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Full length article

PETROLOGY AND GEOCHEMISTRY OF THE LATE CRETACEOUS PAB FORMATION, WESTERN SULAIMAN FOLD- THRUST- BELT, PAKISTAN: IMPLICATIONS FOR PROVENANCE AND PALEO-WEATHERING

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ABSTRACT

Late Cretaceous sandstone succession of the Pab Formation in western Sulaiman Fold Thrust belt Pakistan was investigated for petrology and bulk rock chemistry to determine its source terrain, paleo-weathering and tectonic setting. The formation is mainly comprised of sandstone with reddish to maroon color shale and arenaceous limestone. Texturally, the sandstone is fine to coarse grained, sub-angular to well-rounded and moderately to well sorted. The sandstone is petrologically and geochemically classified as quartz arenite to sub lithic arenite. The detritus was mainly derived from plutonic acidic source. QtFL and QmFLt suggests that recycled orogeny and Craton Interior setting were major sources of sediments. Geochemical models support that the detritus was derived from quartzose sedimentary source terrain, suggest deposition in a passive continental margin setting. Average values of chemical indices are CIA 59% CIW 67% and CIV 12.70%, which suggest moderate to high degree of chemical weathering in source area, that may reflect humid climate condition in the source area. The petrographic study and geochemical models demonstrate that the Pab Formation is mostly composed of mature sandstone from acidic plutonic and low-grade metamorphic rocks terrain in recycled and Craton Interior setting deposited on western passive margin of Indian plate in Tethys Ocean.

KEYWORDS: Pab Sandstone; Quartz Arenite; Passive Margin; Tethys Ocean; Craton Interior

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1. INTRODUCTION

Provenance studies of siliciclastic sedimentary rocks often aim to determine the composition and geological evolution of the sediments' source region. The composition of siliciclastic rocks is a function of a complex interplay of several variables, including the composition of source rock, transportation history, paleoclimatic conditions and diagenetic alteration (1,2,3,4) Various tectonic environments may supply various types of source materials with different chemical signatures (5 6 7). The clastic rocks in the passive continental margin tend to have more stable features (rich in Si, low in Mg and Fe, etc.), whereas the sediments in the back-arc basin are always rich in mafic rather than felsic detritus (4). The Pab Formation is the Late Cretaceous unit exposed in different parts of the Kirthar and Sulaiman Fold-Thrust Belts. Pab Formation has thoroughly been studied in Kirthar Fold-Thrust Belt for facies variation, provenance and reservoir potential for hydrocarbons (8, 9, 10, 11). The Pab Formation is also documented to represent thick succession in different parts of the Sulaiman Fold -Thrust Belt such as Qilla Saifullah, Loralai, Zhob and Mughal Kot (12) but poorly studied in terms of its petrography, composition, provenance and facies. The present work mainly focuses on provenance, tectonic setting and paleo-climatic conditions by carrying out modal analyses and bulk rocks geochemistry of three well exposed sections of the Formation in the western Sulaiman

Fold-Thrust-Belt showing Late Trassic to Pleistocene rocks, while the regional basal detachment is located below Jurassic sediments (26). The enormous sedimentary thickness that was considered to be accommodated by passive roof duplex model geometry, partly explains the deformational front of the Sulaiman (27). It is assumed that the Sulaiman Basement Fault is north-south trending step fault with a throw towards the west and it developed the Zhob Valley Thrust in the Oligocene and continued during the Miocene and Pliocene.

2. GEOLOGICAL SETTING

The area under investigation lies within western Sulaiman Fold-Thrust- Belt (SFTB) (Fig. 1) (13, 14). It comprises of Triassic to Eocene and recent sedimentary succession. The SFTB is a south-southwest extension of the Himalayas developed as a result of the Indo-Pakistan plate colliding with the southern margin of the Eurasian plate during the Paleocene-Eocene epoch (15, 16, 17, 18, 19). The SFTB is bounded by Zhob-Muslim Bagh Ophiolite and Pishin Belt in the west and by Indus Plain and Sulaiman fore-deeps in the east (20, 21, 22). The SFTB represents a thick sedimentary succession ranging in age from Triassic to Recent (23). The Mesozoic and lower Paleogene (Paleocene-Eocene) strata are of marine origin whereas the post-Eocene strata are fluvial (Siwaliks/Urak Group) (23, 24). It is believed that basement faults have controlled the shape of the SFTB. Regionally, the Sulaiman Block was bent towards the north along the Sulaiman Basement Fault in the west and the overlying sediments were detached. They were moved southwards as nappes in large lobes now forming the Mari Bugti Hills and the Sulaiman Ranges (14). The SFTB has assumed its present shape due to an interplay of strike-slip and thrust faults because of oblique convergence of Indian plate (25). The existing basement structures may have developed due to the collision and formed the structures along the Zhob Thrust, which bounds the belt in the west. The resultant deformation style is indicative of thin skin tectonics. The tight folds and imbricate thrusting in the northern part may be due to an upper-level detachment in Cretaceous shale

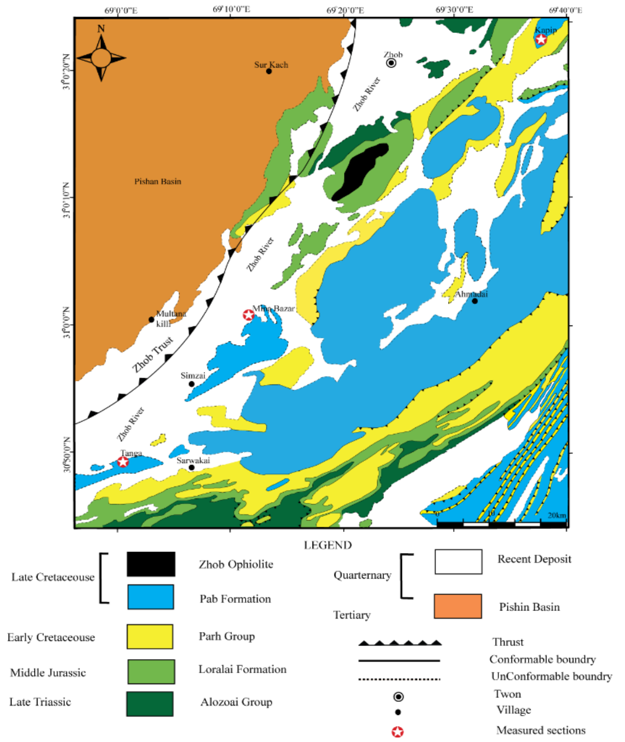

Figure 1: Geological map of the study area western Sulaiman Fold Thrust belt Pakistan (modifed after Jones, 1961).

3. STRATIGRAPHY

The western part of the SFTB contains over thousands of meters thick sedimentary and volcanic/volcano-clastic succession of rocks that are Triassic to Recent (28, 23) (Table 1). The Late Cretaceous Pab Sandstone is named after Pab Ranges in Kirthar ranges in southeast Balochistan, near Khuzdar and the section along Drabber Dhora (N 25o 31' 12", E 67o 00' 19") is designated as its type section (29, 30, 31,). The formation is exposed in different parts of the K-SFTB with a thickness range from a few meters to hundreds of meters. In the type section 478 m thickness has been recorded and further southward from the type section in the Jakkher Pass the formation is 498 m thick, whereas in the Sulaiman Belt its maximum thickness is 1524 m (31, 32). The Pab Sandstone is dominantly composed of thick-bedded to massive sandstone with subordinate mudstones, shales, conglomerates and marls in some areas (32, 33, 9,10) Medium to coarse grained sandstone is well sorted, and thick bedded quartz arenite to sublitharenite (9, 33, 11). Weathered color of sandstone is light brown and fresh surfaces are yellow-brown to varnish (32). The sandstone displays a variety of facies such as trough cross-bedding, large scale planar cross bedding, parallel bedding, massive, bio-turbated and hummocky cross stratification. This suggests a wide variation in depositional settings from fluvial-deltaic, shallow marine to deep marine (32, 34 9,10). Lower contact of the Pab Formation is conformable with either Fort Munro or Mughal Kot formations, but in some localities where Fort Munro and Mughal Kot formations are not deposited the Pab Formation formed a disconformable basal contact with the Parh Group (12). The Pab Sandstone is conformably overlain by Moro Formation but in some localities Pab Formation has an unconformable upper contact with Paleocene Khadro Formation or Dungan Formation in Mughal Kot Gorge (35).

Table 1. Stratigraphic succession of the western Sulaiman Fold-Thrust-Belt.

Age	Formation	Lithology
Pleistocene	Lei Conglomerate	Conglomerate, Sandstone.
Miocene-Pleistocene	Urak Group	Sandstone, clays-tone, and conglomerate.
Angular Unconformity		
Middle-Late Eocene	Spintangi Limestone	Limestone, shale, and sandstone.
Early Eocene	Ghazij Formation	Clay stone, sand-stone, conglomerate, limestone and coal seam.
Paleocene	Dungan Formation	Limestone and shale.
Late Cretaceous	Pab Formation / Mughal Kot Formation	Sandstone, siltstone, shale, arenaceous limestone
Early-Middle Cretaceous	Parh Limestone / Goru Formation / Sembar Formation	Limestone (bio-micritic), marl and, shale.
Disconformity		
Jurassic	Loralai Formation	Limestone and minor shale.
Triassic	Wulgai Formation	Shale and limestone.
Base not exposed		

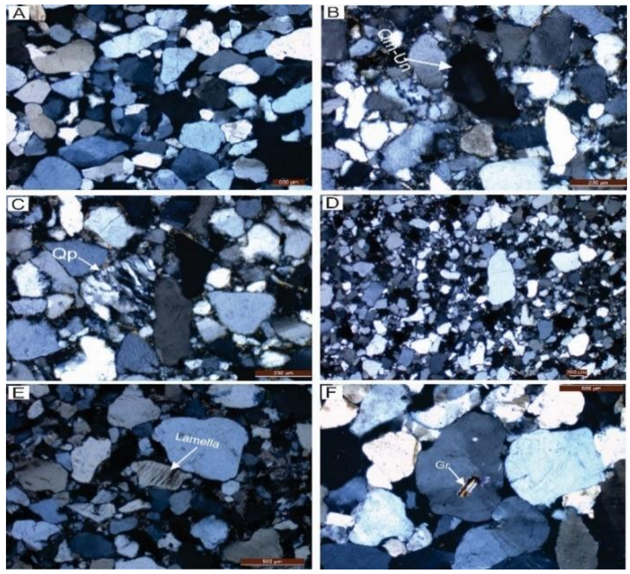

Figure 2. Photomicrographs of the sandstone of the Pab Formation shows: (A) the minerals constituents and texture, Medium to coarse grained, sub rounded, moderately sorted, tightly packed sandstone, X-Nicols, scale bar is 500 µ;. (B) Mono-crystalline quartz with straight and undulose extinction, X-Nicols, scale bar is 200 µ; (C) Polycrystalline quartz more than five sub crystals with straight and sutured boundaries, X-Nicols, scale bar is 200 µ;.(D) Quartz grains with different types of contact from concave to convex contact, point to suture, X-Nicols, scale bar is 200 µ; (E) Boehm lamellae on quartz grain X-Nicols, scale bar is 500 µ; (F) Inclusions of heavy mineral garnet X-Nicols, scale bar is 500 µ

4. MATERIALS AND METHODS

30 sandstone samples from three stratigraphic sections were used for petrographic study while for point counting study 24 medium to coarse grained samples were selected (Table 2). Point counting was carried out with digital Pelecon Point Counter equipped with software, in the laboratory of the headquarters of the Geological Survey of Pakistan Quetta. In every thin section five hundred points were counted using the Gazzi-Dickinson method (35, 36). Quartz mono-crystalline (Qm), Quartz polycrystalline (Qp), Plagioclase (P), K- feldspar (K), Muscovite (M), Biotite (B), heavy minerals (H), Chert (Ch), Volcanic lithic (V), Metamorphic lithic (M), Sedimentary lithic (S) and Matrix (Ma) were counted. For geochemistry 15 sandstone samples were crushed and pulverized for major and trace element analysis. For major oxides analyses SP8/400 UV-VIS Spectrometer and 700 Perking Elmer graphite furnace Atomic Absorption Spectrometer (PE/AAS) were used for whole-rock geochemistry and for trace elements analysis X-Ray Fluorescence (XRF) was used in the laboratory of NCEG in Geology, university of Peshawar.

5. RESULTS

5.1 Petrology

Sandstone of the Pab Formation ranges from coarse to very fine grained, grain supported, moderate to tightly packed, moderately to well sorted and sub angular to sub rounded (Fig. 2a). Grains are mostly cemented by calcite, subordinately by chlorite, quartz and iron oxide. The roundness, sorting and low clay content in study samples suggest that the sandstone is texturally mature.

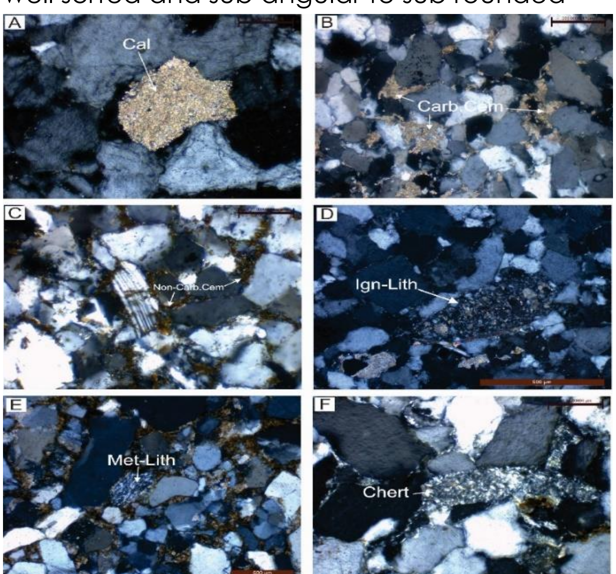

Figure 3. Photomicrographs of the sandstone of Pab Formation shows: (A) the K-Feldspar grain displaying Carlsbad type of twinning X-Nicols, scale bar is 500 µ: (B) is the Plagioclase grain with albite twining X-Nicols, scale bar is 500 µ: (C) Muscovite flakes with speckled texture X-Nicols, scale bar is 500 µ: (D) Biotite grain with red brown to yellow brown color twisted between quartz grains X-Nicols, scale bar is 100 µ: (E) heavy mineral zircon grain with high relief and perfect cleavage X-Nicols, scale bar is 200 µ: (D)heavy mineral tourmaline grains X-Nicols, scale bar is 500 µ:

5.1.1 Mineral constituents

Quartz is the most abundant framework grain in the sandstone of the Pab Formation both as mono-crystalline and polycrystalline quartz (Table 2). Mono-crystalline quartz is more abundant than polycrystalline quartz, mono-crystalline quartz has straight as well as undulatory extinction (Fig. 2b). Polycrystalline quartz is composed of several sub crystals (Fig. 2c) having straight or sutured boundaries, quartz grains are sub angular to sub rounded, quartz grains display concave to convex contact, point to sutured, and tangential contact (Fig. 2d). Boehm lamellae are also present in some quartz and indicate intense deformation of quartz grains in source rocks (Fig. 2e), mono-crystalline quartz grains also contain the inclusion of garnet, tourmaline, opaque minerals, rutile, muscovite and chlorite (Fig. 2f). Feldspars, both plagioclase and K-feldspar, were identified by their cleavage, twinning, and cloudy appearances and susceptibility to diagenetic alterations. K-Feldspar comprises microcline, orthoclase and perthite. They occasionally display Carlsbad type of twinning (Fig. 3a) Plagioclases were identified by pericline and albite type of twining (Fig. 3b.) Feldspar is altered slightly (clouded) or completely and replaced by secondary calcite or clay minerals. Micas include biotite, muscovite and chlorite. Muscovite displays high order interference color (Fig. 3c), biotite appears yellowish-brown to dark brown and green in crossed nicols (Fig. 3d). Biotite is pleochroic in plane-polarized light, also contains pleochroic halos. Mica grains are often twisted, broken and squeezed between competent grains. Accessory minerals include tourmaline, zircon (Figs. 3e and 3f) rutile and glauconite; opaque minerals include hematite and magnetite. Cements include both carbonate and non-carbonate cement, carbonate cement includes sparry calcite (Fig. 4a, b) while non-carbonate cements include chlorite, iron oxide and quartz (Fig. 4c), silica cement was observed in the form of quartz overgrowth. Calcite cement is frequently present at the boundary of framework grains and partially replaces the grains. Varieties of lithic fragments were observed in studied samples that include igneous (Fig. 4d), metamorphic (Fig. 4e), and sedimentary (Fig. 4f). Lithic fragments collectively make up the second most common components in studied sandstones. Igneous lithic fragments include both volcanic and plutonic fragments characterized by granular, porphyritic and lathwork texture. Metamorphic lithic fragments include schist, gneiss and slate.

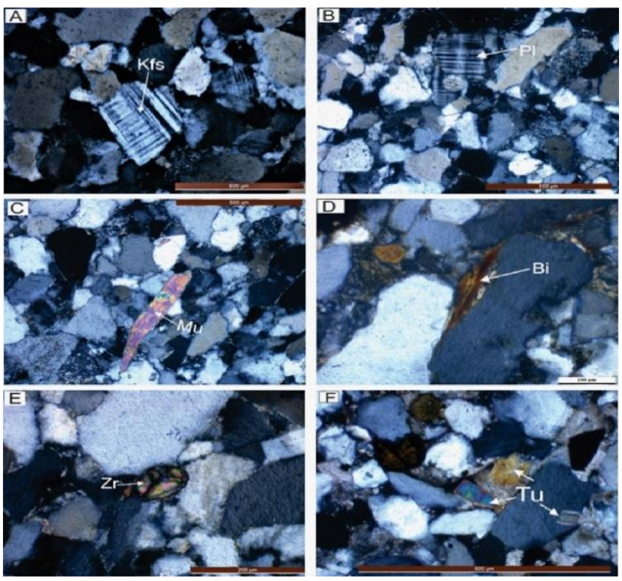

Figure 4. Photomicrographs of Pab Formation showing the various type of cements and lithic fragments. (A) Sparry calcite grain X-Nicols, scale bar is 100 µ. B is Carbonate cements present at edges of quartz grains and also replacing some grain completely X-Nicols, scale bar is 200 µ). C is Non carbonate cements with edges of quartz grains and surrounding a plagioclase grain X-Nicols, scale bar is 100 µ: (D D) Basic is an igneous lithic fragment X-Nicols, scale bar is 500 µ: (E) Low grade metamorphic lithic fragment X-Nicols, scale bar is 500 µ: (F) Sedimentary lithic fragment of chert grain X-Nicols, scale bar is 100 µ

5.1.2 Modal Composition and Provenance

The sandstone composition is fundamentally affected by the source rock composition so modal investigation of detrital framework grain is useful for provenance determination (36, 37, 38). The relationship between depositional basins and provenance is controlled by plate tectonic. Ternary diagrams have been used to show compositional fields containing different provenances (37 and 38).

Six ternary models were plotted using fourteen recalculated variables (Qt F L, Q F L, Qm F Lt, Qm P K, Qp Lvm Lsm, Lm Lv Ls; Table 3) (after 39, 37, 40, 41, 42). The Qt-F-L diagram (37) is traditionally used for the first-order sandstone classification. It contains three types of tectonic settings i.e. Recycled orogeny, Continental Block and Magmatic Arc. In Qt-F-L almost all the sandstone samples plotted in the field of Recycled Orogen, which suggests that the detritus of the Pab Formation has been recycled enroute from the source belt (Fig. 5b).

The average mode is Qt93 F2 L5, feldspar and lithic fragments are very low as compared to total quartz. Qm-F-Lt ternary diagram (38) is used for further subdivision of recycled orogen of (37) into transitional recycled, quartzose recycled, and lithic recycled fields. Most of the samples in the Qm-F-Lt diagram plotted in continental block setting very close to Qm apex while few in quartzose recycled (Fig. 5c). The average values of Qm-F-Lt for Pab Formation are Qm90 F2 Lt8, due to the high percentage of mono-crystalline quartz all samples plot near Qm pole of the compositional diagram. 42 devised the Qm-P-K compositional plot to show partial framework mode of minerals grains only. The Qm-P-K ternary plot of sandstone of the Pab Formation shows a high percentage of the mono-crystalline quartz (Qm) as compared to feldspars. Mean values of $Qm_{98}P_2K_0$ indicate that the proportion of mono quartz is far higher than both K- feldspar and plagioclase, that is why all the sample plot on Qm pole of Qm-P-K ternary diagram (Fig. 5c). 40 and 43 suggested Lm-Lv-Ls ternary diagram, which highlights the class of lithic content in sandstone.

The Lm-Lv-Ls compositional plot shows that the sandstone of the Pab Formation is abundant in igneous and sedimentary lithics, however, poor in metamorphic lithic fragments. The mean values of Lm-Lv-Ls are Lm19Lv36Ls44 (Fig. 6a). Samples are highly scattered and samples plot in Mixed Magmatic Arc and Subduction Complex and Suture Belt. The mean values of the compositional diagram also plot in the field of the Mixed Magmatic Arc and Subduction Complex, which suggest a substantial input from mafic igneous source. The Qp-Lvm-Lsm ternary diagram suggested by 37, 43 and 38 is used to discriminate the detrital modes of Suture Belt, Magmatic Arcs, Rifted Continental Margins and Mixed Subduction Complex. The ternary diagram combines plots of 37 and 38 (illustrated by dashed lines). 40 divided Collision Orogen into Suture Belts, Continental Margin, Mixed Subduction Complex and Magmatic Arcs, (solid lines) (Fig. 6b).

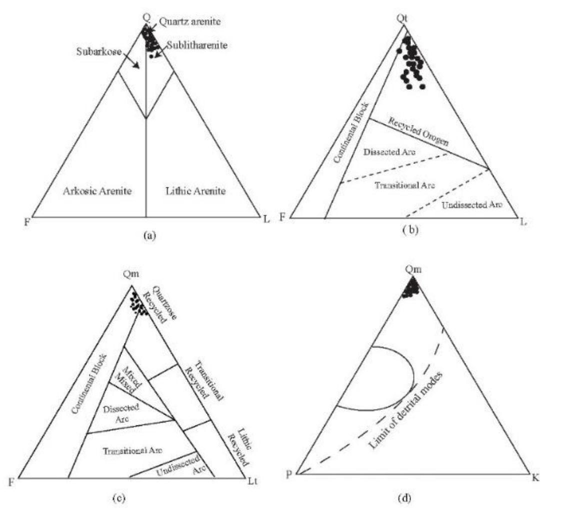

Figure 5. (a) QFL classification plot of Pettijohn (5). for sandstones of the Pab Formation; (b) Qt-F-L tectonic plot of Dickinson and Suczek (37) (c) Qm-F-Lt compositional diagram of sandstone of the Pab Formation; (d) Qm-P-K compositional diagram of the Pab Formation.

Most of the samples plot in Collision Orogen, Subduction and Magmatic Arc Complex. Two samples plot in Suture Belt and two samples also plot in Rifted Continental Margin. The mean values of Qp41Lvm9Lsm50 ternary diagram plot in Collision Orogen

Qt-F-L plots indicate that the sandstone of the Pab Formation is sourced from Recycled Orogen. The Qm-F-Lt ternary plot (Fig. 5 b.) indicates that the detritus is derived mainly from the Continental Blocks and Quartzose Recycled orogen belt. Qm-P-K plot shows that the Pab Formation is highly rich in mono-crystalline quartz and low in feldspars that indicate arenite nature of sandstone. According to 44 for determining the nature of sandstone source terrains lithic fragments are very important; The ternary plots Lm-Lv-Ls and Qp-Lvm-Lsm indicate that meta-sedimentary and igneous sources have mainly contributed to the detritus of the Pab Formation. In Lm-Lv-Ls and Qp-Lvm-Lsm ternary plots samples are scattered across the Subduction Complex and Collision Orogen, however mean values of Lm19Lv36Ls45 and Qp50Lvm41Lsm9 plotted in Collision Orogen. The higher sorting, roundness and low concentration of clay in sandstones indicates that sandstone is compositionally mature, which may suggest long transportation route. The great proportion of mono-crystalline quartz over polycrystalline quartz can be caused by the destruction of primary polycrystalline quartz during high energy and long-term transportation (45). Heavy minerals such as zircon and tourmaline, which ranges between 0.2-3.2 might have been derived from an acidic igneous source (Table 2) (46).

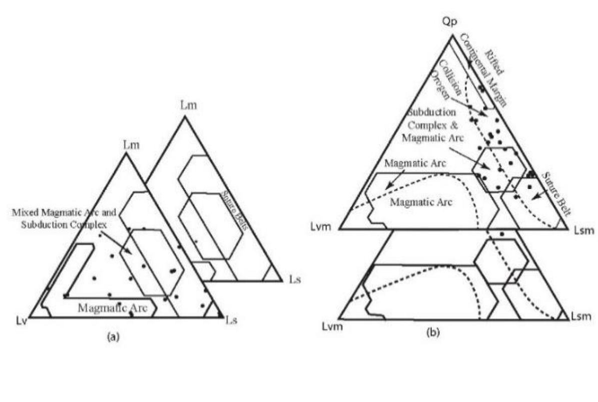

Figure 6. (a) LmLvLs plot of sandstone of the Pab Formation (40, 43), background plot shows average values; (b) QpLvmLsm compositional diagram of Pab Formation, the dotted lines show compositional fields of 37, solid-lines indicate compositional fields of 40.

5.2 Geochemistry

5.2.1 Major elements

Major elements percentages of Pab Formation and mean values of upper continental crust (UCC 46) as references are present in Table 4. Sandstone samples exhibit a large degree of variation in major oxide elements. SiO_2 is the highest major oxide in samples, which ranges from 75.50% to 85.30% and the average is 80.81. SiO_2 values are high in Pab sandstone when compared to UCC value of 66% (46). Al_2O_3 is the second highest major oxides in sandstone, which ranges from 3.0% to 7.55% (average is 5.63), the average value is slightly depleted compared to UCC values (15.2). The Fe_2O_3 value ranges from 0.34% to 6.20% and the average value is 2.33, which is slightly depleted as compared to UCC value (5.03). The MgO ranges from 0.21% to 1.49% and the average value is 0.49, which is slightly depleted as compared to UCC (value is 2.2). MnO values ranges from 0.1 to 0.28%. The bivariate plots of 47, and 48, are normally used to show relationships among various major elements. Harker variation diagrams (48) were used to plot different major elements against SiO_2 and Al_2O_3 (Fig. 7). It has been noticed that SiO_2 has a strong positive correlation with other major oxides except Na_2O and K_2O, which may be due to feldspars. TiO_2 and Fe_2O_3 show positive correlation in some samples. Different major oxides were also plotted against Al_2O_3, which show a positive correlation except SiO_2 and MnO that may be due to enrichment of quartz and calcite cement.

5.2.2 Trace elements

Trace elements concentration (in ppm) ranges, mean values and other geochemical parameters of Pab Formation are given in Table 5. The concentration of Barium (Ba) is highest and range 80 to 940 with an average value of 259.87 (UCC value 550). Zirconium (Zr) is the second most abundant trace element in studied samples ranging from 93 to 534, and mean value is 253, which is greater than UCC value of 190. The higher concentration of Zr may be due to high concentration of heavy minerals such as zircon that was observed in our petrographic study. The studied samples are also enriched in Tungsten (W) and Zinc (Zn), Tungsten ranges between 132 to 1869, and the means value is 423 while the values of Zn range from 17-155 and mean value is 35.33, which is variation diagram of Hossain (49) to correlate different trace elements with Al_2O_3 for the sandstone samples of the Pab Formation, Zn, Pb, and Th make linear correlation with Al2O3, however, the rest of the trace elements such as Zr, W, Sr, Rb and Ba do not correlate well with Al_2O_3 (Fig. 10). The average values of trace elements of Pab Formation (in ppm) are greater as compared to the UCC (46). Studied sandstone samples are high in Zr when compared to UCC values, rest of the trace elements Ba, Rb, Sr, Y, Pb, Zn and Th show a depleted trend as compared to UCC value.

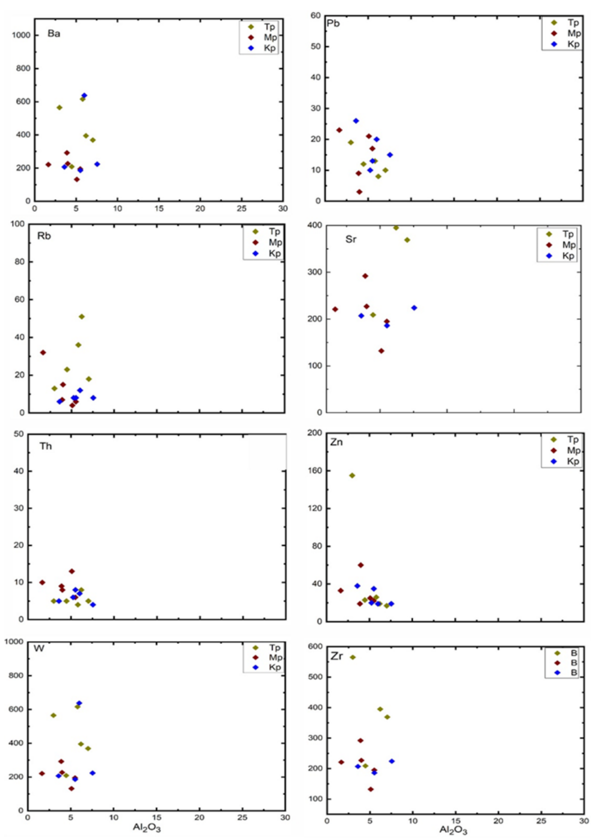

Figure 7. Harker diagrams plotted major oxides Vs Al2O3 Of Harker (48) for the sandstone of the Pab Formation (Tp Tanga section, Mp Mina Bazar

section, Kp Kapip section) in western Sulaiman Fold-Thrust Belt Pakistan depleted as

5.2.3 Classification

The sandstone of the Pab Formation according to classification scheme of Pettijhon (39) is quartz arenite (Fig. 5a) (20 out of 24 samples plot in quartz arenite) due to very high percentage of quartz and low percentage of feldspar and lithic fragments. Three samples plot in subarkose field and one sample in sublithranite. The classification scheme of Crook (50) indicates that majority of the samples plot in quartz-rich field except two, which goes in the field of quartz intermediate

5.2.4 Geochemistry and Provenance

In order to evaluate the tectonic setting and provenance determination of the sandstone of Pab Formation the tectonic discrimination diagrams of Bhatia (51) and Roser and Korsch (52) were used. Bhatia (51) classified the bivariate plots into discrimination fields, which are: Active Continental Margin, Oceanic Arc, Passive Margin and Continental Arc.

The MgO and TiO2 are predominantly utilized for their low mobility and ratios of Al2O3/SiO2 give an estimation about the quartz in sandstones (48). Plotting the samples in the bivariate diagram of Bhatia (50) Fe2O3+MgO vs Tio2, (Fig. 9a) indicates that almost all samples fall in the field of Passive Margin, further plotting of the samples in the bivariate diagram of 48 Fe2O3+Mg vs Al2O3/Si2O3 (Fig. 10.b) shows that all samples plot inside or very close to field of a Passive Margin (Fig. 9b). Roser and Korsch 51 introduced the discrimination function diagram to establish the provenance signature of the sandstone. Using ratios of oxides of TiO2, MgO, CaO, Fe2O3, Na2O, and KO with Al2O3. Four kinds of provenance are indicated by the discrimination function diagram that includes, mafic igneous, intermediate igneous, felsic igneous and quartzose sedimentary field. Plotting the samples of diagram, almost all the samples plot in the field of quartzose sedimentary provenance (Fig. 10) and one sample fall in fields of mafic igneous.

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Table 2: Recalculated percentage of point count data of the Pab Formation of the study area

Samples No	Qm	Qp	P	K	M	B	Hv	Op	Ch	Ls	Lm	Li	Ccm	Nccm	Matrix	Total
TP3	77.4	3	1.4	0.4	0.6	0	1.8	0.4	5.8	0.2	0.2	1.6	7	0.2	0	100
TP4	78.2	5.4	4.8	0.6	0.4	0.2	0.8	0.4	3.8	1.4	0.2	0.6	2.8	0	0.4	100
TP5	83.8	0.6	0.4	0	1.6	0	3	3	2.4	0.2	0.2	0.6	1	3.2	0	100
TP8	89.8	2.6	0.4	0	0	0.8	1.6	0	1.4	0.2	0	0.2	0.4	1.8	0.8	100
TP9	90.6	3	0.4	0	0	0.6	0.2	0.8	0.8	0.4	0	0	1.4	1.4	0.4	100
TP10	88	1.6	2.4	0.2	0.2	0.2	0.8	0.4	2.2	0.6	0.4	0.4	0.8	0.6	1.2	100
TP11	74.2	3.2	0.6	0	0.6	0.4	1	1.2	2.8	0.6	0.2	1	13.2	0.4	0.6	100
TP13	65	4.4	1.4	0	0.6	0.2	0.4	2.2	3.4	1.4	0.2	2.2	17.4	0.8	0.4	100
TP14	87.8	1.4	2.4	0.2	0.2	1	0.4	0.6	2.4	1.2	0.2	0	0.8	0.8	0.6	100
MP2	80.2	1.2	1	0	0.2	0.2	1.4	0.4	2.4	0	0.2	1.2	9.6	1.4	0.6	100
MP3	79	2	0.2	0	0.2	0	1.4	1.6	0.6	0.2	0.6	0.4	11.6	1.6	0.6	100
MP5	77.2	3.4	3.4	0	1	0	1.8	1.8	2.6	0.4	0.6	0.8	1	6	0	100
MP7	89.6	0.8	0.8	0	0	0	1	0.4	2	0.4	0.6	0.2	3	0.4	0.8	100
MP8	71.2	9.4	2	0	1	0	2	0.8	2.8	1.4	0.2	1.8	4.6	2.8	0	100
MP9	77.2	5.4	0.6	0	0.2	0.2	2.4	0.8	3	0.2	0.2	1.4	1.4	7	0	100
MP10	77.2	3.4	3.4	0	1	0	1.8	1.8	2.6	0.4	0.6	0.8	1	6	0	100
KP1	64	1.8	1.8	0	0.4	1.6	1.6	0.6	0.6	0.2	0	0	26	1	0.4	100
KP3	80.4	2.2	2	0.2	0.8	0	1.2	1.4	5.4	0.6	0.4	0	2.6	2.6	0.2	100
KP4	72.6	4.6	2	0	0.8	1.2	3.2	1	3.2	0.2	0.4	0.2	6.6	3.8	0.2	100
KP5	78.2	2.8	2.2	0	1.4	0.6	2.4	1.8	3	1.4	0.2	0.4	3.6	1.6	0.4	100
KP6	78.6	4.6	1.8	0.2	0.2	0	1	1	4.2	0.8	0.4	0.8	1.8	4.6	0	100
KP7	88.6	1.2	0.6	0	0.4	1.6	1.2	0.4	1.6	0.2	0	0.2	1	2.8	0.2	100
KP8	78	3.8	1	0.2	0	0.4	1	0.8	5.2	1	0.4	0.2	3	4	1	100
KP9	78	1.6	3.8	0.6	1.4	0.2	1.2	2.2	3	1	0.4	0.2	4.6	0.8	1	100

Table 3: Recalculated parameters used for composition and provenance study of Pab Formation of the study area

	QFL			QtFL			QmFLt			QmPK			LmLvLs			QpLvmLsm		
Samples no.	Q %	F %	L %	Qt %	F %	L %	Qm %	F %	Lt %	Qm %	P %	K %	Lm %	Lv %	Ls %	Qp %	Lvm %	Lsm %
TP4	88	6	6	88	5	6	82	6	12	94	6	1	9	27	64	47	5	47
TP5	96	0	4	96	0	4	95	0	5	100	0	0	20	60	20	15	15	70
TP8	98	0	2	98	0	2	95	0	5	100	0	0	0	50	50	59	5	36
TP9	98	0	1	98	0	1	95	0	4	100	0	0	0	0	100	71	0	29
TP10	94	3	4	94	3	4	92	3	5	97	3	0	29	29	43	31	8	62
TP11	94	1	6	94	1	5	90	1	9	99	1	0	11	56	33	41	13	46
TP13	89	2	9	89	2	9	83	2	15	98	2	0	5	58	37	38	19	43
TP14	93	3	4	93	3	4	92	3	5	97	3	0	14	0	86	27	0	73
MP2	94	1	4	95	1	4	93	1	6	99	1	0	14	86	0	24	24	52
MP3	98	0	2	98	0	2	95	0	5	100	0	0	50	33	17	53	11	37
MP5	91	4	5	91	4	5	87	4	9	96	4	0	33	44	22	44	10	46
MP7	96	1	3	96	1	3	95	1	4	99	1	0	50	17	33	20	5	75
MP8	91	2	7	91	2	7	80	2	18	97	3	0	6	53	41	60	12	28
MP9	94	1	5	94	1	5	88	1	12	99	1	0	11	78	11	53	14	33
MP10	91	4	5	91	4	5	87	4	9	96	4	0	33	44	22	44	10	46
KP1	96	3	1	96	3	1	94	3	4	97	3	0	0	0	100	69	0	31
KP3	91	2	7	91	2	7	88	2	9	97	2	0	40	0	60	26	0	74
KP4	93	2	5	93	2	5	87	2	10	97	3	0	50	25	25	53	2	44
KP5	92	2	6	92	2	5	89	2	9	97	3	0	10	20	70	36	5	59
KP6	91	2	7	91	2	6	86	2	12	98	2	0	20	40	40	43	7	50
KP7	97	1	2	97	1	2	96	1	3	99	1	0	0	50	50	38	6	56
KP8	91	1	8	92	1	7	87	1	12	98	1	0	25	13	63	36	2	62
KP9	90	5	5	90	5	5	88	5	7	95	4	1	25	13	63	26	3	71
averages	93	2	5	93	2	5	90	2	8	98	2	0	19	36	44	41	8	51

Table.4 Major Element's concentration averages, and ranges of the major elements in weight percentage and UCC (average value for upper continental crust) (Mclennan2001) and other geological parameters of Pab Formation in western Sulaiman Fold Thrust belt Pakistan.

Sample No	CaO%	MgO%	Na_2O%	K_2O%	MnO%	Fe_2O_3%	P_2O_5 %	TiO_2%	Al_2O_3%	SiO_2 %	LOI %	CIA	CIW	CIV	K_2O/Na_2O	SiO_2/AL_2O_3	TiO_2/Al_2O_3
Tp-4	1.637	0.582	0.745	0.570	0.008	1.503	0.6	0.45	7.2	83.3	1	70.92	75.54	5.11	0.76	11.57	0.06
Tp-7	1.1095	0.520	0.626	0.657	0.002	1.537	0.07	0.16	7.03	80.6	1	74.60	63.61	4.47	1.05	11.47	0.02
Tp-10	1.37375	0.425	0.926	0.890	0.001	1.300	0.24	0.15	5.8	85.3	2	64.51	93.64	4.94	0.96	14.71	0.03
Tp-13	4.438	0.452	0.866	0.513	0.111	4.513	0.28	0.55	4.48	79.9	6.5	43.50	87.57	11.01	0.59	17.83	0.12
Tp-14	7.43575	0.307	0.589	0.518	0.002	1.432	0.01	0.48	3	82.3	1.5	25.99	59.89	10.44	0.88	27.43	0.16
Mp-1	1.74125	1.485	0.518	0.718	0.008	5.105	0.01	0.41	5.51	79.5	2.5	64.92	52.81	9.65	1.39	14.43	0.07
Mp-2	2.89625	0.514	0.555	0.362	0.060	2.190	0.06	0.68	6.4	78.8	6.5	62.66	56.52	6.68	0.65	12.31	0.11
Mp-3	1.757	0.210	0.793	0.232	0.056	3.092	0.09	0.5	3.9	80.4	5.5	58.36	80.31	6.27	0.29	20.62	0.13
Mp-5	2.4535	0.349	0.689	0.764	0.142	2.301	0.01	0.2	3.2	80.8	7.5	45.02	69.90	6.76	1.11	25.25	0.06
Mp-11	2.07725	0.588	0.518	0.512	0.043	0.338	0.24	0.54	5.1	82.6	4	62.14	52.81	4.18	0.99	16.20	0.11
Kp-2	1.9975	0.365	0.595	0.216	0.009	1.737	0.04	0.35	7.55	83.2	1	72.88	60.47	4.97	0.36	11.02	0.05
Kp-3	2.952	0.359	0.605	0.331	0.009	0.618	0.05	0.15	6	81.8	1	60.67	61.53	4.90	0.55	13.63	0.03
Kp-7	1.18425	0.305	0.503	0.789	0.222	1.228	0.08	0.12	7.5	79	6.5	75.15	51.30	4.25	1.57	10.53	0.02
Kp-8	8.01325	0.454	0.766	0.651	0.280	1.852	0.16	0.07	6.6	75.5	3	41.17	77.57	12.03	0.85	11.44	0.01
Kp-9	1.73425	0.448	0.746	0.054	0.012	6.201	0.09	0.3	5.25	79.2	1.5	67.44	75.59	9.25	0.07	15.09	0.06
Ucc	4.2	2.2	3.9	3.4	0.08	5.03	0.15	0.68	15.2	66					0.87	4.34	0.04
Range%	1.1095-8.013	0.210-1.485	0.503-0.926	0.503-0.926	0.001-0.280	0.338-6.201	0.01-0.6	0.07-0.68	3-7.55	75-5.85	1-7.5	25.99-75.15	51.30-93.64	4.18-12.03	0.11-0.96	11.30-25.17	0.02-0.09
Mean %	2.853367	0.491	0.669	0.669	0.064	2.33	0.135	0.341	5.635	80.813	3.4	59.32	67.94	6.99	0.77	14.34	0.06

Table.5; Trace elements (ppm) concentration of the studied sandstones from Pab Formation, in western Sulaiman Fold-Thrust Belt Pakistan

Sample No.	Zr	Ba	Rb	W	Sr	Y	Pb	Mo	Zn	Th
TP-4	470	421	51	395	60	13	8	3	19	8
TP-7	198	98	18	369	24	7	10	2	17	5
TP-10	262	661	36	616	52	8	13	1	26	4
TP-13	157	360	23	209	133	7	12	3	23	5
TP-15	219	240	13	565	18	8	19	2	155	5
MP-1	93	305	6	195	17	5	17	2	22	6
MP-2	202	105	15	227	110	9	3	2	60	8
Mp-3	301	209	7	292	95	12	9	3	19	9
Mp-5	534	940	32	221	140	18	23	3	33	10
MP-11	276	397	4	132	126	14	21	2	25	13
KP-2	194	250	8	224	30	7	15	2	19	4
KP-3	352	95	12	638	30	6	20	1	19	7
KP-7	139	105	8	186	83	8	13	2	35	8
KP-8	147	80	6	207	78	11	26	3	38	5
KP-9	238	82	8	1869	23	11	10	1	20	6
PG1 XRF	52	183	34		163	3	30	2	40	4
AGV1 XRF	112	497	35		319	9	21	1	43	5
PG1 Reference		1026	173		683	7	61	1	88	3
AGV1		1230	67		660	20	36	1		
Ucc	190	550	122		350	22	17		71	10.7
Range	93-534	80-940	4-51	132-1869	5-140	3-186	3-26	1-3	17-55	4-13
Mean	252.13	289.87	16.47	423.00	67.93	14.60	9.60	2.13	35.33	6.87

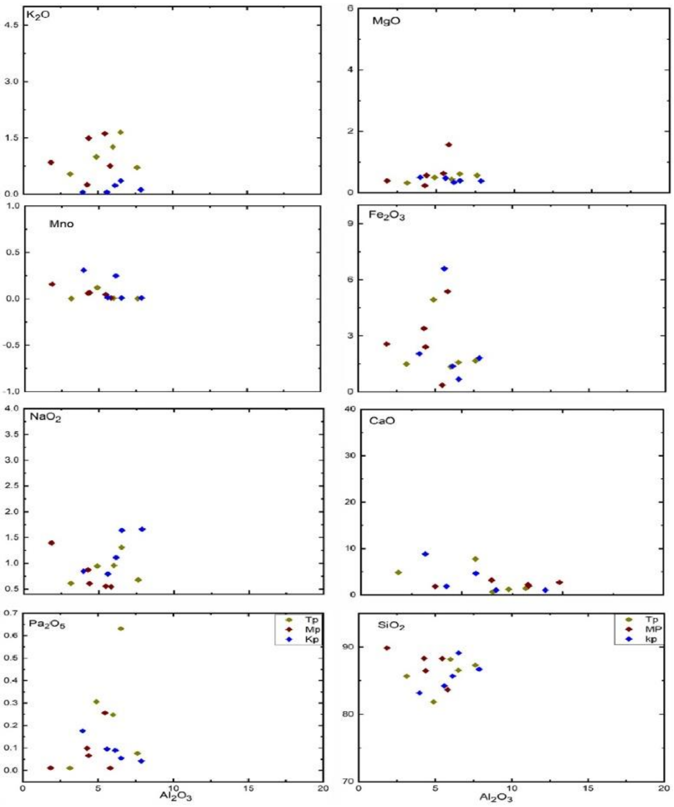

Figure 8. Plots of various trace elements against Al2O3 (48) for sandstones of the Pab Formation (Tp Tanga section, Mp Mina Bazar section, Kp Kapip section) in western Sulaiman Fold-Thrust-Belt Pakistan.

5.3 Source area weathering

The weathering of the source area is mainly controlled by relief, the composition of source rocks, climatic conditions, tectonic uplift and intensity of weathering (52). Depletion of the alkali and alkaline earth elements occurs during weathering (52), which provide constraints on chemical and physical weathering and also sedimentary environments 53. The chemical index of alteration (CIA, 54), chemical index of weathering (CIW 55, and index of chemical variability have been used to assess the palaeo-weathering state of the source area (ICV 56). The chemical index of alteration or CIA shows the intensity of chemical weathering occurred in the source area (54). The molar equation is used to calculate the index.

CIA = [Al2O3+CaO+Na2O+K2O]*100

CIA = [Al2O3/ (Al2O3+CaO*+Na2O+K2O)] × 100.

The variation in the CIA values may indicate alterations of feldspar and a variety of clay minerals (54). The high CIA values (76–100) show intense chemical weathering while the low values of CIA indicate (50 or less) fresh source areas. The values of CIA in the studied samples range from 26% to 75% and the average value is (59%), which suggest that source region may have experienced intermediate chemically weathering. The average to high values of CIA may reflect humid to semi-humid palaeo-climatic conditions in the source area.

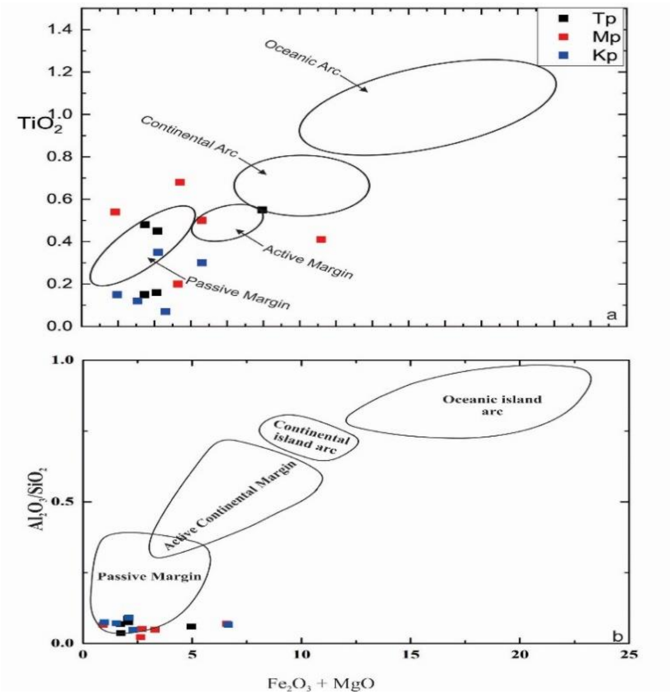

Figure 9. (a) Fe2O3+MgO vs TiO2; (b) Fe2O3+MgO vs Al2O/ SiO2 after after Bhatia (51)

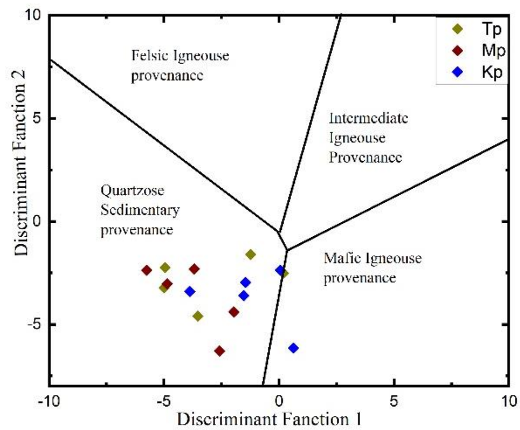

Figure 10. after Roser and Korsch (52) discrimination function diagram for the sandstone samples of the Pab Formation (Tp, Tanga section, Mp Mina Bazar section, Kp, Kapip section), in western Sulaiman Fold-Thrust Belt Pakistan. The discrimination functions are as under:

Discrimination function 1 = 1.773TiO + 0.607 A2O3+0.76 Fe2O3-1.5MgO + 0.0616 CaO + 0.00616 CaO +0.509 Na2O-1.224K2O -9.09

Discrimination function 2 = 0.445 TiO2 +0.07 Al2 O3-Fe2O3-1.142 Mgo+0.438 CaO+1.475 Na2O+1.426 k20-6.861

The Chemical Index of weathering (CIW) can reveal a better understanding of source area weathering conditions (57)

CIW = [Al2O3/Al2O3 + CaO + Na2O]*100

The CIW values of the Pab Formation range from 95% to 52% and the average value is 70%, which indicates intermediate to high-intensity chemical weathering in the source area. The index of chemical variability (ICV) proposed by 58 measures the percentage of alumina compared to other main cations, which may be used for evaluating the maturity of Murdock.

ICV=(Fe2O3+K2O+Na2O+CaO+MgO+MnO+TiO2)/ Al2O3

*CaO molecule in detrital grains

The ICV values range from 6.37 to 12.03 (mean 12.18). The samples with higher alteration products have low values of ICV, less than 1, such as clay minerals and formed within low topography with intense chemical weathering (59). The plot of Si2O vs total Al2O+k2O+Na2O introduced by (60) was used to identify the maturity of the sandstone as a function of climate this plot (Figure 11) indicates a humid climate and intense weathering conditions and higher degree of mutuary in the source region.

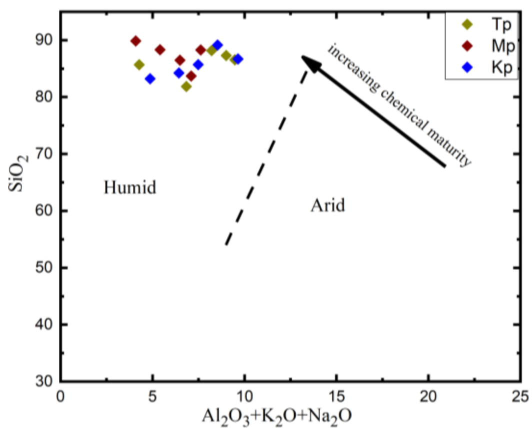

Figure 11. Plot showing chemical maturity of the sandstone, (Tp, Tanga section, Mp Mina Bazaar section, Kp, Kapip section) in western Sulaiman Fold-Thrust Belt Pakistan, as expressed by plotting SiO vs Al2O3+K2O+Na2O after Suttner and Dutta (61).

6. DISCUSSION

Sandstone of the Pab Formation is quartz arenites. The mineral assemblages of Pab Formation after being plotted in different ternary diagrams indicates the detritus derivation from recycled orogeny and Craton Interior. The petrographic and model analysis data point towards plutonic as well as metamorphic rocks in the source. The higher percentage of mono-crystalline quartz over poly-crystalline quartz indicates the derivation of sediments of the Pab Formation largely from an acidic plutonic source and represents a long transporting route. Such kind of interpretations have been done by (Blatt 1967) 62, by examining the characteristics of the quartz grains. (Tucker 2001) 63 proposed a set of heavy minerals used for the identification of source lithology, he mentioned epidote, staurolite, and garnet as minerals of metamorphic source terrain, while tourmaline, zircon and rutile indicate igneous source. The inclusions of mica and garnet within quartz grains are another indication of metamorphic source (64). Besides quartz grains, Pab Formation also contains the lithic fragments of basic igneous and metamorphic rocks. The sorting, roundness, and low clay concentration indicates that the sandstone is mature and sediments were transported over a long distance. The compositional diagrams such as Qm-F-Lt indicate quartzose recycled and lithic recycled while Lm-Lv-Ls indicate mixed Magmatic Arc and Subduction Complex fields. Identified minerals after being plotted on different compositional diagrams indicate that both quartz and feldspars are derived from a granitic body with some contribution of metamorphic and basic igneous rocks. The Comparison between the present findings with the Triassic and Jurassic sandstones of the Wulgai and Loralai formations in western Sulaiman Fold-Thrust Belt and Cretaceous Mughal Kot and Pab formations in Kirthar and Sulaiman Fold Thrust belts show that they have similar characteristics (33, 65, 66,67, 68 ,69). Detrital modes of the Triassic sandstone of the Wulgai Formation (69) in western Sulaiman Fold Thrust Belt has detrital modes of Q96F4L0.2, Qt71F4L25, Qm96F3Lt1, Qm96P1K2, Lm55Lv1Ls16 and Qp71Lv6Ls29 are very close to our detrital modes (Q93F2L5, Qt93F2L5, Qm90F2Lt8, Qm98P2K0, Lm19Lv36Ls44, Qp41Lvm8Lsm50). Durrani et al., (68) carried out the detrital modes of the Jurassic Loralai Formation in western Sulaiman-Fold-Thrust Belt, they classified Jurassic sandstone as quartz arenite and in Qt-F-L, samples plot fall in the field of Craton Interior and quartose-recycled field. Umar et al (65) analyzed the Pab Formation in Kirthar Fold Thrust

Belt, they also reported high percentage of quartz in the sandstone. Umar [66] concluded that the detritus of the Pab Formation in Kirthar Fold-Thrust-Belt was supplied from Craton Interior and quartzose recycled settings. Kakar et al [67] studied the petrographic and provenance studies of Late Cretaceous Pab Formation and Mughal Kot Formation in northeastern Sulaiman Belt, their results are also close to our findings, they also proposed Craton Interior and recycled orogeny setting. Kassi et al., (33) also classified Pab Formation as quartz arenite, sublithic-arenite and lithic arenite and suggested acidic igneous and metamorphic terrain within Craton Interior and recycled orogenic belt. Sultan and Gibson [65] analyzed the sandstone of the Pab Formation in eastern Sulaiman Fold-Thrust-Belt and also reported lower degree of maturity in sandstone due to its proximity to source terrain. The Indian Craton which is exposed as inliers in the northeast and southeast of the Sulaiman Belt is believed to be the most probable area for the sandstone of the Pab Formation and it remained the dominant source for the sandstones of the belt until Cretaceous. The grains sorting, roundness and low clay concentration suggest that the detritus of Pab Formation travelled a long transporting distance before deposition into the basin.

Studied samples of the Pab Formation are high in SiO_2 due to enrichment of Quartz. Al_2O_3 is the second highest oxides in sandstone, which ranges from 3.00% to 7.55% (average is 5.63), the average value is depleted when compared to UCC values (15.2). These values suggest mature types of sandstone The relationships between various major oxides such as CaO, Al_2O_3, MnO, TiO_2, Fe_2O_3, MgO, K_2O, and Na_2O with SiO_2 show a positive correlation except Na_2O and K_2O Harkar 1983 (48) that may be due to scarcity of feldspar. Plots of different major oxides against Al_2O_3 show a stronger positive correlation except SiO_2 and MnO that may be due to the enrichment of quartz and calcite cement. Plots of the trace elements vs Al_2O_3 indicate positive correlations of the trace elements with Al_2O_3, the reason may be the absorption of most of the trace elements by alumino-silicates (49). The classification scheme of Pettijon and crock (5, 50) showed that the samples plotted in the field of sublithic arenite to quartz arenite. The index of chemical weathering and alteration of source areas such as CIA, CIW and ICV (after 54, and 55) indicates moderate to intense chemical weathering in the source region. The provenance of the Pab Formation was also investigated using discriminant function diagrams, (52) discriminant function diagram indicates that Pab Formation is derived mainly from recycled quartzose sedimentary source. The discriminate plots of 51 favor a passive margin environment for the deposition of the Pab formation. In such setting the sediments are largely quartz-rich and the sandstones are derived from plate interior or stable continental areas and deposited in the intra-cratonic basin or passive continental margins (52). The Indian Shield in Pakistan comprises many Precambrian outcrops comprising crystalline rocks of Kirana Group in Sargodha High, Sargodha-Shakot area and Nagar-Parkar Complex, Thar, Sindh (18). Rocks of Kirana Group are composed of meta-sedimentary and metavolcanics assemblages such as quartzites, slates, phyllites and minor volcanics (70). Rocks of Nagar Parkar Complex comprises grey granite, pink granite, metabasites, acid dykes of rhyolite/quartz trachyte in metabasites and dykes of mafic composition (18). Till collision in Paleocene the northwestern margin of the Indian plate remained passive in the enormous Tethys Ocean (71). The Wulgai Formation (Triassic) and Loralai Formation (Jurassic) demonstration a slow progradation from deep to shallow marine environmental setting and final emergence, which is marked by the disconformity between the Jurassic Loralai Formation and Late Jurassic-Early Cretaceous Sember Formation (23). The eastern Indian Shield interior was thermally uplifted when the Indian Plate was passing over the Hot Spot (Reunion hot spot) during Late Cretaceous. As a result a large amount of sandy detritus was derived from the interior and deposited onto the passive margin as the Pab Formation (10). The supply of terrigenous detritus to the basin was diminished during Paleocene due to a large scale transgression, which initiated the deposition of pelagic-hemipelagic shales and very thick shallow marine limestone of the Dungan Formation. The oblique convergence of Indian Plate with the Eurasian Plate (Afghan) block during Paleocene initiated the obduction of Bela-Muslim Bagh Ophiolite onto the western passive margin of the Indian plate (72,73, 74). The collision affected the geometry of the margin and as a result flexural foreland-basins started evolving in far west side. The sedimentation still continued on western passive margin and thick Ghazij deltaic shales and the shallow marine limestone of Kirthar Formation were deposited. The continued collision between the Indian Plate and Eurasian Plate uplifted the gigantic Himalayan Mountain belts on the northern and northwestern margin. The Kirthar-Sulaiman Fold-Thrust-Belts are the south-southwestern extensions of Himalayas. Compressional deformation continued until Pliocene–Pleistocene time and is recorded in imbricated thrust sheets in the Kirthar Fold Belt (75).

CONCLUSIONS

The sandstone of the Late Cretaceous Pab Formation in western Sulaiman Fold and Thrust Belt is quartz arenite to lithic arenite. The petrography reveals that low grade metamorphic and granitic rocks were the dominant source terrains. The geochemical ternary diagrams indicate the derivation of sandstone from quartzose recycled and lithic recycled orogeny. The weathering and alteration indices of source areas such as CIA, CIW and ICV indicate intense to moderate chemical weathering in the source area. In discriminant function diagrams the Pab Formation is plotted in quartzose recycled sedimentary source and favor a passive margin environment for the deposition. Eroded sediments were largely derived from stable craton areas and laid on passive continental margin of the Indian Plate. Well sorted and rounded grains of sandstone and low concentration of clay indicate that the detritus of the Formation had travelled a long distance before deposition into the basin. The Indian Craton which is exposed as inliers in the northeast and southeast of the Sulaiman Fold and Thrust Belt, remains the most logical source terrain for the detrital material of the Pab Formation and it remained the dominant source for the sandstones in western Sulaiman Fold -Thrust belt until Late Cretaceous.

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Farooq Ahmed: Field data collection, Laboratory work, Initial draft preparation; **Aimal Khan Kasi**, **Mohibullah**: Conceptualization, Supervision, Methodology, Writing- Original draft preparation; **Razzaq Abdul Manan**: Field work, reviewing and editing.

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