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Mineralogical and Reservoir Characteristics of Well Cutting Samples of Sandstone of the Permian Tobra Formation from Adhi Field, Potwar Basin, Pakistan

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ABSTRACT

Adhi Oil and Gas Field represents a NE – SW trending salt cored pop-up structure which hosts three reservoirs i.e. Sakesar Limestone (Eocene), Tobra Formation (Permian) and Khewra Sandstone (Cambrian). This study is aimed at examining the depositional texture and diagenetic features of the well cuttings from the sandstone unit of the Tobra Formation and their influence on its reservoir characters using a combination of petrographic, XRD, SEM-EDX and grain size analysis techniques. On the basis of framework grains (Quartz$_{80.81}$ Feldspar$_{12.35}$ Lithic fragments$_{6.6)}$, the Tobra Sandstone samples are classified into sub-feldspathic arenites, sublithic arenites, and feldspathic wackes as the most abundant varieties while quartz arenite and subfeldspathic-sublithic arenite are encountered in few intervals. Grain size analysis of Tobra Sandstone samples shows sub-angular to sub-rounded and poor to moderate sorting as indicated by the polymodal nature of majority of the samples (~1.22 -≤5.2 Φ) with few being moderate to well sorted. The matrix is dominantly consisting of ferruginous clays which shows variable concentration in the studied samples and ranges from 6 to 17% with a mean value of 6.6%. XRD and SEM-EDX analysis of the fine fraction shows illite as the principal clay constituent while kaolinite and montmorillonite occur as the minor mineral phases. Along with sandstone fragments, individual shale cuttings are also encountered in the studies Tobra samples which may occur as interlaminations with the sandstone layers. These shale fragments are also consisting dominantly of Illite, a clay mineral. Mineralogical and textural characteristics exhibit that the Tobra Sandstone bears poor to moderate reservoir potential with few being better ones. Several features such as the abundance of Illite, occurrence of planer to concavo-convex grain boundaries and the rarity of growth structures propose an intermediate burial compaction model for the studied sandstone unit of the Tobra Formation. Mineralogical results indicate that the detritus for the sandstone was derived from the craton interior of the Indian Plate as well as recycled orogen located to the south and southeast of the present-day Potwar Basin and Salt Ranges.

INTRODUCTION

Potwar Basin falls in the Upper Indus basin which is bounded by Main Boundary Thrust (MBT) in the north and Salt Range Thrust (SRT) in the south while Jhelum strike slip fault and Indus River (Kala Bagh strik slip fault) lie in the east and west, respectively (Figure 1). Kohat Basin lies in the western strike extension of Potwar Basin with relatively more severe deformational structures (Kazmi and Jan, 1997). Potwar Basin is one of the oldest oil provinces of the Pakistan where both structural and stratigraphic traps occur. The Eastern Potwar represents, thrust and salt cored anticlines and local pop ups. The Northern Potwar Basin represents Passive Roof Duplex geometry (Lillie et al., 1987), where fault propagation folds/fault bend folds or faulted anticlines are the potential targets for petroleum. Further to north, in the Northern Potwar Deformed Zone, imbricated antiformal stacks are the main potential targets. Adhi Field, in the Eastern Potwar region of the study area, is a salt cored classical pop-up structure bounded by thrust faults (Nusrat et al., 2003) and hosts multiple petroleum reservoirs. More than 30 wells have been drilled so far and the gas and oil is being produced from Khewra Sandstone (Cambrian), Tobra Sandstone (Permian) and Sakesar Formation (Eocene; Figure 2). The current study of Tobra Sandstone is carried out on the selective ditch cutting samples obtained from different wells (T-20 T-21, T-22, T-23 T-27) of Adhi Asset, by using the techniques of petrography, X Ray Diffraction, SEM-EDX (energy dispersive system). The study focuses on evaluation of reservoir potential of the sandstone samples through petrographic classification and quantifying and characterizing its interstitial clay types. Possible control of textural and diagenetic characters on reservoir quality of the sandstone intervals, within the Tobra Sandstone, has been investigated. Well cutting samples of Tobra Sandstone were used for modal mineralogical SEM-EDX and XRD studies. Sieve analysis was also conducted for grain size analysis of 16 representative samples.

The Tobra Formation refers to the lowest formation of Nilawahan Group and depicts a very mixed lithology in which the following three facies are recognized (Teichert, 1967): 1. Tillitic facies, exposed in the eastern Salt Rang, grades into marine sandstone containing Eurydesma and Conularia fauna (Dandot Formation). 2. Freshwater facies with few or no boulders is an alternating facies of siltstone and shale containing spore flora. This facie is characteristic of the central Salt Range. 3. The unit with mixed facies of diamictite, sandstone and boulder bed increases in thickness in the western Salt and Khisor Ranges. In the eastern Salt Range, the Tobra Formation represent true tillite where the rock unit is composed of boulders of granite with fragments of quartz, feldspar, magnetite, garnet, claystone, siltstone, quartzite, bituminous shale, diabase and gneiss. The matrix of the conglomeratic bed is generally clayey, sandy and at some places calcareous. The formation at the type locality in the eastern Salt Range is about 20 m thick which varies in the adjoining areas and at places, it is totally missing. It contains flora and fauna including Glossopteris, Gangamopteris and several species of freshwater bivalves and ostracods (Reed, 1936).

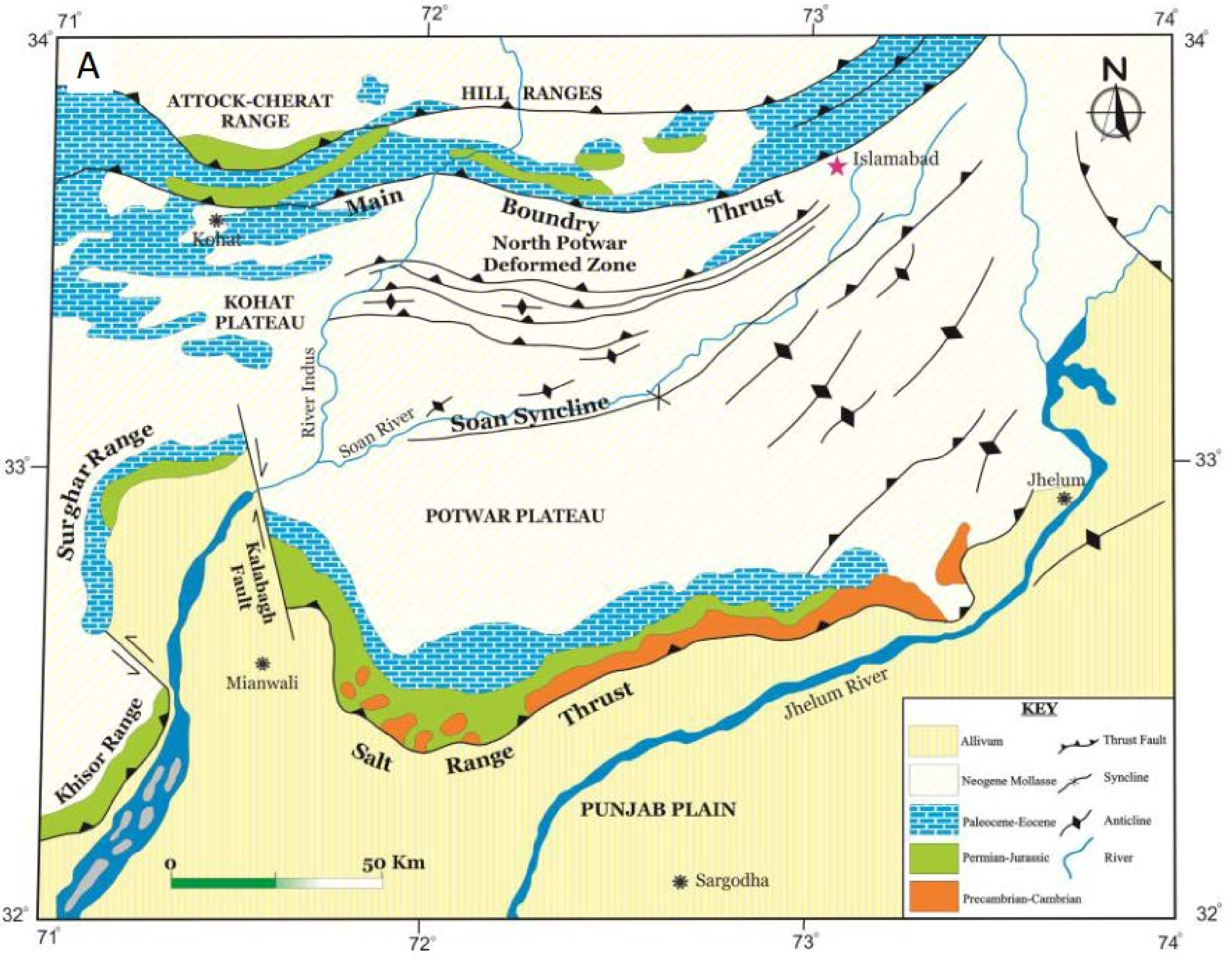

Figure 1 Generalized Geological map of Upper Indus (after Kazmi and Rana, 1982; Khan et al., 1986)

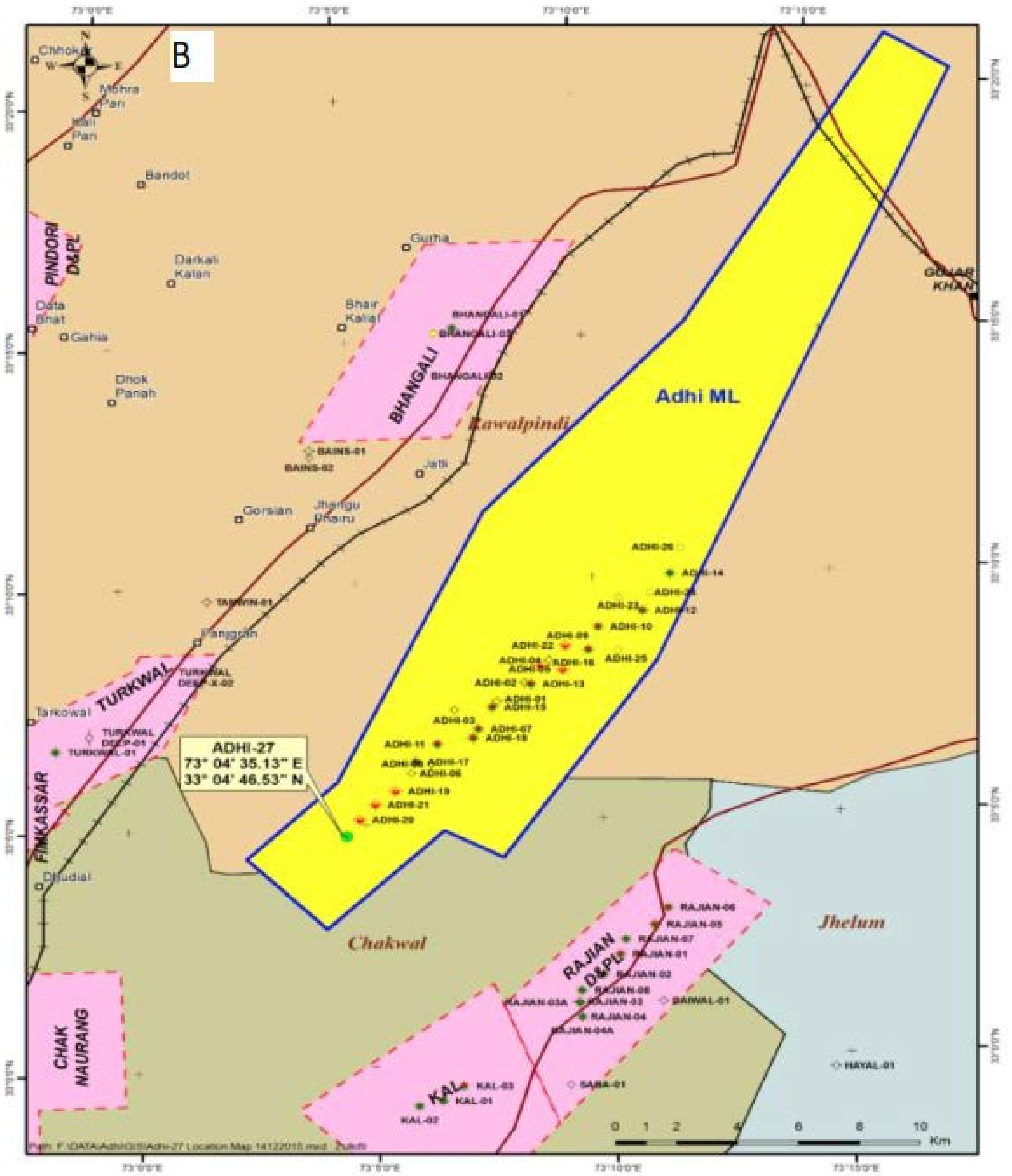

Figure 2 Map showing locations of different wells in Adhi Field

In the western Salt Range, the formation is divisible into 3 units: (a) Brownish green, massive unit consisting of unsorted clastic material including clay, silt, sand and boulders, (b) a middle part, composed of medium to coarse-grained, thick-bedded, dark to light olive grey sandstone containing conglomeratic beds at the base and conglomerate pockets near the top and (c) upper part is similar to the lower one and consists of dark green to grey clay and sandstone lithologies with pebbles and boulders. In the eastern Salt Range section, the formation grades into the overlying Dandot Formation but in west of the Salt Range and in the Khisor Range, it is overlain by the Warcha Sandstone. Its lower contact with the Cambrian rocks is disconformable. The formation attains the maximum thickness in the western Salt Range at Zaluch Nala where it is more than 133 m. In the eastern Salt Range, it is about 33 m and in the central Salt Range it varies from 0 to 25 m. The age of Tobra Formation based on pollen and spores is Early Permian (Balme, in Teichert, 1967).

METHODOLOGY

A total of 16 representatives well cutting samples were used from four wells for textural and mineralogical studies using petrographic microscope under both cross and plane light properties and low and high magnification powers. Photomicrographs of various features were also obtained. Classification scheme of Dott. (1964) was used as this also include an extra dimension for clay matrix (more than 15%), in addition to three corners of QFR (Quartz-Feldspar-Rock fragments). Additionally, quartz was divided into monocrystalline (Q_m) and polycrystalline (Q_p). Both framework (Quartz, feldspar and Lithics) and accessory constituents (mica, heavy minerals, matrix etc.) were determined. Polished thin sections were prepared for Scanning Electron Microscopy (SEM) investigation using gold and carbon coating.

X-ray Diffraction and SEM having attached EDX (Energy Dispersive X-ray diffraction) analyses were performed to identify the type of clay minerals and their relative abundance. High resolution images were acquired to see clay mineral morphology, grain boundaries, textural relationship among various grains and the matrix. The scheme of Dickenson et al. (1983) was utilized for provenance study. In order to determine the maturity of the samples both the grain textures and mineralogical features were used. All the analyses were carried out in various laboratories of the University of Peshawar.

RESULTS AND DISCUSSIONS

The Tobra Sandstone is petrographically classified into various sub-classes and names are assigned based on percentage of framework elements and the abundance of matrix (after Dott. 1964). The sandstone that contain less than 15% matrix is termed as “arenite”, while the term “wacke” is used for the sandstone consisting of 15% or more matrix. Tobra Sandstone is very fine to coarse-grained with majority of the grains ranges from coarse silt to coarse grain size (Figure. 3A-F). Overall, these rocks are texturally sub-mature. Sorting ranges from poor to medium but very few are medium to well sorted. The grains vary in the sandstone samples, from sub-angular to sub-rounded predominantly. Grain contacts are planer-pointed to concavo convex (Figure 3A-F). The average framework composition of the sandstone is $Q_{80.81}$ $F_{12.35}$ $L_{6.6}$. Plots on QFL diagram of dott (1964) divide the studied Tobra Sandstone samples into quartz-arenite (01 sample), sub-feldspathic arenite (05 samples), subfeldspathic-wacke (05 samples), sub-lithic arenite (04 samples) and sub-feldspathic-sublithic arenite (1 sample) with quartz being the most abundant mineral in all of the samples, showing a modal mineralogical range of 60-79% (Table1; Figure 4). Quartz is mainly monocrystalline (Q_m) in all of the samples with minor amount of polycrystalline quartz (Q_p) being in the range of 0-3%.

The texturally sub-mature sub-feldspathic arenites sub-group (T-21/2, T-21/3, T-22/3, T-23/2, T-23/3) is characterized by sub-angular to sub-rounded framework grains showing poor-moderate sorting and moderate sphericity. Grain contacts are pointed-planer and concavo-convex. These samples are also sub-mature minerlogically, containing relatively high amount of ferruginous-clays in the form of matrix, ranges from 3-11% with an average value of 9.2%. Quartz (61-78%) and feldspar (9-20%) are the framework grains with the lithics variably visible (3-13%; Table 1). Feldspar is predominantly occurring as alkali feldspar and plagioclase (Table1) while the accessories including muscovite (trace), biotite (trace to 1%), and ores (hematite, limonite; trace-3%) are also observed in thin sections.

The felspathic wackes (T-20/1, T-20/2, T-21/1, T-22/1, T-22/2; Table 1-2) are the grain-supported and fine to medium-grained sandstones. The grain packing is ranging from floating to plane and planer to concavo-convex. The framework grains are consisting of quartz having 62-72% by volume while feldspar (alkali feldspar) is in the range of 8-15% with averages of 67.6% and 11.6% respectively (Table 1). The lithics are also observed with an average value of 4% (range = 1-8%). Texturally these samples are sub-mature as are characterized by grains of sub-angular to sub-rounded and low to high sphericity (sub-spherical dominantly). Amphibole and tourmaline are rarely found while ores (hematite, limonite) are also observed (traces-2%). The framework grains are poor to well sorted. The concentration of clay matrix is ranging from 14-17% with a mean value of 15.6%.

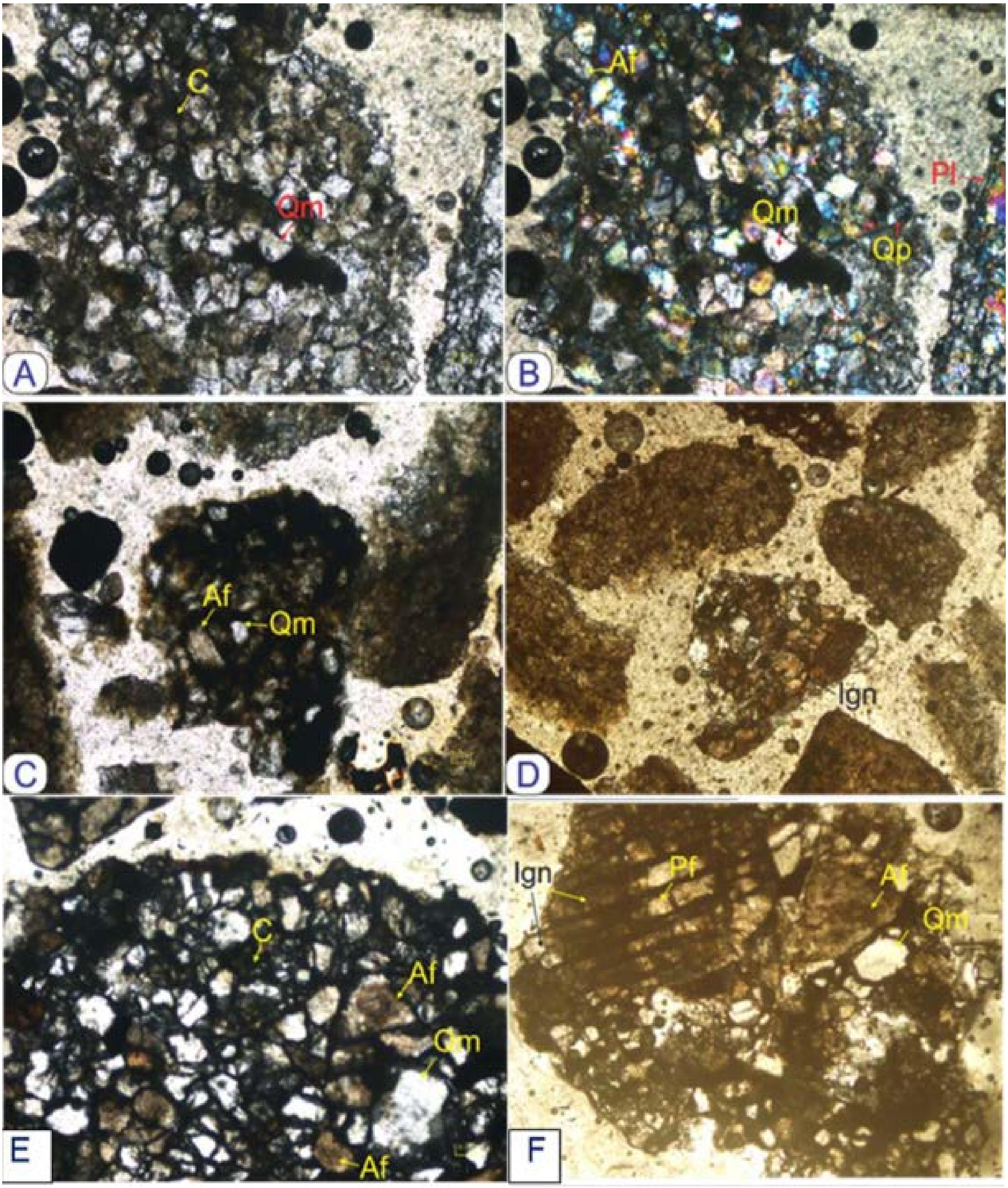

Figure 3 Representative Photomicrographs of the Tobra sandstone unit, A) very fine sand to medium sand with pointed to planar contacts, monocrystalline quartz (Qm) and clay matrix (C). B) alkali feldspar (Af), monocrystalline quartz (Qm), polycrystalline quartz (Qp) and plagioclase (Pl). C) monocrystalline quartz (Qm), alkali Feldspar (Af). D) igneous lithic (Ign) and shale fragments. E) Very Fine Sand to Medium Sand with Planar contacts, monocrystalline quartz (Qm), Alkalo Feldspar (Af) and clay matrix (C). F) monocrystalline quartz (Qm), plagioclase (Pg), Sedimentary lithic (Sed) and Clay Matrix (C). Figures A, B, C and E are in cross polarized light and while D and F are in cross polarized light.

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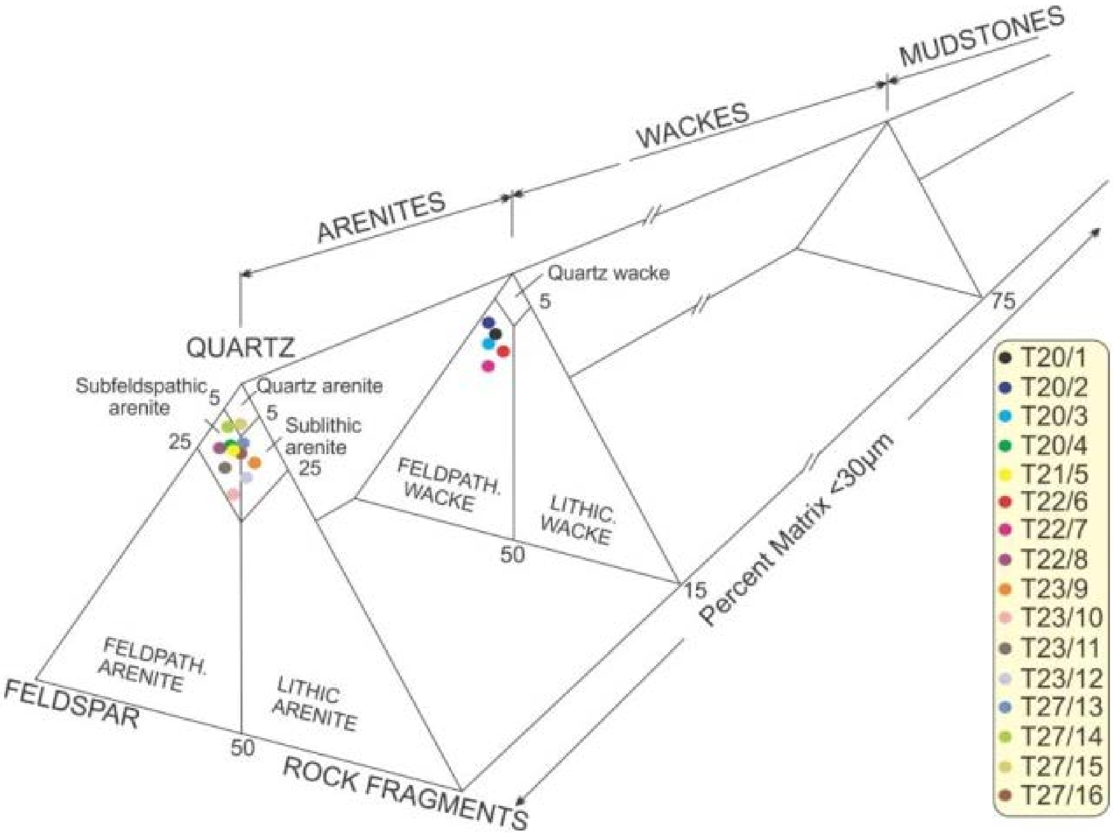

Figure 4 Classification of Tobra Formation samples (after Dott, 1964).

Table 1 Showing model mineralogy of Tobra Sandstone unit

number	Qm	Qp	Af	Mic	Plag	Sed	Chert	Ign	Clay	Calcite	Amp	Bi	Mus	Ore	Tour
Tobra Formation															
T20/1	69	1	7	-	3	-	1	1	17	-	-	-	-	1	-
T20/2	71	1	6	-	2	-	-	1	17	-	-	-	-	2	-
T21/1	71	1	8	-	3	-	1	1	15	-	-	-	-	-	-
T21/2	65	-	7	2	4	-	-	6	13	-	-	-	1	2	-
T21/3	78	-	8	-	1	-	-	4	8	-	-	-	-	1	-
T22/1	60	2	4	2	8	-	-	8	15	-	1	Tr.	Tr.	Tr.	-
T22/2	62	-	8	2	5	1	1	5	14	-	1	Tr.	Tr.	1	-
T22/3	68	3	8	-	8	-	-	3	8	-	-	2	Tr.	Tr.	Tr.
T23/1	65	1	3	1	5	3	-	10	9	-	-	1	-	1	1
T23/2	58	3	5	2	10	2	1	12	7	-	-	-	-	Tr.	Tr.
T23/3	62	1	8	-	12	1	-	4	10	-	-	1	-	Tr.	1
T23/4	60	-	8	2	2	4	-	9	13	-	-	1	-	Tr.	1
T27/1	69	2	3	-	1	-	1	4	10	-	-	2	6	1	1
T27/2	69	-	3	-	1	-	1	2	8	-	1	4	10	1	-
T27/3	79	-	3	1	1	-	1	-	6	-	4	2	2	1	-
T27/4	72	-	4	1	1	-	5	1	7	-	4	-	3	2	-

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The sub-group of sub-lithic arenites (T23/1, T23/4, T27/1, and T27/2) is composed of coarse silt to medium grained sandstone and is mineralogically submature. These samples are dominantly composed of monocrystalline quartz (range = 60-71%), appreciable amounts of feldspars (4-12%) and igneous rock fragments (3-13%). Accessory minerals include ore grains (trace to 1%), mica (biotite/muscovite; 1-14%), amphibole (0-1) and tourmaline (0-1%). Texturally the rock is submature and is composed of sub angular to sub rounded grains with moderate sphericity. The grains are poor to moderately sorted and have planar to pointed contacts. The clay matrix is having an average concentration of 10 % (range = 8-13 %) that occupy the inter-particle spaces. Although these samples are texturally and mineralogically sub mature but the reservoir potential is moderate, as the clay content (10%) is comparatively low.

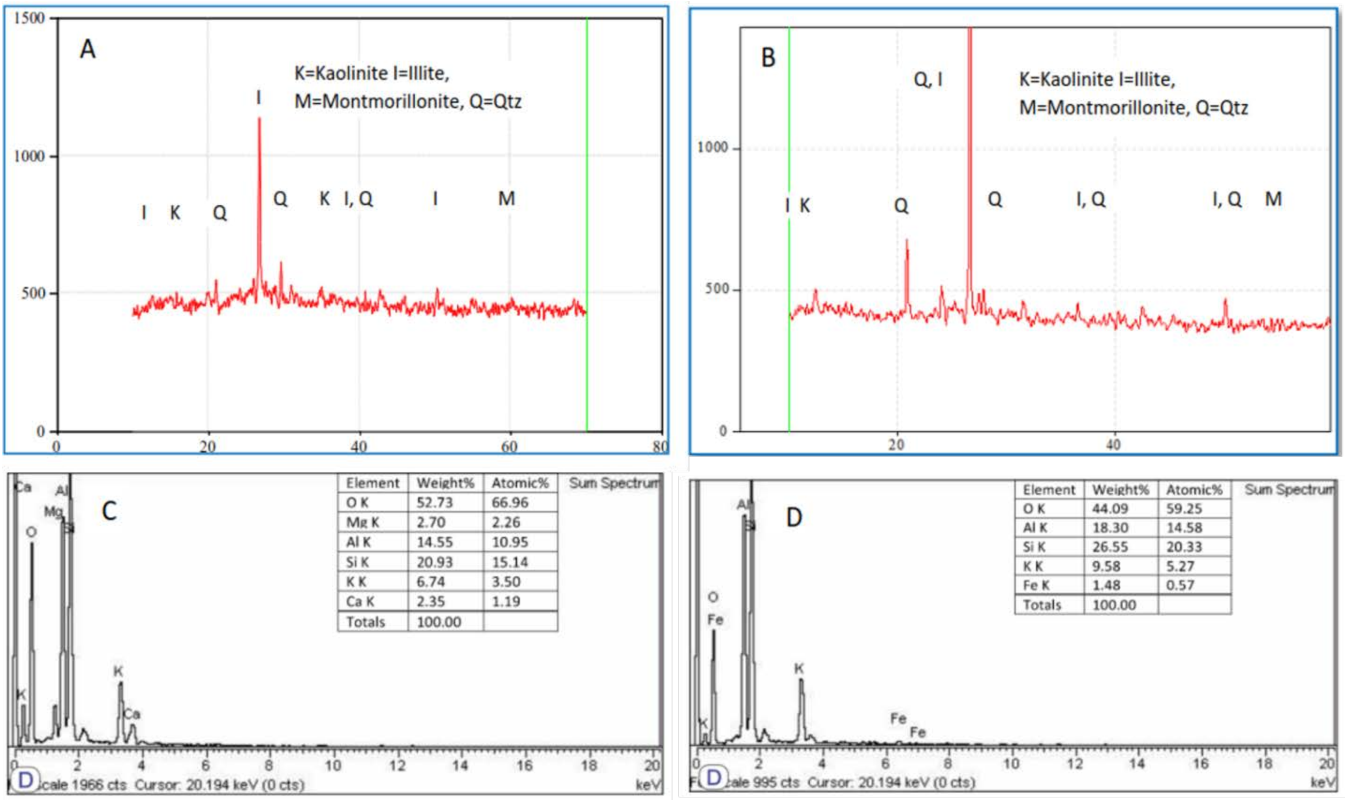

Figure 5 Representative XRD pattern (A, B) and EDX graphs of Tobra Sandstone clay matrix (C, D)

Quartz arenite (K27/3) is very fine to medium grained, texturally sub-mature to mature and is exhibiting

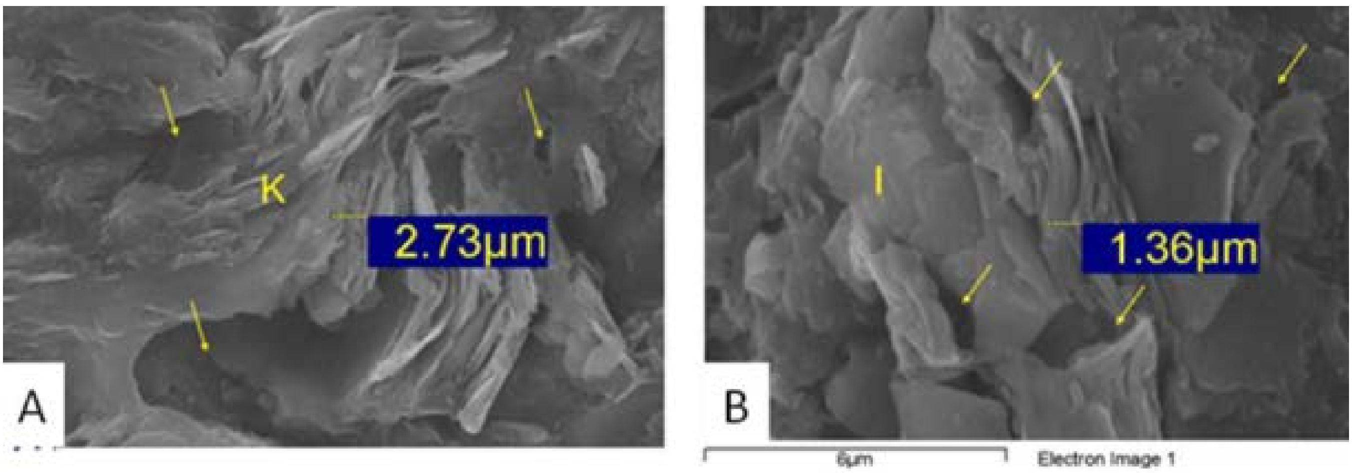

Figure 6 Shows Kaolinite and illite as the dominant inter-particle clays, the arrows points

moderate to well sorting. The grains are sub-angular to well-rounded with majority of the grains exhibiting medium to well roundness and moderate to high sphericity. The grain contacts are dominated by pointed to planer with some being concavo convex. The volume percentage of quartz is 79% and that of feldspar is 5% (Table 1). Quartz occurs as monocrystalline grains while the feldspar occurs as alkali feldspar (microcline) and plagioclase and shows their characteristic cross hatched and polysynthetic twining respectively (Figure 3). The alkali feldspar grains also showing cloudy surfaces for being altered. Lithics occupy very less volume (1%) and is mostly chert (Table 1). Mica occurs as detrital muscovite and biotite and constitutes around 4% on average (Table 2). Amphibole (4%) and discrete ore minerals (magnetite, hematite; 1%) also occur. Reddish ferruginous clays are forming the matrix and form about 6% of the studied sample. The clays are more probably of detrital nature (Figure 3).

Clay Mineralogy

All the sandstone samples contain variable concentration of ferruginous clays in the form of matrix. The XRD and SEM-EDX is used for the determination of different clay phases and their relative abundance. Analytical data reveal that illite is the most dominant clay phase while kaolinite and montmorillonite constitute the minor components in all of the analyzed samples (Figure. 5A-D). Illite occurs in the form of irregular flakes or sheets with some secondary pores as observed through SEM images and is variably present in all of the studied samples (Figure 6A-B; Table 1). EDX- analysis is showing relatively high amount of Fe content that further confirm that the dark-brown color of the clay matrix is due to occurrence of the Fe-content (Figure 5C-D). Change (several tens of meters) in the depth has no effect on the clay mineralogy (Table 1 and 2). The shale fragments associated with the sandy units are also consisted predominantly of Illite with sub-ordinate amount of kaolinite and montmorillonite (study in progress). The montmorillonite shows variable concentration which may reach equal in amount to that of illite (work in progress) in some intervals.

Reservoir Quality

Reservoir quality in clastic rocks is mainly controlled by grain size, sorting, matrix and diagenetic changes by affecting mainly the pore-grain and pore interconnectivity (Pettijohn et al., 1987; Rossi et al., 2002). Similarly, the interrelationship of porosity and

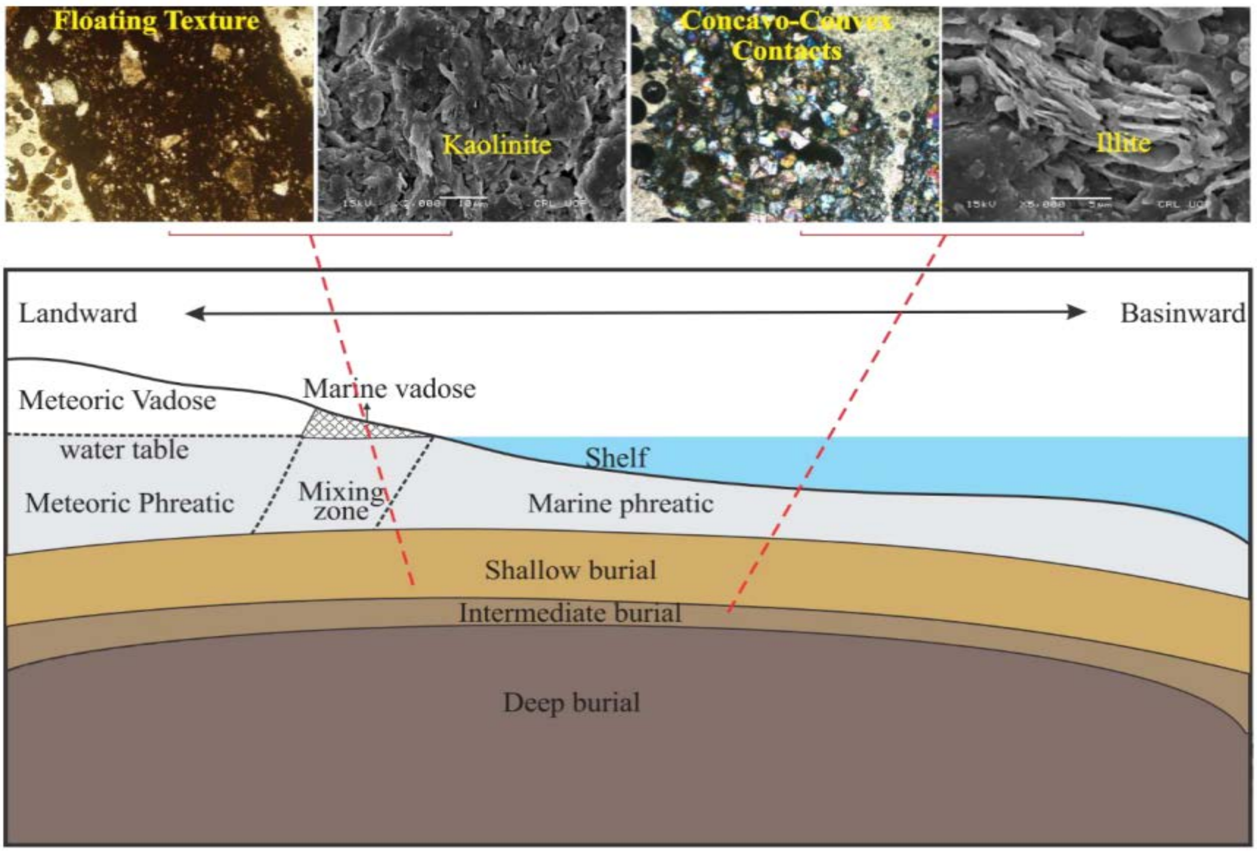

Figure 7 Diagenetic environment model for the Tobra Sandstone

Table 2 Showing recalculated values of framework grains for classification and provenance

Sample	Depth	Framework Composition			Rock Type (Dott, 1964)
		Quartz	Feldspar	Lithics	
T20/1	2928.5m	85.36	12.19	2.4	Feldspathic wacke
T20/2	2829m	88.88	9.88	1.23	Feldspathic wacke
T21/1	2721m	84.21	12.94	2.3	Feldspathic wacke
T21/2	2725m	77.38	15.47	7.14	Subfelspathic Arenite
T21/3	2746m	85.71	9.89	4.39	Subfelspathic Arenite
T22/1	2648m	73.81	14.29	9.52	Feldspathic Wacke
T22/2	2657m	73.80	17.85	8.3	Feldspathic Wacke
T22/3	2662m	78.88	17.77	3.3	Subfeldspathic Arenite
T23/1	3251.5m	75.28	10.11	14.60	Sublithic arenite
T23/2	3261m	65.59	18.27	16.12	Subfeldspathic Arenite
T23/3	3269m	71.59	22.72	5.68	Subfeldspathic Arenite
T23/4	3275m	70.58	14.11	15.29	Sublithic Arenite
T27/1	2910m	88.75	05	6.25	Sublithic arenite
T27/2	2914m	93.42	5.2	1.3	Sublithic arenite
T27/3	2920m	94.05	4.7	1.1	Quartz arenite
T27/4	2928m	85.71	7.14	7.14	Subfeldspathic sublithic arenite

the pores control hydrocarbon accumulation and expulsion in a sedimentary setting (Ramm, 2000). Among the studied sandstone samples, feldspathic wackes the dominant facie, consists of high contents of clay matrix (illite-kaolinite, 14-17%; 15.6%) which has clogged major volume of the inter particle pore spaces as well as have reduced the pore size (Figure 3A-B). The sub-angular to sub-rounded, sub-spherical, poor sorting and high clay matrix decline the reservoir quality (in terms of both porosity and permeability) in these samples (Figure 3A-D). Samples of sub-lithic arenites and sub-feldspathic arenites have an average concentration of 10% and 9.2 % clays respectively and are textually sub-mature which also renders them a low to moderate reservoir flow potential. Quartz arenite samples exhibit relatively high interconnectivity of the pores, owing to low clay matrix, moderate-well sorting, spherical and sub-rounded to well-rounded grain constituents has rendered these samples as relatively better reservoirs.

Diagenetic Environment

Textural characteristics within the sandstone samples of Tobra unit such as the predominance of planer and concavo-convex grain contacts, the development of illite as a major ferruginous-clay and lack of occurence of growth structures around the grains implies that the sandstone has undergone intermediate compaction level (Mackenzie and Guildford, 1984; Dutta, 2007; Figure 7). Majority of the grains are texturally immature through sub-mature to mature while mineralogically, these sandstones are poor to mature with an overall sub-mature nature which suggest that the clastics were derived under the conditions of both physical and chemical weathering. It is also assumed that transportation and deposition took place in a hot and semi-humid climate (Figure 7).

Grain Size Analysis

A total of 16 samples were used for grain size analysis and the histograms and phi diagrams for each sample is displayed (Figures 8, 9). Majority of the samples are showing mixtures of variable grain sizes which ranges from 1.22 to ≤5.2 Φ (medium-sand through silt to clay size) and hence can be classified as bi-modal to poly modal in nature. This moderately to poorly sorted nature is also discernable through petrographic analysis. Only one of the samples of Tobra sandstone unit i.e. T18/3 at 3.24 Φ unit, shows unimodality and is well sorted. The values of median

in the studied sandstone samples are dominantly exhibiting a range of 1.74-3.24 Φ.

Provenance

Provenance of Tobra Sandstone is based on modal proportions of the three framework grains (quartz-feldspar-lithics) as determined through petrography and are plotted on QFL diagram of

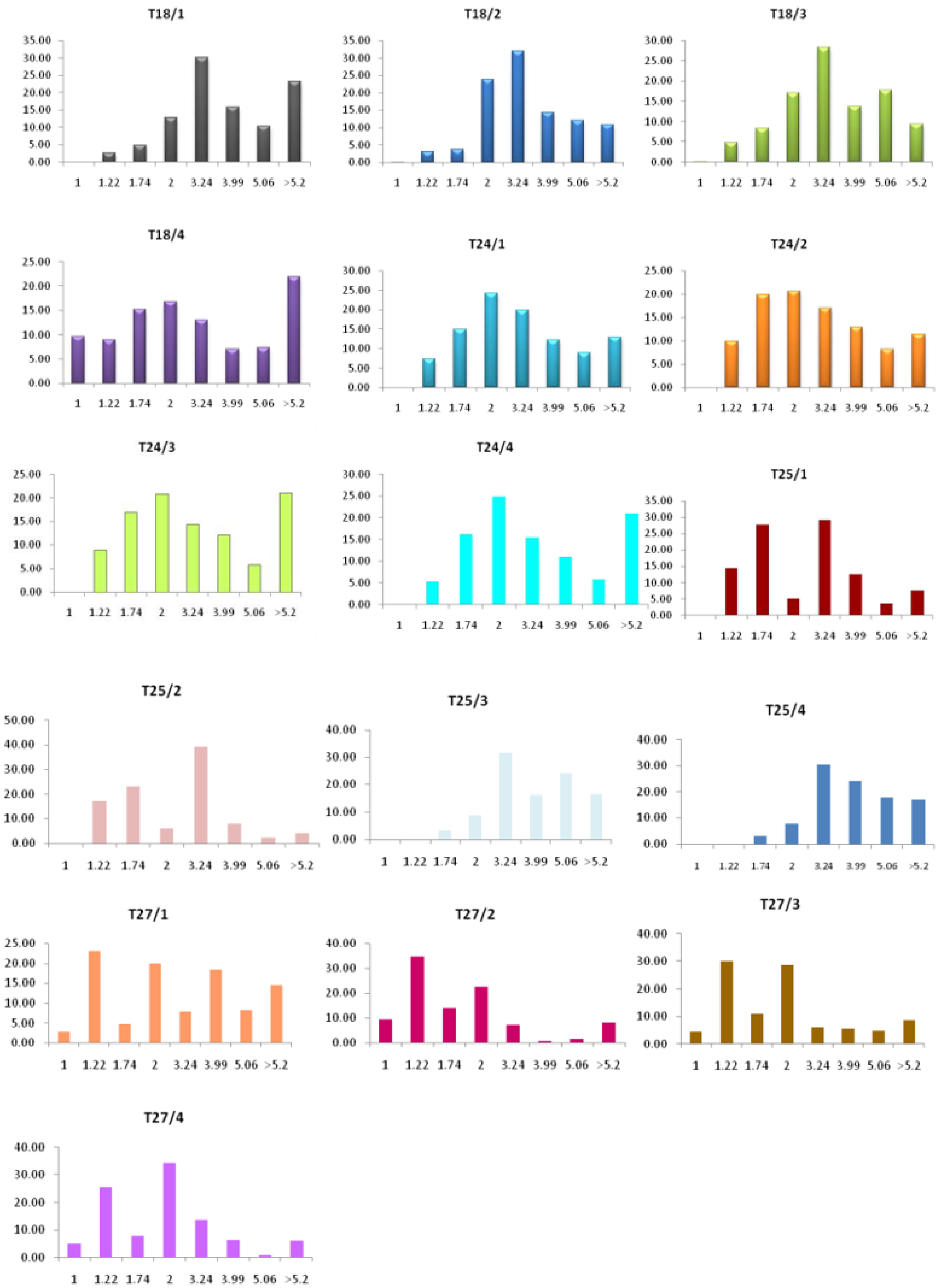

Figure 8 Histograms exhibiting grain size in phi (Φ) along Horizontal-Axis versus weight percent % retained along Vertical-Axis.

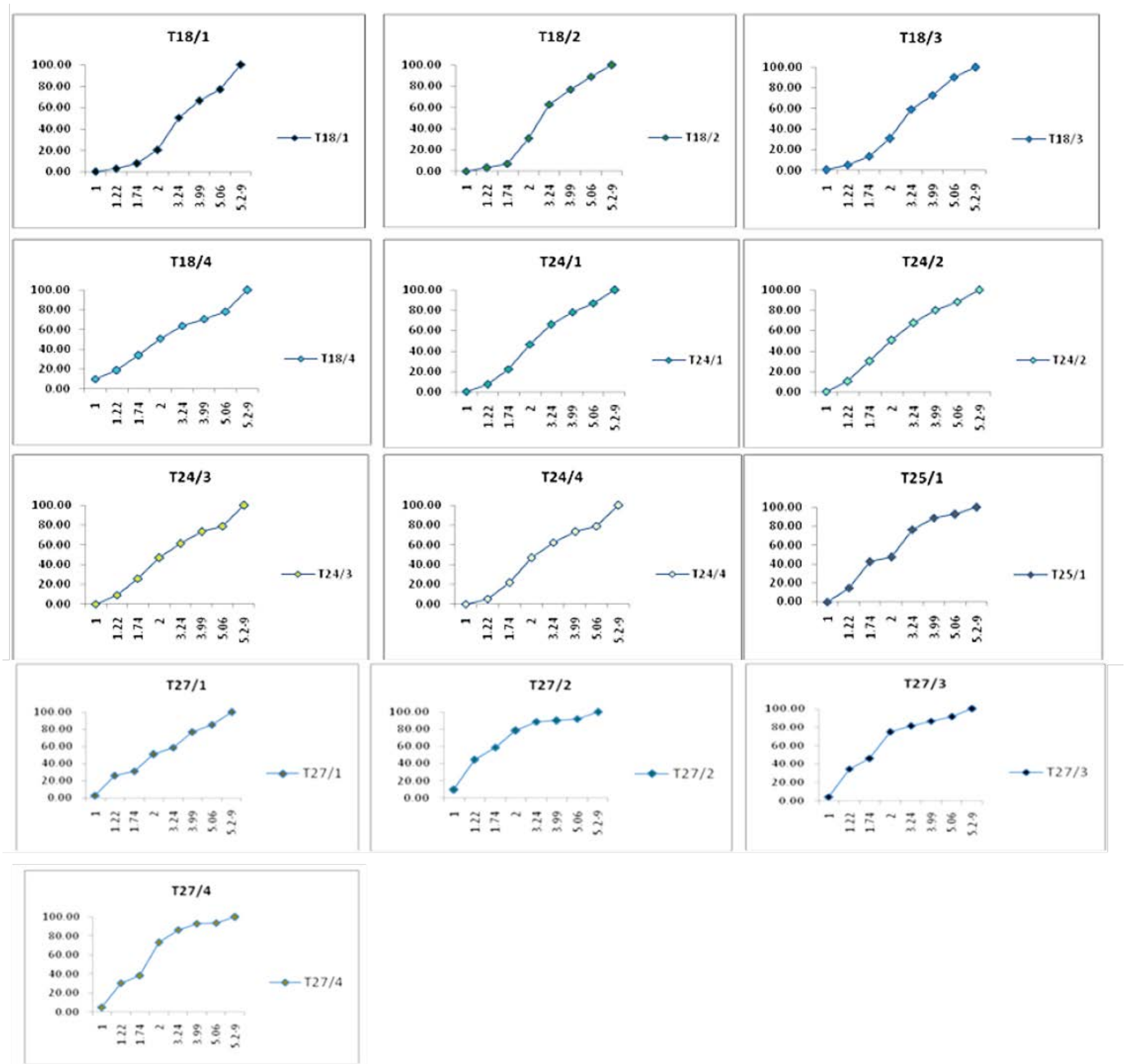

Figure 9 Plots of Tobra Sandstone showing grain size in phi (Φ) versus cummulative weight percent % retained

Dickinson et al.,1983 (Figure 10B). According to the ternary plot (QFL triangular diagram), the detrital grains for sandstone were derived from the regions of cratonic interior (intracontinental basin) as well as recycled orogen (Dickenson, 1985; Figure 10A**)** The abundance of monocrystalline quartz and very high ratio of Qm/Qp shows that source rocks have been mainly granitic in nature (Dutta, 2007; Pettijohn et al., 1987; Pettijohn and Potter, 1987). The abundance of monocrystalline quartz and occurrence of feldspar further confirm that the sandstone was formed as a result of several cycles of weathering and deposition in a semi-humid enviroment (Franzinelli and Porter, 1983). Petrographic study shows a ratio of total feldspar to total lithics around 1.65, which is indicative of a plutonic provenance (Pettijohn, 1975). The polycrystalline quartz with wavy undulation and sutured margins propose their derivation from a metamorphic zone (Adam, 1991). The occurrence of illite and kaolinite, that the sandstone was formed as a result of several cycles of weathering and deposition in a semi-humid environment (Franzinelli and Porter, 1983). Petrographic study shows a ratio of total fieldspar to total lithics around 1.65, which is also indicative of a plutonic provenance (Pettijohn 1975).

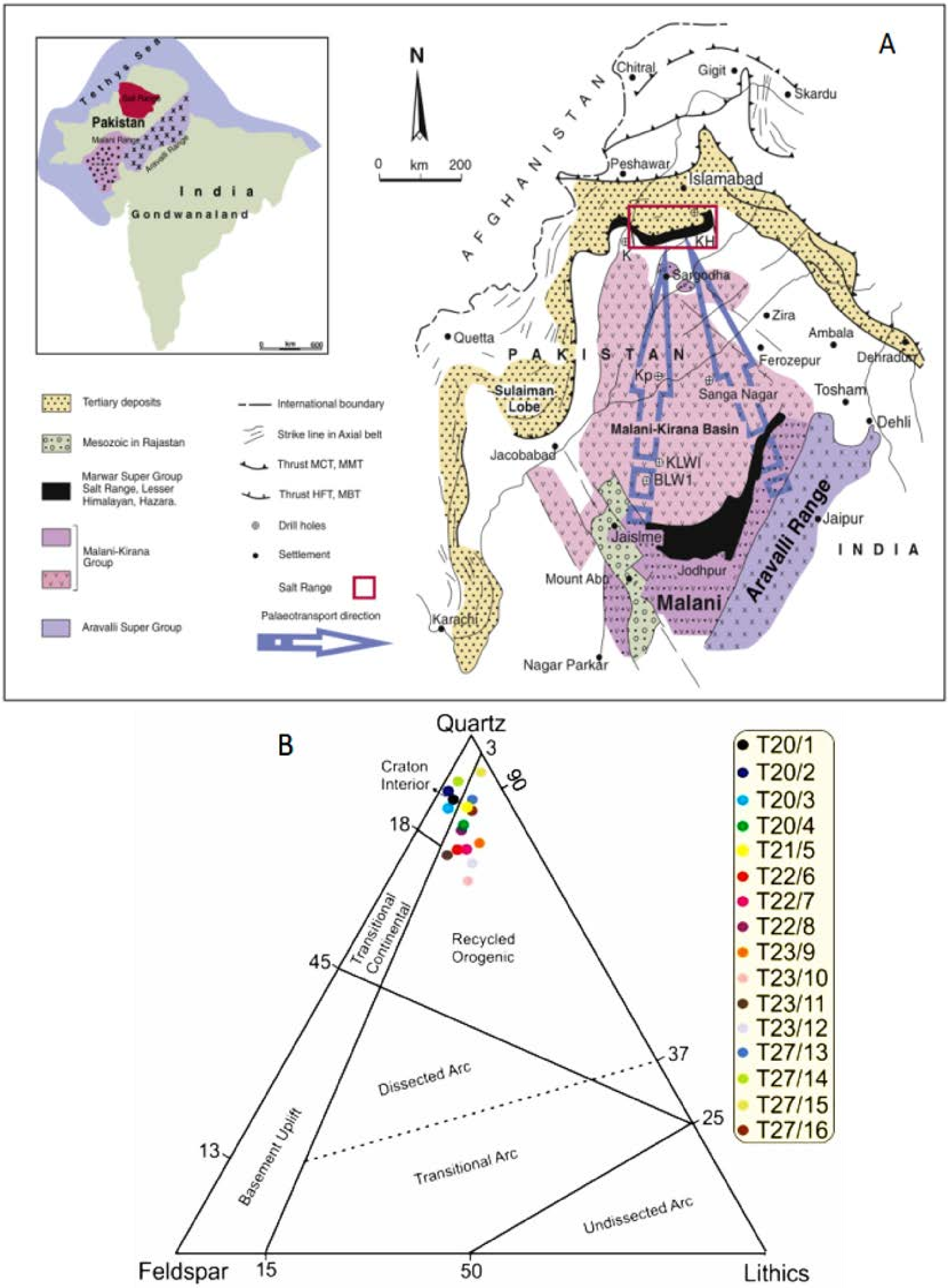

Figure 10-(A) Q-F- plot for detrital modes of Tobra samples showing tectonic provenances after Dickinson et al. (1983); (B). Geological map of Pakistan and northwest India depicting the location of the Potwar-Salt Range together with the likely source areas for the Tobra, the Aravalli and Malani Ranges (after Virdi, 1998).1

The polycrystalline quartz with wavy undulation and sutured margins propose their derivation from a metamorphic zone (Adam, 1991). Tobra sandstone (Millot, 1970; Weaver and Pollard, 1973). The data obtained during our research is compatible with the previous studies (Pascoe, 1959) which show that the Gondwana sediments have been weathered mainly from Precambrian granite and Gneiss.

The occurrence of illite and kaolinite, as the common clay minerals, also suggest that felsic igneous rocks have been the source rocks for the sandstone. A minor amount of metasedimentary rocks have also contributed the sediments for forming the Tobra Sandstone. The most probable locations of source area as revealed by paleogeographic histroy are located to the south of present day Potwar-Salt Range like Aravalli system and Melani range (Figure 10A).

CONCLUSION

Based on framework grains (Average = $Q_{80.81}$ $F_{12.35}$ $L_{6.6}$), the Tobra Sandstone well cuttings are subdivided into sub-feldspathic arenites, sublithic arenites, and feldspathic wackes as the most abundant varieties. The quartz arenite and subfeldspathic-sublithic arenite are encountered in few horizons. The matrix, in the studied samples, is dominantly consisted of ferruginous clays and have range of 6 to 17% with an average value of 6.6%. Illite is occurring as the principal clay type while kaolinite and montmorillonite are forming the minor clay minerals. Individual shale fragments are also observed as laminations with the sandstone horizons. These shale cuttings are also predominantly illite minerals. Grain size analysis of Tobra Sandstone samples reveal an overall sub-angular to sub-rounded and poor to moderate sorting nature as shown by the polymodal nature of majority of the samples (~1.22 - ≤5.2 Φ) with few being moderate to well sorted. Mineralogical and textural characteristics exhibit that the Tobra Sandstone samples have poor to moderate reservoir quality with few showing a better reservoir quality. Several features such as the abundance of illite, the presence of planer-pointed and concavo-convex grain boundaries and the lack of growth structures suggest an intermediate burial history for the studied sandstone unit of the Tobra Formation. Modal Mineralogical studied indicate that the detritus for the studied sandstones was derived from the craton interior as well as recycled orogen located to the south and southeast of the present-day Potwar Basin as well as Salt Ranges.

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