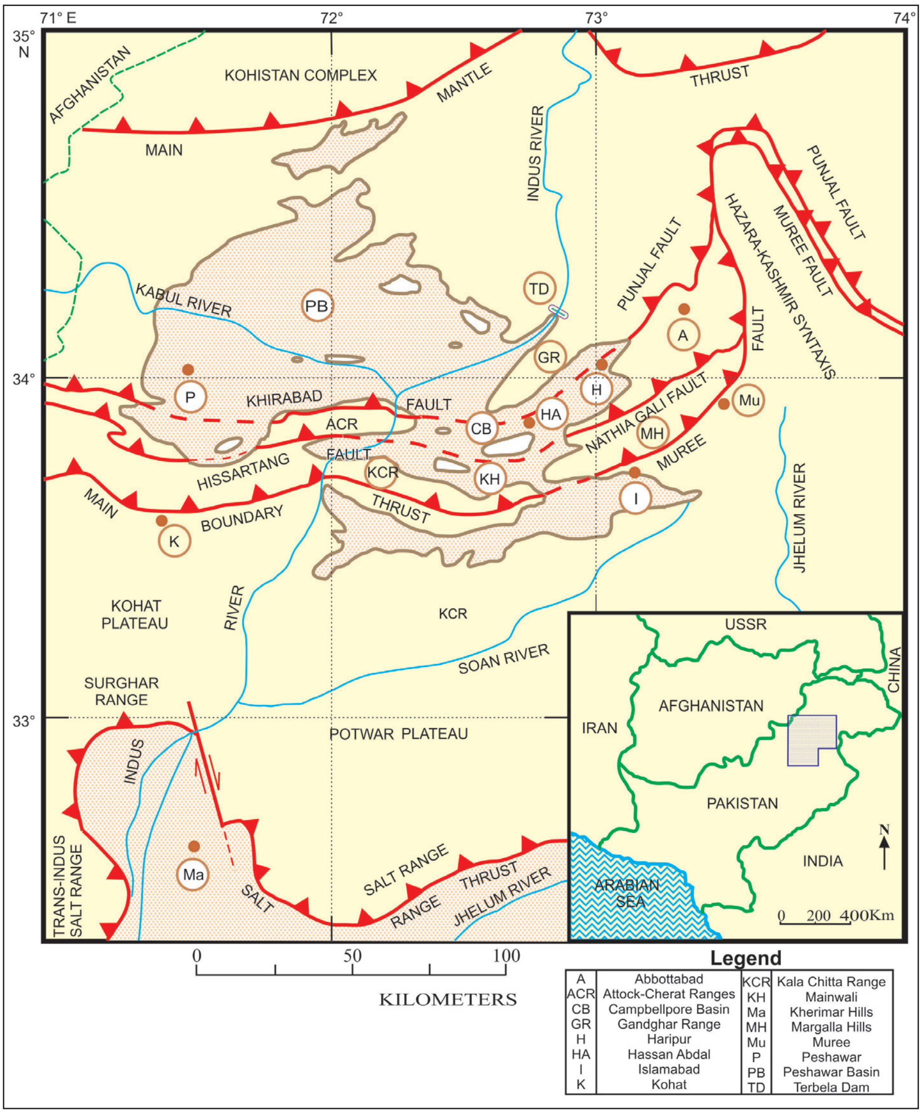

Fig. 4 - Tectonic Map of Northern Pakistan, showing major structural boundaries (After Hylland et al. 1988).

Bioturbated sandstone lithofacies (L1). The bioturbated sandstone is present in the lowermost part of the Dandot Formation along with the contact of the underlying Tobra Formation and is comprised of fine to medium-grained sandstone (i.e. Figs 6 and 7). The lithofacies is 3.5 m-thick in the both stratigraphic sections, and is overlain by flaser bedded sandstone at the Pail-Khushab road section and planar sandstone at the Nilawahan Gorge section (Fig. 8A and B). The sandstone is thoroughly bioturbated and the intensity decreases upwards. Rootlets occur at the top of the bedding planes in the upper parts of the formation, associated with horizontally laminated sandstone. The sandstones are internally featureless, having erosive basal surfaces and having cross beds towards the top of the unit. The upper contact with the planar bedded sandstone lithofacies (L6) is sharp. Horizontal burrows and glaucony are common on the bedding planes of the sandstone. The lithofacies displays tabular geometry in both sections.

The base of the formation is erosive and grades upwards into wave-rippled sandstone lithofacies, which contains hummocky cross stratification and represents shoreface sandstone (Reading 1996; Duke 1990; Cheel & Leckie 1993). The lithofacies represents deposition during flooding, resulting in the winnowing of the shoreface sandstones by waves or tides (Shukla & Singh 1990; Davies & Walker 1993; MacEachern et al. 1999; Al-Qayim et al. 2005). The cross-bedded sandstones were deposited in estuarine or tidal channels cutting across the lagoonal fill, where bioturbation also developed in protected areas (Singh & Shukla 1991). However, the absence of erosional surfaces and the tabular geometry of the lithofacies seldom support deposition in estuarine or tidal channels (Dalrymple et al. 1991). Glaucony present in the sandstone also supports deposition in a shallow marine environment.

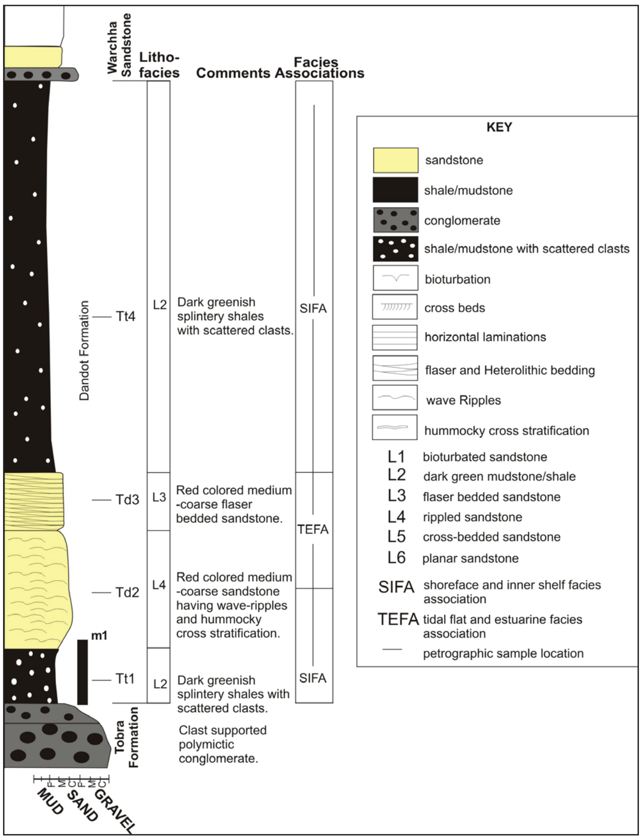

Fig. 5 - The distribution of lithofacies and facies associations of the Dandot Formation at the Choa-Khewra road section, eastern Salt Range. See the figure inset for key.

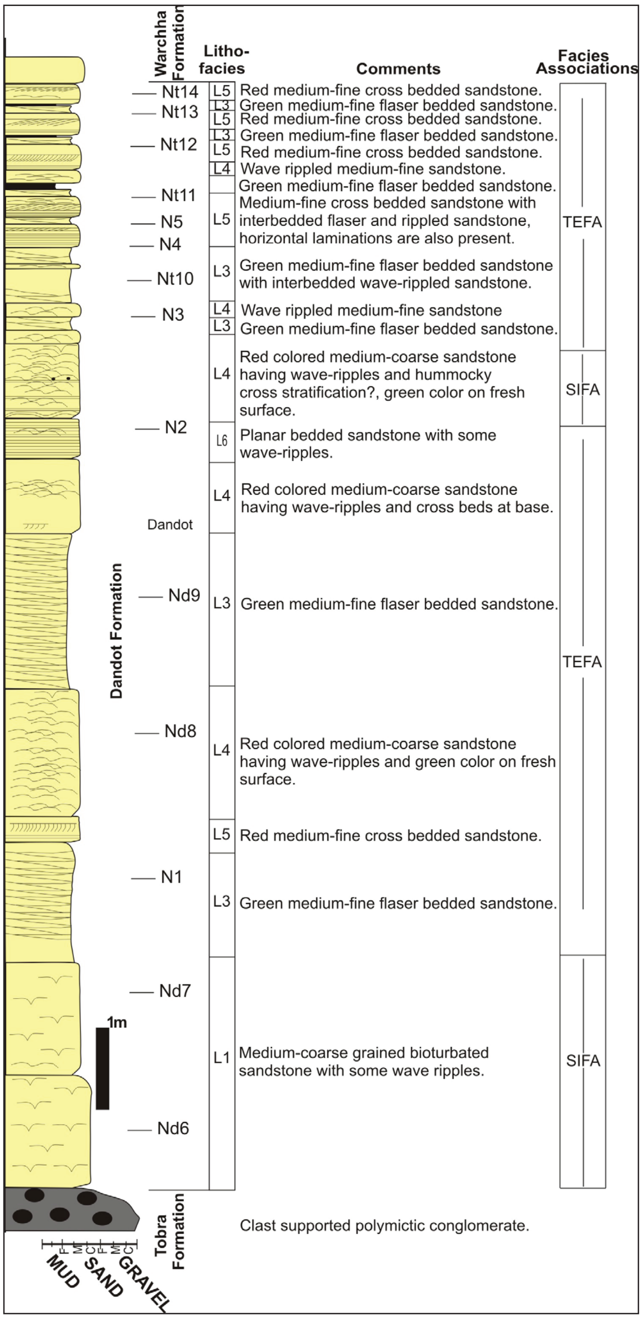

Fig. 6 - The distribution of lithofacies and facies associations of the Dandot Formation at the Pail-Khushab road section. See inset figure 5 for key.

Dark green mudstone/shale lithofacies (L2). Dark green splintery shales constitute the basal part of the Dandot Formation at the Choa-Khewra road section (Fig. 1) and are repeated in the uppermost part of the formation beneath the contact with the overlying Warchha Sandstone (Figs 4 and 8C). The thickness of L2 varies from 0.8 m in the basal part to 6 m in the uppermost part. The lower L2 unit contains scattered clasts of varying compositions including granite, volcanic, and sedimentary lithics derived from the underlying Tobra Formation. This unit grades into rippled sandstone, showing soft sediment deformation in the upper parts (Fig. 8C). The number of scattered clasts increases in the upper part of the formation. The lower contact of L2 is sharp with the underlying Tobra Formation, however it does not show erosive surfaces. L2 possesses a tabular geometry.

Fielding et al. (2006) attributed the presence of clasts to the melting of icebergs and the dropping of clasts in the marine environment. The absence of varves and other glacial features point to a non-glacial origin. The dark green shale shows deposition in the nearshore environment (Genneseaux 1962; Stanley & Swift 1967). The presence of soft sediment deformation also indicates deposition in a marine environment (Crowell 1956; Altermann 1986).

Flaser bedded sandstone lithofacies (L3). L3 is present at the Pail-Khushab road and Nilawahan Gorge sections (Figs 6 and 7). The sandsto-

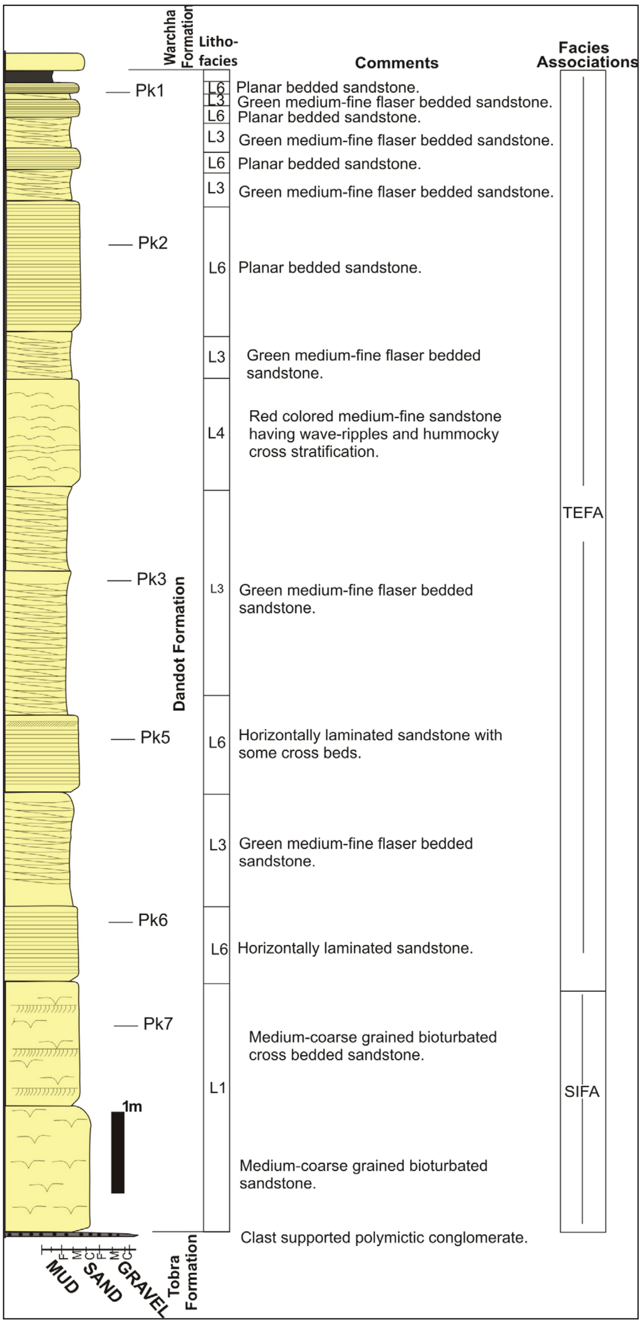

Fig. 7 - The distribution of lithofacies and facies associations of the Dandot Formation at the Nilawahan Gorge section. See inset figure 5 for key.

nes are fine- to medium grained, well sorted and green in color. The lithofacies is repeated several times at the Pail-Khushab road section (Fig. 6), having fining upward succession with thickness ranging from 0.2 to 3 m (Fig. 8D). Sand lenses are 1 to 2 cm in thickness with internal laminations, cross laminations and asymmetric ripples. In places these sand flasers sharply overlie cross-bedded sandstones. Similar fining upward successions are present at the Nilawahan Gorge section (Fig. 7) but with lesser thicknesses than those present at the Pail-Khushab road section (Fig. 6). In places, flaser and lenticular bedding is replaced by tidal bedding, i.e. cyclic pattern of planar bedded sandstone and shale.

Flaser bedded sandstones are interpreted to represent deposition in a tidal setting, i.e., tidal flats and tidal channels (Terwindt 1971). The repeated fining upward cycles represent tidally-influenced estuarine channel fills (Fielding et al. 2006).

Rippled sandstone lithofacies (L4). This facies constitutes fine grained, well sorted sandstone with a red weathered surface and green fresh surface color. The sandstone is laminated with abundant wave ripples, combined flow ripples, and rare climbing ripples. Low angle hummocky cross stratification and herringbone cross stratification are common (Figs 5 to 7 and 8E). The upper surfaces of the ripples in places are marked by thin shale beds. The rippled sandstone grades into flaser bedded sandstones. This lithofacies is present in all the three stratigraphic sections and is repeated at the Pail-Khushab and Nilawahan Gorge sections with 0.2 m to 2 m variation in thickness (Figs 5 to 7). At the Nilawahan Gorge section, L4 displays thickening beds giving massive appearance and has fine- to medium grain size. Current-ripples predominate over asymmetrical ripples. These sandstones grade upward into flaser bedded units and overlie bioturbated sandstone lithofacies. Extensive horizontal burrows are present on the upper surfaces of these rippled beds in the upper parts of the formation. At the Choa-Khewra road section, this lithofacies is similar in appearance to that found at the Nilawahan Gorge section, with sandstone being much coarser, having red color with green shale on the rippled surfaces (Fig. 5).

An abundance of wave ripples and current ripples points towards deposition in a coastal environment (Reineck & Singh 1971; Wunderlich 1972). The association of this lithofacies with flaser bedded sandstone lithofacies upwards represents deposition in the intertidal environment (Reineck & Singh 1983). Thick sandstones with asymmetrical ripples of the Nilawahan Gorge and Choa-Khewra road sections represent deposition in relatively deeper waters of the shoreface (Newton 1968). The presence of hummocky cross stratification also supports this interpretation (Newton 1968; Reineck & Singh 1983). The comparatively large size of the

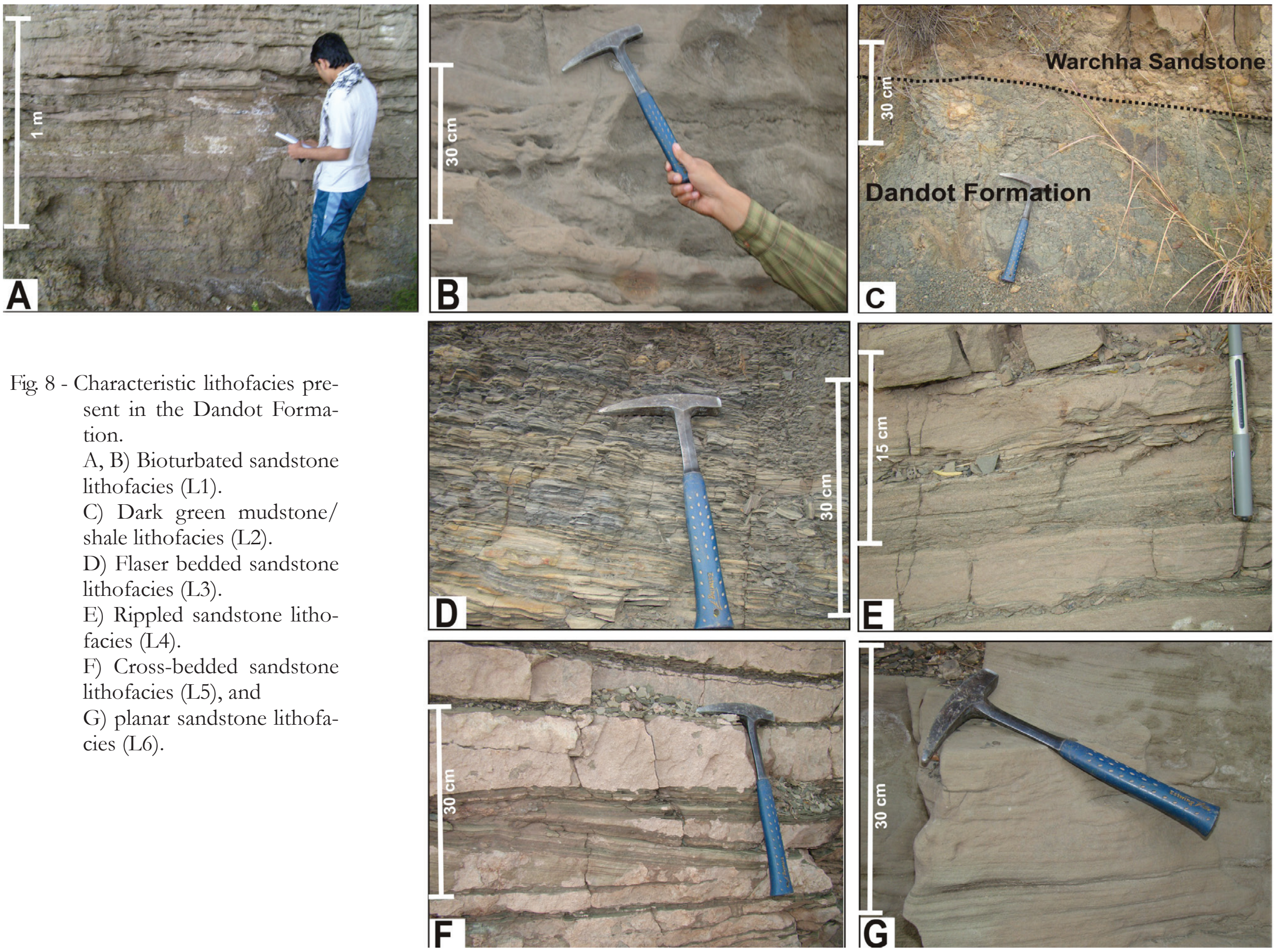

Fig. 8 - Characteristic lithofacies present in the Dandot Formation.
A, B) Bioturbated sandstone lithofacies (L1).
C) Dark green mudstone/shale lithofacies (L2).
D) Flaser bedded sandstone lithofacies (L3).
E) Rippled sandstone lithofacies (L4).
F) Cross-bedded sandstone lithofacies (L5), and
G) planar sandstone lithofacies (L6).

ripples is also evidence of deposition in deeper waters (Reineck & Singh 1983).

Cross-bedded sandstone lithofacies (L5). L5 is present at the Pail-Khushab road section in the central Salt Range and comprises coarse grained, occasionally friable reddish to whitish green sandstone (Figs 6 and 8F). This lithofacies is present in the middle and upper parts. Low angle planar cross bed sets are present within the sandstones, and are associated with the horizontally-laminated sandstone, and grade upwards into flaser bedded sandstone (Figs 6 and 8F). At some places, low angle planar cross bed sets also occur (Fig. 6).

The association of this lithofacies with the planar sandstones lithofacies and tidally influenced channel fills of estuarine environment suggest deposition on tidal flats in the tidal channels and estuarine fills (Davis 1983; Dalrymple et al. 1991).

Planar sandstone lithofacies (L6). L6 is present at the Pail-Khushab road and Nilawahan Gorge sections only (Figs 5 to 7). This lithofacies is repeated vertically in the stratigraphic sections and is associated with the bioturbated sandstone below and flaser bedded sandstone above. It is also associated with the rippled sandstone lithofacies. The facies comprises medium to coarse-grained, well sorted, and friable sandstones and occurs in beds (thickness varies from 0.5 to 2 m) with planar/horizontal laminations. A fining upward trend is observed in L6 and grades into flaser bedded units (Figs 6 and 7). Low angle cross laminations also occur towards the top in the lithofacies (Fig. 6G). At Nilawahan Gorge section, horizontal burrows are found on the upper surfaces of the thin horizontal fine clayey beds interlaminated with sandstone (Fig. 7). These beds constitute fine grained well sorted and friable sandstones.

The stratigraphic position of L6 suggests an intertidal depositional setting. In the Nilawahan Gorge, the heterolithic bedding in L6 also represents cyclic change in the energy conditions due to the tidal activities.

Facies associations

The lithofacies in the Dandot Formation can be grouped into two facies associations:

Shoreface and inner shelf facies associations (SIFA). SIFA is composed of L1 and L2. Part of the rippled sandstone lithofacies (i.e. L4) is also included in this association (Figs 5 to 7). The presence of sedimentary structures and textural trends and presence of wave ripples, hummocky cross stratification, bioturbation and mudstone/shale containing scattered pebbles indicate deposition in nearshore to slightly deep water settings (Reading 1996; Fielding et al. 2006). The shoreface and inner shelf facies association is present in all three stratigraphic sections (Figs 5, 6 and 7). The Dandot Formation at the Choa-Khewra road section (i.e. eastern Salt Range) contains pebbly mudstone/shale of this association in the lower and upper parts. In the central Salt Range (Fig. 1), lithologies representative of this facies association are restricted to the lowermost part of the Dandot Formation.

Tidal flat and estuarine facies association (TEFA). TEFA comprises L3, L4, L5 and L6 (Figs 5 to 7). The abundance of wave ripples, combined flow ripples, heterolithic bedding, tidal channel fill sequences and bioturbation indicate deposition of this facies association in tidal flats and an estuarine environment (Reineck & Singh 1983; Fielding et al. 2006). This facies association is present in all the three stratigraphic sections. At the Choa-Khewra road section, rippled sandstone and flaser bedded sandstone of this facies association are present in the middle part of the Dandot Formation while the other lithologies representing this facies association are present in the Nilawahan Gorge and Pail-Khushab road sections, where they represent the middle and upper parts of the formation.

Vertical and lateral facies variations

The Dandot Formation in the eastern part of the Salt Range (Fig. 1) shows relatively deeper facies of SIFA at the base which grade upwards into shoreface sandstone with development of ripples and hummocks subsequent to sea level rise possibly as a result of Carboniferous-Permian deglaciation (Dickins 1996; Angiolini et al. 2003; Ghazi & Mountney 2011; Fig. 9). In the central part of the Salt Range, i.e., Pail-Khushab road and Nilawahan Gorge sections (Figs 1, 6, 7 and 9), trangressive bioturbated shoreface sandstones grade upwards into relatively shallow marine bioturbated sandstone. The progradation continues and the succession grades into tidal flat and estuarine sandstones and heteroliths. Several cycles of the fining upward successions indicate that the presence of estuarine/tidal channels is quite dominant in the upper and middle parts of the Dandot Formation at Nilawahan Gorge and Pail-Khushab road sections. Overall, a progradational sequence is recorded in the Dandot Formation which sharply truncates against the fluvial succession of the overlying Warchha Sandstone (Figs 2 to 7).

In the east, the Dandot Formation constitutes deeper facies of SIFA with presence of mudstone/shales with scattered pebbles. In the central part of the Salt Range, lithologies of shallow-marine settings predominate. Shoreface facies are present only at the basal part while the rest of the formation appears to have been deposited in a marginal marine setting, i.e., tidal flat and tide-dominated estuarine sequence. It is suggested that the eastern part of the Salt Range occupied a relatively distal position on the northwestern margin of the Indian Plate and as a result relatively deeper water facies were deposited in this part and the western part occupied a more proximal position and thus the central and western parts represent shallower facies.

Depositional system and regional setting. The distribution of the lithofacies at the three stratigraphic sections (i.e. Choa-Khewra road, Pail-Khushab road and Nilawahan Gorge sections; Figs 5, 6 and 7 respectively) shows interbedding with little cyclicity in the upper parts of the formation in two stratigraphic sections i.e. Pail-Khushab road and Nilawahan Gorge sections (Figs 6 and 7), and in the middle part of the formation at the Nilawahan Gorge section (Fig. 7). Major erosional surfaces like sequence boundaries were not identified within the vertical stacking patterns except the surface separating estuarine channel fills from the shoreface facies evident at the basal part of the Dandot Formation at Pail-Khushab road and Nilawahan Gorge section (Figs 6 and 7). This surface can be considered a sequence boundary because of an abrupt change in

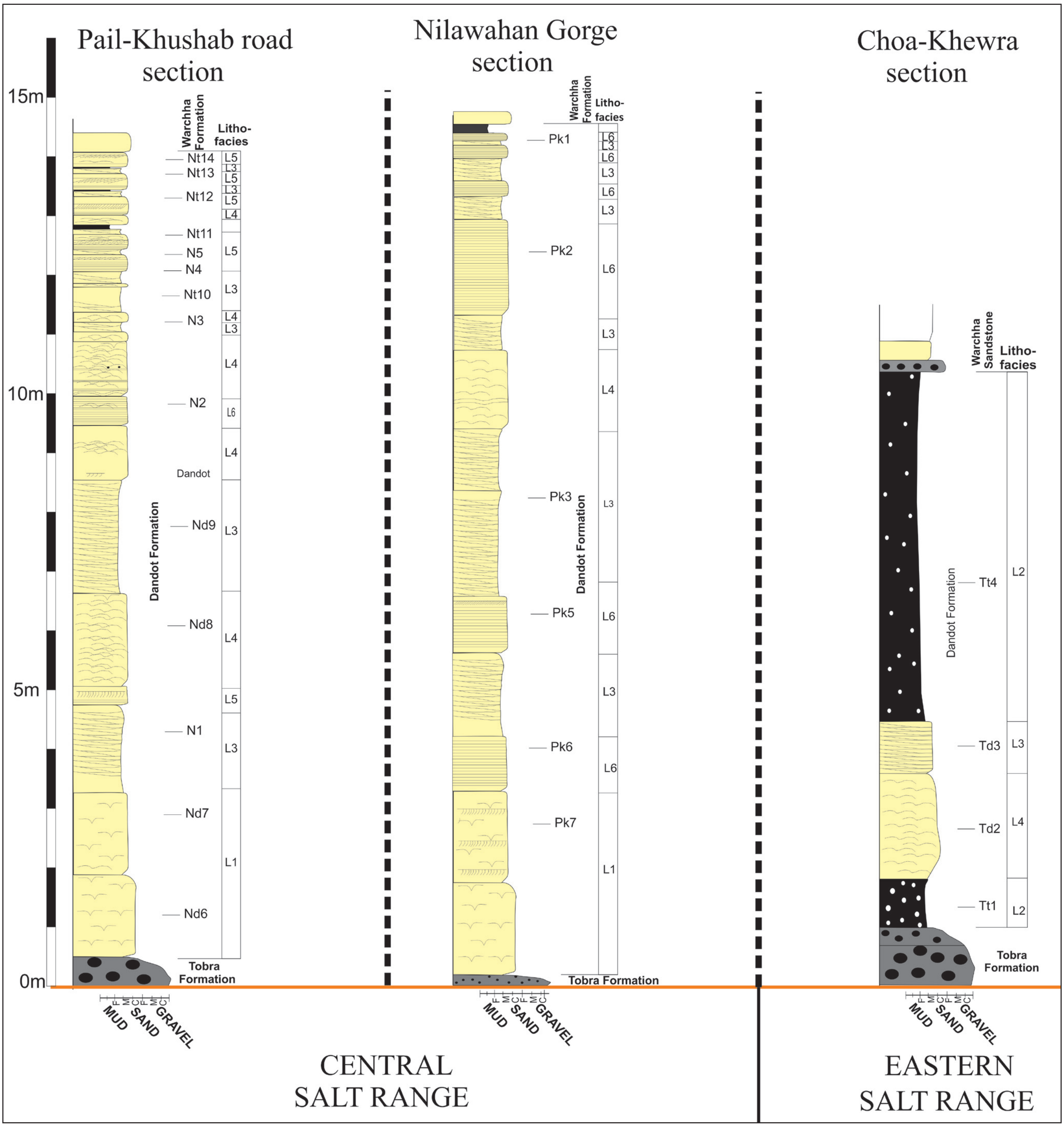

Fig. 9 - The Dandot Formation facies correlation in the eastern and central Salt Range. Refer to figure 1 for locations and inset figure 5 for key.

the facies and because the surface is traceable laterally for long distances. At the Choa-Khewra road section, an abrupt deepening is observed and lithofacies L3 is overlain by L2 of shoreface to inner shelf environment. Similar surfaces showing abrupt deepening are also present in the Nilawahan Gorge section (Fig. 5) in the middle and upper part where the cyclicity of upper shoreface sands and heterolithic bedding of the TEFA is observed. In the lower to middle part, the pattern in the sequence may be attributed to the short term cyclicity in sea level (Fig. 7), while in the upper part (Fig. 5), the presence of shoreface sandstone interbedded with the tidal flat and estuarine fill facies association represents abrupt deepening and thus a marine flooding surface. Overall, the vertical stacking pattern in the Dandot Formation represents a progradational sequence with shallow marine facies overlying the deep marine facies.

		Quartz				Feldspar							Lithic Fragments						
Section	Sample#	Qm	Qp	Qt	Ch	Kf	Pl	Ft	Mica	Ca	Ioc	Qc	Ls	Lv	Lm	Po	Op	Gl	Matrix
Nilawahan Gorge section	N1	78	1	79		2	1	3	2	1	10	2					3		
	N2	76		76		2	1	3	5	1	10						4		
	N3	68	3	71		1	1	2	15		8						3		
	N4	67		67		3	2	5	10	5	9	1					3		
	N5	69		69		3	4	7	10	5	6	1					2		
	Nd7	68	1	69		2	1	3	4	6	4						2	14	
	Nd8	81		81		3	2	5	1	1	9					1	2		
	Nd9	65	2	67		4	3	7	14	1	8						3		
	Nd10	74	1	75		2	1	3	10		7						1		4
	Nd11	78,5	1	79,5		2	0,5	2,5	3	8	6						1		
	Nd12	81	1	82		5	3	8	0,5	6	3						0,5		
	Nd13	77	1	78		5	3	8	1	5	4						1		
	Nd14	82	3	85		4	2	6	0,5	5	3						0,5		
	Nw15	65	3	68		8	4	12	1	1	3		5		2	1	1		6
Pail-Khushab road section	Pk1	84		84	1	4	3	7	1	3	3		2				1		
	Pk2	74,5	1	75,5		4	5	9	6	0,5	4	2	1				1		
	Pk3	80,5	1	81,5		2	1	3	4	0,5	5	2				1	2		
	Pk5	75	1	76		2	1	3	5	1	10	1				3	2		
	Pk6	83	1	84		1	1	2	1	1	8	1				1	1	1	
	Pk7	69	1	69,5		1	0,5	1,5		2	6	0,5					0,5	20	
Choa-Khewra road section	Td3	83,5	1	84,5		0,5	1	1,5	1	3	5	2					3		
	Td1	70	5	75		2	3	5		1	1		3	5			1		10
	Tw5	58	4	62		9	4	13		8	4	1	5	3		3	1		

Tab. 1 - Proportions of rock components of the sandstone of the Dandot Formation. Sample Tt1 belongs to underlying Tobra Formation and Tw5 and Nw15 belong to overlying Warchha Sandstone. For samples locations see figures 5, 6 and 7. Qm = Non undulose microcrystalline quartz, Qp = Polycrystalline quartz, Qt = Total quartz present (monocrystalline and polycrystalline including chert), Ch = Chert, Kf = Alkali feldspar (orthoclase and microcline), Pl = Plagioclase feldspar, Ft = Total feldspar (both K-feldspar and plagioclase), Ca = Clacite cement, Ioc = Iron oxide/hydroxide, Qc = Quartz cement, Ls = Sedimentary lithics, Lv = Volcanic lithics, Lm = Metamorphic lithics, Po = Porosity, Op = Opaque minerals, Gl = Glaucony.

Sandstone petrography

Sandstone constitutes about 85%, of the Dandot Formation; shale and mudstone is less common (Figs 5 to 7). The sandstones are homogeneous with fine- to medium-grain size, however occasional coarse-grained sandstones occur in the basal parts of the formation. Sandstones are moderately to well sorted and very well sorted in places. Texturally, the grains are rounded to sub-rounded, with occasional angular to sub-angular shapes and display loose packing; however in some places sandstone is compact and tightly packed. Contacts between the grains are mostly straight, with some concavo-convex, tangential and rare sutured contacts (Fig. 10C). Two sandstone samples collected from the base of the overlying Warchha Sandstone are moderately to poorly sorted and feldspatho-quartzose (Tab. 1).

Characteristics of the framework grains.

Clasts. Quartz crystals constitute 65-84% of the rock; 99% are monocrystalline, clear of inclusions, and mostly display unitary or slightly undulatory extinction (Figs 10A and B). Abraded overgrowths also occur. Mostly altered feldspar forms 1-9% of the rock, alkali feldspar prevails over plagioclase, and microcline is rare (Tab. 1). Sedimentary lithics (i.e. siltstone and rare chert) represent 0.2% on average and up to 2% of the rock (Fig. 10F). Igneous and metamorphic lithics seldom occur. Micas are aligned parallel to the bedding planes and are most common in heterolithic and fine grained sandstone, decreasing in medium and coarse sandstone. Muscovite is more common than biotite and accounts for 4.6% on average of the total grains. Glaucony was observed only in bioturbated sandstone lithofacies at the base of the Dandot Formation (Figs 10B & E). Opaque magnetite and haematite comprise ~1.8% of the total rock grains (Tab. 1).

Cement. The color of the sandstone varies between red, reddish green, green, grey and white. This can be attributed to the types of cement and amount of the interstitial haematite in the matrix (Schluger 1976). Haematite is dominant with very rare siderite observed, and is found as filling in pore spaces, corroding the grain boundaries and coating and replacing grains and other types of cement. Calcite constitutes 2.8% of the rock grains. Percentages of calcite tend to increase upwards in the section with a decrease in ferruginous cementing material. The volumetric percentage of quartz overgrowths is 0.62%, and some of these overgrowths have a rounded periphery while others are recycled, precipitated around the grains in original sandstone.

Provenance. Twenty representative samples from three stratigraphic sections were selected for provenance studies. Sandstone compositions mainly depend on the type of the source rock, tectonic settings, climate conditions in the source area, nature, and chemical composition (in case of water) of the transporting agent and depositional settings (Weltje & Eynatten 2004). In general, com-

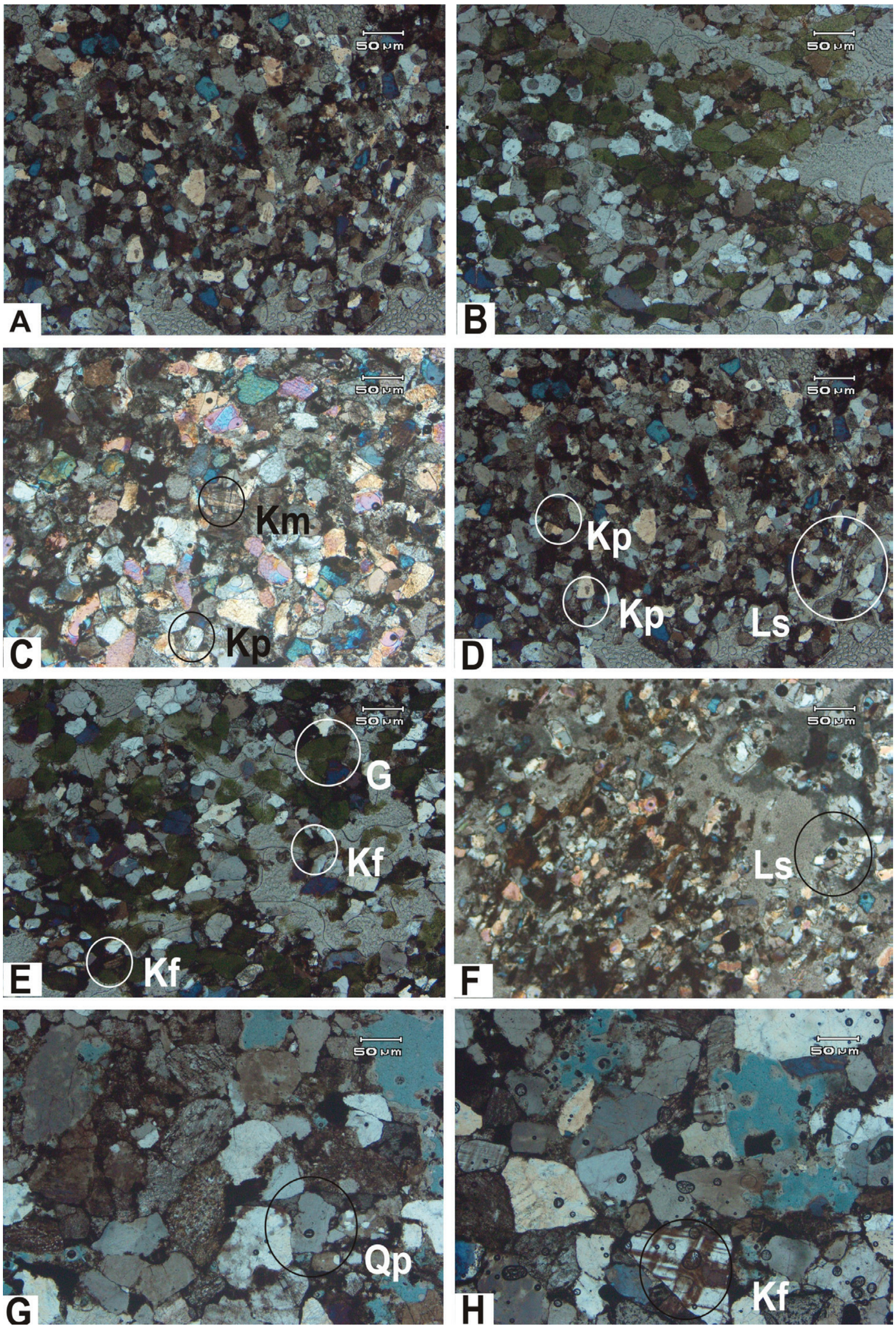

Fig. 10 - Representative photomicrographs of the lithofacies in the Dandot Formation. Km = Cross hatched twinning in microcline, Kp = Polysenthetic twinning in plagioclase, Ls = Sedimentary lithic fragment and Kf = Alkali Feldspar grains.

positions of the sandstones are not much affected by physical processes (Garzanti et al. 2015). Types of quartz grains could be used alone to determine the source rock type. Monocrystalline quartz having uniform to slightly undulose extinction is considered to be derived from plutonic rocks, e.g. granites (Basu et al. 1975; Pettijohn et al. 1987; Datta 2005). Polycrystalline and monocrystalline quartz grains having undulatory extinction are generally derived from a metamorphic source (Blatt et al. 1980; Asiedu et al. 2000), however these are seldom found in the studied samples. The K-feldspar is mainly derived from crystalline rocks i.e., granites and gneisses (Ghose & Kumar 2000; Tucker 2001). Higher ratios of K-feldspar as compared to plagioclase indicate derivation from mixed plutonic and metamorphic source (Dickinson 1970; Tucker 2001). Further, the presence of rounded overgrowths of quartz in some quartz grains indicate recycled sedimentary sources (Basu et al. 1975; Tucker 2001; Jafarzadeh & Barzi 2008). Based on the petrographic evidence, e.g. presence of sedimentary lithics, abundance of monocrystalline quartz and presence of abraded overgrows, a derivation from sedimentary source is interpreted (Fig. 7).

The deposition of the Dandot Formation took place in a cold climate. The sandstone represents derivation from crystalline rocks and enrichment of the quartz in the sandstone is because of the recycled sedimentary source rocks. Extensive reworking in the shallow marine environment was not responsible for the composition of the sandstone which is mainly affected by the source area.

Stratigraphic setting

The upper part of the Tobra Formation at the Choa-Khewra road section contains palynomorphs assignable to the earliest Permian 2141B Biozone (Stephenson et al. 2013). In Oman, the 2141B Biozone is closely associated with the Rahab Shale Member, a widespread shale unit in Oman, which is considered to represent part of a Permian deglaciation sequence which culminates in the marine beds of the Lower Gharif Member, interpreted as due to post glacial marine transgression (Stephenson et al. 2005).

Palynological sampling of the Dandot Formation conformably overlying the Tobra Formation yielded only barren samples, however the marine nature of the Dandot Formation and its stratigraphic position suggests that like the Lower Gharif Member it may represent post glacial marine transgression.

A similar transition is seen elsewhere across Gondwana (Angiolini et al. 2003; Stephenson et al. 2007) where deposition of marine strata occurred on the top of glacially-dominated facies.

For example in India, a transition at the top of the glacigene Talchir Formation is observed, whereby the basin evolution is controlled by deglaciation as a result of climatic warming (Maejima et al. 2004). The Talchir Formation deposits are represented by mudstone with intercalations of sandstone and siltstone. The mudstone shows discrete beds of ripple cross- or climbing-ripple cross-laminated siltstone. The presence of a marine incursion at the top of the Talchir Formation in India is attributed to a eustatic sea level rise associated with the Carboniferous-Permian deglaciation (Maejima et al. 2004). This is then followed by the deposition of the fluvial succession of the Karharbari Formation (Maejima et al. 2004; Bhattacharya et al. 2005), which can be correlated with the Warchha Sandstone (Maejima et al. 2004).

The uppermost part of the Itarare group in Brazil, the Taciba Formation, also records the deglaciation sequence of the Early Permian and contains marine invertebrates including brachiopods overlying the Campo Muroa Formation (Vesely & Assine 2006).

A similar marine transgression has been observed in the Carboniferous-Permian deposits of Australia with the development of marine fauna (e.g. Foster & Waterhouse 1988). The marine fauna of the Dandot Formation e.g. *Fenestella fossula*, *Dielasma dadanense*, *Pterinea* cf. *lata*, *Nucula pidhensis*. *Cardiomorpha*? *pusilla*, *Maeonia* cf. *gracilis*, *Astartila* cf. *ovalis* and *Eurydesma cordatum,* reported by Reed (1936) has been correlated with the "Lower Marine Series" of New South Wales, Australia (Kummel & Teichert 1970). This fauna was attributed by Reed (1936) to the development of contemporaneous marine conditions in Australia and Salt Range, Pakistan.

The age-equivalent unit of the Dandot Formation in Australia, the Pebbly Beach Formation represents various stratigraphic surfaces and stacking pattern diagnostic of the sequences formed under icehouse conditions, showing cyclicity of the stacking pattern (Fielding et al. 2006). However, the Carboniferous-Permian paleogeographic reconstruction of Gondwana shows that Australian basins were exposed to open oceans whereas the Salt Range basin was located along a narrow depression where the effect of sea level rise was soon dominated by progradation due to the uplift of the basement (Valdiya 1997; Garzanti & Sciunnach 1997; Ghazi & Mountney 2011).

Conclusions

Overall the Dandot Formation represents deposition in a shallow marine to intertidal environment.

The sedimentological nature and the stratigraphic position of the Dandot Formation suggests that the Dandot Formation was deposited as a result of global sea level rise associated with the demise of Carboniferous-Permian glaciation, however robust biostratigraphy is required to place the Dandot Formation within a framework of deglaciation.

Petrographic investigations of the Dandot Formation indicate that the sandstones are compositionally quartzose; texturally, and mineralogically mature; and represent derivation from continental blocks with input from recycled sedimentary rocks. Based on petrographic studies, the Malani Range and Aravalli ranges may be the potential source areas for the Dandot Formation.

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