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Petrogenesis of Middle Triassic Volcaniclastic Rocks from Balochistan, Pakistan: Implications for the Break-Up of Gondwanaland

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ABSTRACT: Basaltic volcanic conglomerates near the Wulgai Village in Balochistan occur in the undivided sedimentary rock unit of the Bagh complex which is the mélange zone beneath the Muslim Bagh ophiolite. The presence of Middle Triassic grey radiolarian chert within the upper and lower horizon of the conglomerates suggests that the lavas, from which these conglomerates were principally derived, were eroded and re-deposited in the Middle Triassic. The Wulgai conglomerate contains several textural and mineralogical varieties of volcanic rocks, such as porphyritic, glomerophyric, intersertal and vitrophyric basalts. The main minerals identified in these samples are augite, olivine, plagioclase ($An_{35–78}$) leucite and nosean, with apatite ilmenite, magnetite and hematite occurring as accessory minerals. These rocks are mildly to strongly-alkaline with low $Mg^{\#}$ and low Cr, Ni and Co contents suggesting that their parent magma had undergone considerable fractionation prior to eruption. Trace element-enriched mantle-normalized patterns with marked positive Nb anomalies are consistent with 10%–15% melting of an enriched mantle source in a within-plate tectonic setting. It is proposed that this Middle Triassic intra-plate volcanism may represent mantle plume-derived melts related to the Late Triassic rifting of micro-continental blocks (including Afghan, Iran, Karakorum and Lhasa) from the northern margin of Gondwana.

KEY WORDS: Middle Triassic, Wulgai volcaniclastics, juvenile Ceno-Tethys.

0 INTRODUCTION

The Mesozoic sedimentary, igneous and metamorphic mélange beneath the Muslim Bagh ophiolite is known as the Bagh complex (Mengal et al., 1994). This complex trends in an ENE direction and dips 10°–70° towards west and northwest. It is divided into five tectonic/biostratigraphic units: (1) undivided sedimentary rock unit (Permo–Triassic; Anwar et al., 1993), (2) sedimentary rock unit (Jurassic–Cretaceous; Jones, 1961), (3) basalt-chert unit (Early–Late Cretaceous; Kojima et al., 1994), (4) hyaloclastite-mudstone unit (Late Cretaceous; Sawada et al., 1995), (5) serpentine and mudstone-matrix mélange unit (Late Cretaceous; Mengal, et al., 1994). The Wulgai volcaniclastic rocks occur in the undivided sedimentary rock unit of the Bagh complex as basaltic volcanic conglomerate (e.g., Naka et al., 1996; Fig. 1). This sedimentary rock unit is exposed in a ~100 km long and up to 7 km wide area (Fig. 1). The presence of Middle Triassic (Ladinian) grey radiolarian chert within the upper and lower horizons of the conglomerates indicate that the rocks from which these volcaniclastic rocks were derived were erupted, eroded and re-deposited as volcanic conglomerate in Middle Triassic. The detailed stratigraphy of these volcaniclastic rocks is shown in Fig. 1. The geology, biostratigraphy and tectonics of this complex have already been described by many workers including Otsuki et al. (1989), Kimura et al. (1993), Kojima et al. (1994), Mengal et al. (1994), Naka et al. (1996) and Kakar et al. (2014). This study reports the geochemistry of Wulgai volcaniclastic rocks that occur in the undivided sedimentary rock unit of the Bagh complex and will assess their petrogenesis and tectono-magmatic setting in relation to the break-up of Gondwana.

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1 GEOLOGICAL SETTING

The Wulgai volcaniclastic rocks occur in a 13 m thick bed of volcanic conglomerate, which is well exposed at the base of Wulgai Nala Section (Fig. 1). In the lower 7 m thick part, sub-angular fragments of limestone with minor amygdaloidal basalt fragments occur in a tuffaceous sandy matrix (Fig. 2).

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This is overlain by 1.5 m thick interbedded sequence of micritic limestone, shale and grey chert, which contains Middle Triassic radiolarians (Otsuki et al., 1989). This sequence is succeeded by a 3 m thick bed of volcanic conglomerate which contains abundant sub-rounded fragments of amygdaloidal basalt, ignimbrite and minor limestone in a grayish-green tuffaceous groundmass. The lower contact of the volcanic conglomerate sequence is with an intercalated sequence of micritic limestone, silicious shale and grey chert with Middle Triassic (Ladinian) radiolarian (Otsuki et al., 1989). A 5 cm thick sequence of intercalated shale and limestone unconformably overlies the conglomerate sequence, which is followed by a 40 cm thick greyish green tuff bed. This tuff bed is again followed by about 10 m thick sequence of thin bedded limestone and flaky shale. The presence of Middle Triassic (Ladinian) radiolarian chert (Otsuki et al., 1989) within the conglomerate sequence, and within the underlying intercalated sequence of limestone shale and chert, suggests that the basaltic lava flows were erupted in the Middle Triassic and were subsequently eroded and re-deposited as volcanic conglomerate shortly thereafter.

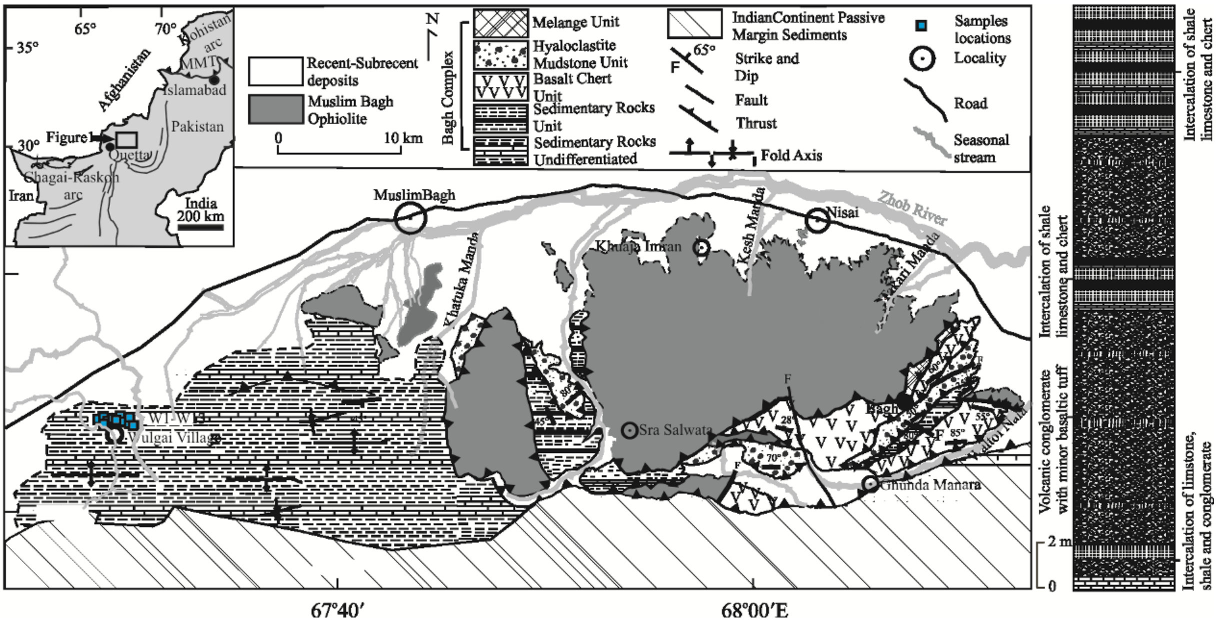

Figure 1. Geological map of Muslim Bagh area showing the location of the Wulgai volcaniclastic rocks and the generalized stratigraphic sequence in the Wulgai area, Balochistan, Pakistan (modified after Kakar et al., 2012; Siddiqui et al., 2011).

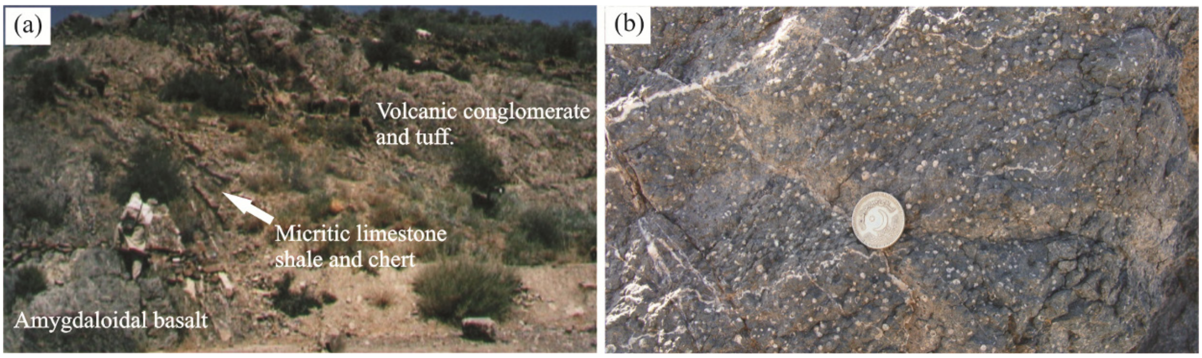

Figure 2. Field views of the Wulgai volcaniclastic rocks. (a) A view showing amygdaloidal basalt at the base, micritic limestone interbedded with shale and grey chert in the middle, while the volcanic conglomerate with tuffs at top; (b) a close view of the amygdaloidal basalt.

2 PETROGRAPHY

Most of the basalt samples collected from the Wulgai Section are amygdaloidal and intensely altered (chloritised). Clinopyroxene and other ferromagnesian phenocrysts are completely altered and occur as chlorite pseudomorphs. Plagioclase is less affected by alteration and occurs as microlites and small crystals in the groundmass, but rarely also as phenocrysts. Petrographic study of the least altered ignimbrites shows that the fragments comprise several textural and mineralogical varieties, with numerous fragments of porphyritic, glomerophyric, intersertal and vitrophyric basalts and large fragments of devitrified volcanic glass, augite, olivine and plagioclase. The main minerals identified are augite, olivine, plagioclase (An_{35-78}) leucite and nosean, which occur as phenocrysts as well as in the groundmass. Apatite ilmenite, magnetite and hematite occur as accessory minerals, whereas chlorite, zeolites, chalcedony antigorite and calcite are found as secondary minerals.

3 GEOCHEMISTRY

3.1 Analytical Methods

Ten rock samples were analysed from the Wulgai area of Bagh complex for major and trace elements in the Geoscience Laboratory, Geological Survey of Pakistan, Islamabad (Table 1). For major elements, the sample powder (<200 mesh) was thoroughly mixed with lithium tetraborate (flux) with a 1 : 5 sample flux ratio and fused to form glass beads that were analysed by XRF. For trace elements powdered pellets of all the samples were analysed by XRF (X-ray fluorescence spectrophotometer, RIGAKU XRF-3370E). The accuracy and precision of the instrument was assessed using international reference material JA-3 (Govindaraju, 1989).

3.2 Geochemical Results

3.2.1 Hydrothermal alteration and elements mobility

The petrographic data, higher values of LOI and CaO and lower values of SiO_2 of the Wulgai volcaniclastic rocks indicate that these rocks have undergone a substantial degree of hydrothermal alteration and although these processes may have mobilized the large-ion lithophile (LIL) elements (Pb, Ba, Rb and K), we note that on Fig. 4 Ba and Rb contents do not display significantly more scattered than other elements usually regarded to be less-mobile (e.g., Nb, Zr and Y). However, that shows, we have avoided the use of LIL elements for the purpose of classification and discrimination, consequently, our discussion on the data is in favour of elements generally regarded to be relatively immobile; high field strength (HFS) elements under the hydrothermal conditions experienced by these rocks (e.g., Hastie et al., 2007; Pearce, 1996; Winchester and Floyd, 1977).

3.2.2 Classification

To classify the samples they were plotted on a Zr/TiO_2 vs. Nb/Y diagram (Fig. 3) which is less-susceptible to the effects of alteration. This immobile element classification diagram confirms that all the volcanic rocks are alkali basalts.

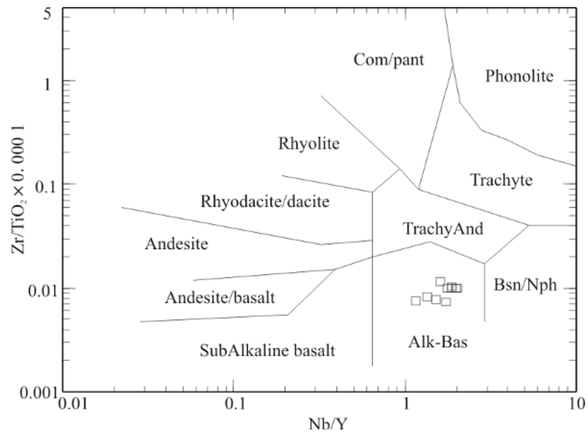

Figure 3. Zr/TiO_2 versus Nb/Y classification plot of the Wulgai volcaniclastic rocks from Balochistan, Pakistan (after Winchester and Floyd, 1977).

Table 1 Bulk Chemistry of volcaniclastic rocks from the Wulgai area, Balochistan, Pakistan

Sample	W1	W2	W3	W4	W5	W6	W-7	W-8	W-9	W-10	W-11	W-12	W-13
SiO_2	27.1	25.91	26.9	46.28	41.83	41.07	39.82	40.47	33.31	30.36	41.5	28.39	36.23
TiO_2	1.99	1.65	1.81	2.27	2.33	2.32	2.37	2.52	1.74	1.94	2.60	1.74	1.62
Al_2O_3	11.21	9.33	9.62	13.19	14.14	13.58	13.51	13.39	11.38	10.9	14.21	10. 0	11.84
Fe_2O_3	9.35	6.87	7.72	10.6	7.87	7.13	9.08	7.5	7.47	8.02	10.00	6.48	6.37
MnO	0.43	0.21	0.22	0.12	0.12	0.13	0.14	0.14	0.21	0.19	0.13	0.19	0.16
MgO	4.75	2.92	2.90	6.46	3.98	3.78	3.77	3.9	3.56	3.88	4.21	3.26	3.04
CaO	22.18	27.29	25.74	7.55	12.39	13.76	13.41	14.35	20.36	21.84	11.0	25.11	19.2
Na_2O	2.47	3.43	3.68	2.67	4.98	4.78	4.71	4.55	3.87	3.29	4.96	3.16	4.43
K_2O	0.68	0.25	0.23	1.17	0.41	0.48	0.47	0.35	0.10	0.08	0.48	0.07	0.31
P_2O_5	0.34	0.6	0.56	0.29	0.53	0.63	0.74	0.61	0.95	0.56	0.72	0.46	0.74
LOI	19.5	21.54	20.62	9.4	11.4	12.33	11.97	12.55	17.6	18.93	10.23	21.23	16.06
Total	100	100	100	100	99.98	99.99	99.99	100.33	100.55	99.99	100.04	100	100
FeO^T/MgO	1.75	2.09	2.37	1.46	1.76	1.68	2.14	1.71	1.84	2.11	1.77	1.86	1.85
$Mg^\#$	50	46	43	55	50	51	45	51	49	49	45	50	49
Ba	8	27	11	88	67	36	63	47	542	140	99	32	34
Rb	20	10	8	35	15	17	17	14	6	5	18	5	14
Sr	527	509	460	188	406	434	554	429	679	513	458	450	544
Y	26	19	18	22	24	27	26	25	21	18	26	16	24
Zr	166	134	140	176	241	236	246	235	161	159	265	143	202
Nb	32	27	29	35	50	50	51	49	30	33	56	30	41
Ni	18	8	7	35	9	10	13	11	14	12	21	12	55
V	183	172	192	222	197	180	239	178	177	208	251	179	161
Cr	64	0.2	1	74	7		1	11	1	1	54	8	56
Co	63	52	46	39	38	18	19	18	19	20	21	18	41
Ti	14 820	12 607	13 669	15 020	15 767	15 862	16 140	15 080	12 646	14 347	17 359	13 242	11 638
K	7 012	2 645	2 405	10 720	3 842	4 544	4 432	3 322	1 001	819	4438	738	3 065
P	193	350	323	146	274	334	390	324	524	316	367	267	409

SiO_2-P_2O_5 are in wt. %, Ba-P are in ppm, $Mg^\#=100\times Mg/(Mg+Fe^{2+})$, FeO^T = total Fe as FeO

3.2.3 Major element characteristics

In the Wulgai volcaniclastic rocks, Na_2O content in some samples reaches up to 6.4 wt. %, possibly due to albitization. The CaO content is also highly variable as some of the samples contain up to 26.9 wt. % due to partial replacement of some minerals by calcite and its presence in vesicles. Similarly, the original contents of SiO_2, Al_2O_3 and other major elements may have been changed maybe due to the alteration processes and infillings of certain minerals like chlorite, chalcedony and zeolites in the vesicles. The Wulgai volcaniclastic rocks show a narrow range in TiO_2 (1.9 wt. %–2.9 wt. %) a wider range for MgO (3.6 wt. %–1 wt. %) and low abundances (13.5 wt. %–16.0 wt.%) of Al_2O_3. The P_2O_5 concentrations are highly variable (0.3 wt. %–1.2 wt. %) in these volcaniclastic rocks. The major elements of the Wulgai alkali basalt show enrichment in K_2O, Na_2O, CaO, TiO_2, MnO and P_2O_5 and depletion in MgO, Fe_2O_3, Al_2O_3 and SiO_2 relative to N-MORB (Table 2) and although the rocks are relatively altered these overall trends are consistent with the reported values in alkaline rocks (e.g., Baker, 1987; Weaver et al., 1987).

Table 2 Major (wt.%) and trace elements (ppm) and their ratios in average basalts from Wulgai, Bibai, N & E-MORBS, Oceanic islands, Hawaii, Reunion hotspot and Mount Kenya

Sample	Wulgai1	Bibai	N-MORB	E-MORB	OIB	Reunion	Hawaii	Mount Kenya
SiO_2	41.67	48.06	50.40	51.18	/	47.03	46.40	41.43
TiO_2	2.44	2.54	1.36	1.69	3.35	2.78	2.40	3.64
Al_2O_3	14.21	16.47	15.19	16.01	/	14.38	14.18	11.87
Fe_2O_3	9.55	11.08	10.01	9.40	/	12.81	14.99	15.57
MnO	0.22	0.16	0.18	0.16	/	0.19	0.19	0.23
MgO	4.6	5.98	8.96	6.90	/	8.10	9.47	10.52
CaO	21.53	10.25	11.43	11.49	/	10.96	10.33	11.1
Na_2O	4.63	3.3	2.30	2.74	/	2.60	2.85	2.33
K_2O	0.48	1.75	0.09	0.43	1.12	0.92	0.93	1.48
P_2O_5	0.67	0.42	0.14	0.15	/	0.36	0.28	0.94
Ba	54.33	616	6.3	57	350	210	300	622
Rb	14.83	37	0.56	5.04	31	19	22	52
Sr	456	1 003	90	155	660	429	500	1230
Y	22.58	28	28	22	29	29	21	26
Zr	195.25	189	74	73	280	209	160	197
Nb	40.25	47	2.33	8.3	48	25	16	59
Ti	14 629.25	15 227	7 607	6 007	17 200	16 666	14 388	21 821
K	3 998.5	14 528	598	2 092	1 200	7 637	7 720	12 286
P	307.75	1 833	510	624	2 700	1 571	1 222	4 102
V	196.83	/	/	/	/	/	/	/

Values in columns: 1 is after Siddiqui et al. 2010; 2, 3 and 4 are from Sun and McDonough (1989); 5 is from Fisk et al. (1988); 6 is from Schilling et al. (1985); and 7 is from Price et al. (1985). The major elements in column 2 & 3 are from Humphris et al. 1985. /. Unmeasured.

3.2.4 Trace element characteristics

The Wulgai volcaniclastic rocks are enriched in the whole range of LIL elements including Rb, Sr and Ba and HFS elements including Nb, Zr and Ti except Y relative to average N-MORB (Sun and McDonough, 1989). Despite the fact the LIL elements have probably been modified by alteration these amounts are consistent with reported values of basaltic alkaline rocks (Tables 1 and 2). Multi-element diagrams are generally used to study the behaviour of incompatible trace elements in the rocks and to constrain their source regions, with reference to N-MORB, primordial mantle or any other tectonically important composition.

The incompatible trace element patterns of the Wulgai volcaniclastic rocks exhibit variable enrichment in a range of trace elements (including LIL and HFS) relative to N-MORB and primordial mantle; however they have lower Y than the N-MORB (Fig. 4a). The patterns exhibit marked positive anomalies on Nb, which further confirms derivation from an enriched mantle source (Kerr et al., 2010; Pearce, 1982).

When normalized to Oceanic Island Basalt (OIB) the Wulgai volcaniclastic rocks samples show a slight depletion in LIL elements, while HFS elements remain almost parallel to OIB suggesting a source identical to OIB (Fig. 4b). These volcaniclastic is much more similar to those of the Bibai volcanics found in Cretaceous Parh Group of the Indian Platform sediments (e.g., Mahoney et al., 2002). Compatible elements in these rocks are generally variable and low in Cr (0–248 ppm), Ni (9 ppm–77 ppm) and Co (18 ppm–41 ppm) (Table 1).

4 DISCUSSION

4.1 Magma Chamber Processes

The rocks contain 2.9 wt.%–4.8 wt.% MgO and so they can be classed as relatively low-MgO basalts and as such they have doubtless undergone a considerable degree of fractionation in

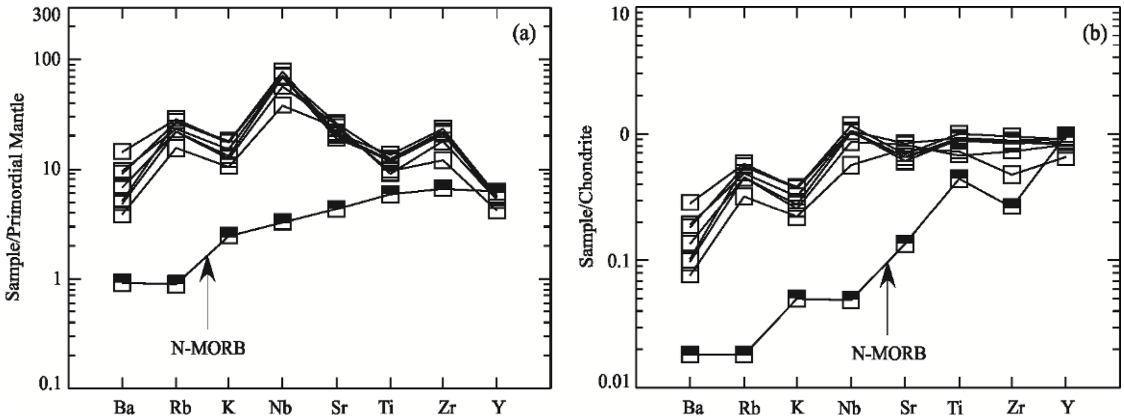

Figure 4. Multi-element diagrams of the Wulgai volcaniclastic rocks from Balochistan, Pakistan. (a) Primordial mantle-normalized; (b) Oceanic islands-normalized. Average N-MORB and normalization values are after Sun and McDonough (1989).

magma chambers en route to the surface. Low Ni and Cr contents (7 ppm–55 ppm and 0.2 ppm–63 ppm, respectively) indicate that significant amounts of olivine and Cr-spinel have fractionated from the Wulgai magmas. The slight negative anomalies for Sr and, to a lesser extent, Ti on primitive mantle- and chondrite-normalised diagrams (Fig. 4) indicate that plagioclase and Fe-Ti oxide have also fractionated from the magmas, but to a much lesser extent than olivine. Clinopyroxene is also likely to have crystallised from these magmas, although based on the moderately high V contents (161 ppm–222 ppm) it was like plagioclase and Fe-Ti oxide not a major fractionating phase.

The lack of any negative Nb anomaly indicates that these magmas are unlikely to have been contaminated with continental crust en route to the surface. Similarly, the fact that Ba and Rb are not noticeably more enriched than other incompatible trace elements supports the contention that the magmas responsible for the Wulgai volcaniclastic rocks may have very little input from continental crust.

4.2 Nature of Parent Magma and the Source Region

As demonstrated earlier by Zr/TiO_2 versus Nb/Y plot (Fig. 3), the Wulgai volcaniclstic rocks are alkali basalts. The alkaline extrusive and intrusive rocks from the Indian Continent margin (Triassic–Cretaceous) sediments have already been reported by earlier investigators (e.g., Kerr et al., 2010; Mahoney et al., 2002; Ahmed et al., 1990).

The criteria generally used in support of basaltic rocks being primary melts of a mantle peridotite source rather than a product of fractionated liquids are: (a) the presence of mantle peridotite (lherzolite) xenoliths, (b) high magnesium number ($Mg^{\#}=100\times Mg/(Mg+Fe^{2+})$), (c) high contents of compatible elements (Ni, Cr and Co).

Basaltic magma derived from up and to 30% partially melted mantle peridotite source will have $Mg^{\#}$ in the range of 68–75 (Frey et al. 1978; Green 1976; Hanson and Langmuir 1978). Gill (1981) has suggested an $Mg^{\#}$=67, whereas Tatsumi and Eggins (1995) have documented $Mg^{\#}$>70 for primary basaltic magmas. Basalts with 250 ppm–300 ppm Ni and 500 ppm–600 ppm Cr contents are considered to be derived from a primary mantle source (Wilkinson and Le Maitre, 1987; Perfit et al., 1980). Likewise the Co contents in primary basaltic magma usually range from 27 ppm–80 ppm (Frey et al., 1978).

No mantle lherzolite xenoliths have been reported from any fragment of the Wulgai volcaniclastic rocks assemblage. The $Mg^{\#}$ (45–55), Ni (9 ppm–77 ppm), Cr (0–248 ppm) and Co (18 ppm–41 ppm) contents in the basaltic rocks of the volcaniclastics are well below those of putative primary mantle melts. It is therefore highly likely that the parent magma of these rocks was not directly derived from a primary mantle source but fractionated in en-route to eruption.

The marked positive Nb anomalies in the multi-element diagram (Fig. 4a) can be explained by the addition of this element in the magma source from the mantle plume (e.g., Arevalo and McDonough, 2010; Pearce, 1982). These volcaniclastic rocks have low Zr/Nb, Y/Nb and Ti/Zr ratios as compared to N-MORB (Tables 1 and 2) and these values are consistent with an enriched mantle source (lherzolite). The very low values Y/Nb ratios (0.46–0.70) suggest the presence of garnet in the source (e.g., Luo et al., 2016; Xiong et al., 2016; Ansari et al., 2011). This implies that garnet-lherzolite was the parent source of magma of these volcaniclastics.

In Table 2, average trace element chemistry of the Wulgai volcaniclastic rocks is compared with average N-MORB, E-MORB, OIB, Reunion hotspot, Bibai, Hawaiin and continental rift basalts from the Mount Kenya. The Wulgai volcaniclastic rocks are very similar to Bibai, Reunion, Hawaii and Mount Kenya basalts. Source diagnostic ratios (Floyd, 1991) including Zr/Y, Ti/Zr, and of Wulgai volcaniclastic rocks, Bibai, Reunion, Hawaii and Mount Kenya basalts are more or less similar (Table 2) and there is little evidence show that the magmas from which the Wulgai volcaniclastic rocks were derived were affected by crustal contamination en-route to eruption.

The Zr versus Zr/Y diagram (Fig. 5) provides useful information about the nature of source, degree of partial melting and fractionation and suggests that the parent magma of the Wulgai volcaniclastic rocks was generated by 10%–15% partial melting of an enriched source. The 0–2 Ma Reunion hotspot alkali basalts (e.g., Fisk et al., 1988) also plotted in the same field, suggesting not only a similar degree of partial melting of a similarly enriched mantle source but also a similar degree of fractionation for both the volcanic groups.

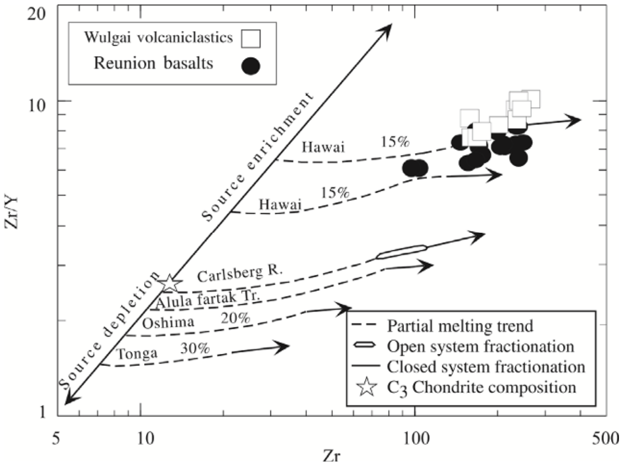

Figure 5. Zr versus Zr/Y plot (after Pearce and Norry, 1979) for the Middle Triassic volcaniclastic rocks from Wulgai. The basalts from Reunion hotspot (0–2 Ma in age) are also shown (Fisk et al. 1989).

4.3 Tectonic Setting

A number of plots and tectono-magmatic discrimination diagrams based on (HFS) elements are designed to study the parent magma and tectonic setting of the volcanic rocks. The plots of samples from the Wulgai volcaniclastic rocks on various tectono-magmatic discrimination diagrams (Fig. 6a: after Fitton et al., 1997, Fig. 6b: after Pearce and Cann, 1973, Fig. 6c: after Pearce, 1982, Fig. 6d: after Pearce and Gale, 1997, Fig. 6e: after Meschede, 1986 and Fig. 6f: after Verma et al., 2006) strongly confirm their within plate alkaline nature and oceanic island basalt (OIB) affinities. The presence of radiolarian chert and shales in the Wulgai succession are suggestive of a deep-water environment and perhaps indicate that the juvenile ocean basin was reasonably well-developed when these igneous rocks were erupted. Accordingly, the Wulgai volcaniclastic rocks may have formed part of a seamount in the opening Ceno-Tethys Ocean. The alkaline and enriched nature of the rocks rules out an oceanic plateau origin for these rocks, since oceanic plateaus are predominantly tholeiitic in composition (see review and discriminating characteristics in Kerr et al., 2014).

During Late Paleozoic to Early Mesozoic many continental blocks (micro-continents) were separated from the northern and northeastern passive margin of Gondwana. These continental blocks drifted towards north and accreted to the southern active margin of Eurasia (Metcalfe, 1995; Brookfield, 1993; Kazmin, 1991; Sengör et al., 1988). A network of ophiolitic sutures, mark the collision zones between these blocks and Gondwana. The Tethys Ocean that once existed between the Gondwana in south and Eurasia in north is further divided into three ocean systems, named; Paleo-Tethys, Meso-Tethys and Ceno-Tethys (Metcalfe, 1995; Brookfield, 1993). These three ocean systems are equivalent to Tethys-1, Tethys-2 and Tethys-3 of Boulin (1981), whereas Meso Tethys and Ceno Tethys correspond to Neo-Tethys of Sengör (1979).

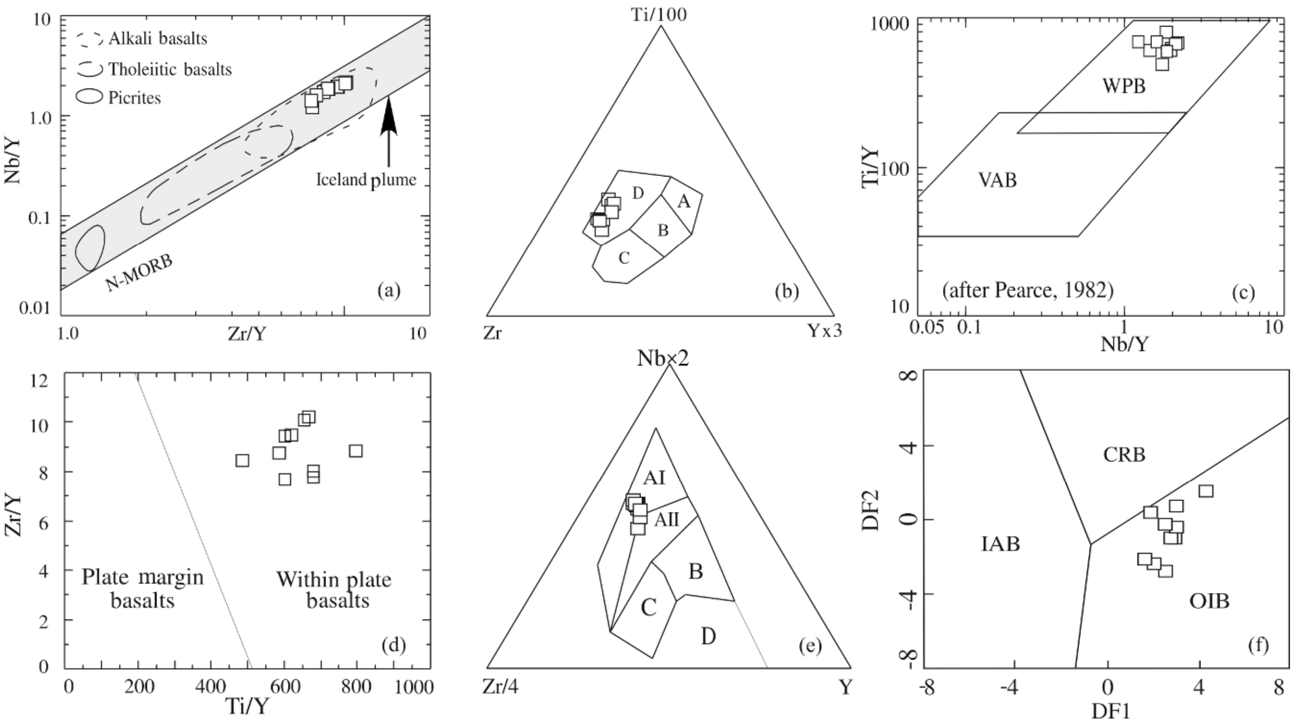

Figure 6. Various tectono-magmatic discrimination diagrams for the Wulgai volcaniclastic rocks from Balochistan, Pakistan. (a) Nb/Y–Zr/Y (after Fitten et al., 1997); (b) Zr–Ti (100)–Y×3 (after Pearce and Cann, 1973); (c) Ti/Y–Nb/Y (after Pearce, 1982); (d) Zr/Y–Ti/Y (after Pearce and Gale, 1977); (e) Zr/4–Nb×2–Y (after Meschede, 1986); (f) DF2–DF1 (after Verma et al., 2006). Key: In Fig. a, A=Island arc tholeiite, B=MORB+Island arc tholeiite, C=calc-alkaline basalts, D=within plate basalt. In Fig. e, AI=within plate alkalic, AII=within plate alkalic+within plate tholeiite, B=PMORB, C=volcanic arc basalt+NMORB+within plate tholeiite, D=volcanic arc basalt+NMORB.

Three main collages of continental blocks separated from the northern margin of Gondwana during Late Devonian to Late Jurassic and accreted with the southern margin of Eurasia during Permian to Eocene (Metcalfe, 1995; Brookfield, 1993). Separation, northward drifting and accretion of each collage of continental block were accompanied by opening and closing of these three successive oceans (Paleo-, Meso- and Ceno Tethys: Fig. 7). This complex network of accreted continents is known as Tethysides, which is further divided into Cimmirides and Alpides produced by Paleo and Neo-Tethys respectively (Sengör et al. 1988). The Alpides are also known as Alpine-Himalayan orogenic belt (Gansser, 1979). Triassic rifting of Alpide collage of micro continental blocks (Afghan, Iran, Karakoram and Lhasa) from the northern margin of the Gondwana, led to the opening of Ceno-Tethys (Fig. 7). It is suggested that the Middle Triassic intra-plate volcanism, reported in this paper and elsewhere) may represent the earliest mantle plume activity related to this Late Triassic rifting (Brookfield, 1993; Metcalfe, 1995) from the northern margin of the Gondwana (Fig. 8).

The Middle Triassic to Eocene history of Ceno-Tethys ocean floor, Indian Continent and Indian Ocean floor is illustrated in Fig. 8 which is based on the earlier research by Boulin (1990, 1988), Sengör et al. (1988), Stöcklin (1989), Treloar and Christopher (1993), Brookfield (1993), Metcalfe (1995), Zaman and Torii (1999), Siddiqui et al. (2012) and Rehman et al. (2011). Figure 8a proposes that Middle Triassic Wulgai volcanism was accompanied by early rifting of the Afghan Block (a part of the Alpides) from the northern margin of Gondwana and subduction of Paleo-Tethys below Eurasia (Turan Block). This was followed by Late Triassic rifting of the Afghan Block, closure of Paleo-Tethys and suturing of Farah Block with Eurasia (Turan), (Zaman and Torii, 1999; Metcalfe, 1995; Brookfield, 1993; Boulin, 1990, 1988; Stocklin, 1989; Sengör et al., 1988; Fig. 8b). Initial rifting of India from Gondwana and inception of intra-oceanic convergence in the Ceno-Tethys occurred in the Mid-Jurassic (Fig. 8c). The rifting of India from Gondwana continued into the Early Cretaceous, along with suturing of the Afghan Block with Eurasia, intra-oceanic convergence in Ceno-Tethys and subduction of Ceno-Tethys below the Afghan Block (Fig. 8d). Obduction of the Muslim Bagh Ophiolite and associated mélange zone along with slivers of Ceno-Tethys Ocean floor and allochthonous blocks of Wulgai volcaniclastic rocks on to the north-western margin of the Indian Plate commenced in the Late Cretaceous (Fig. 8e). Finally, the north-western margin of the Indian Plate (on which was accreted the Wulgai volcaniclastic rocks) collided with the Afghan Block in 50–35 Ma (e.g., Green et al., 2008; Aitchison et al., 2007; Naka et al., 1996; Fig. 8f).

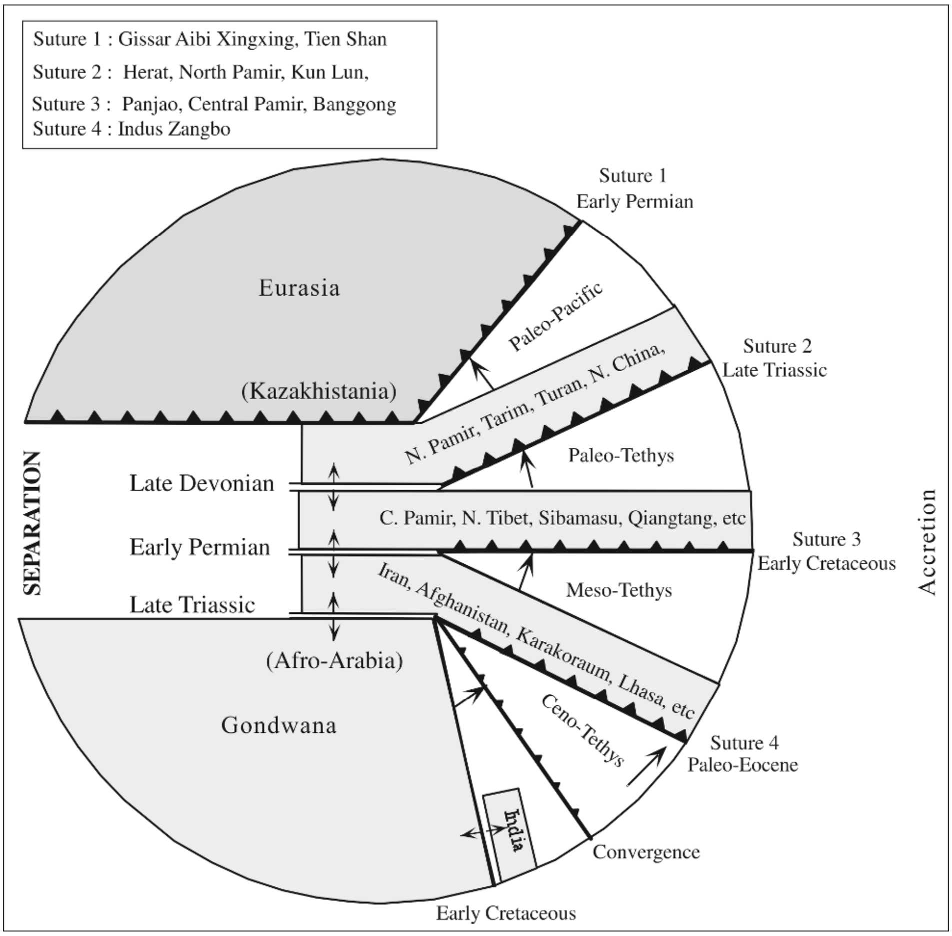

Figure 7. Schematic diagram showing the tectonic history of South Asia (modified after Siddiqui et al., 2012; Naka et al., 1996). The separation and accretion ages of the continents are after Brookfield (1993) and Metcalfe (1995).

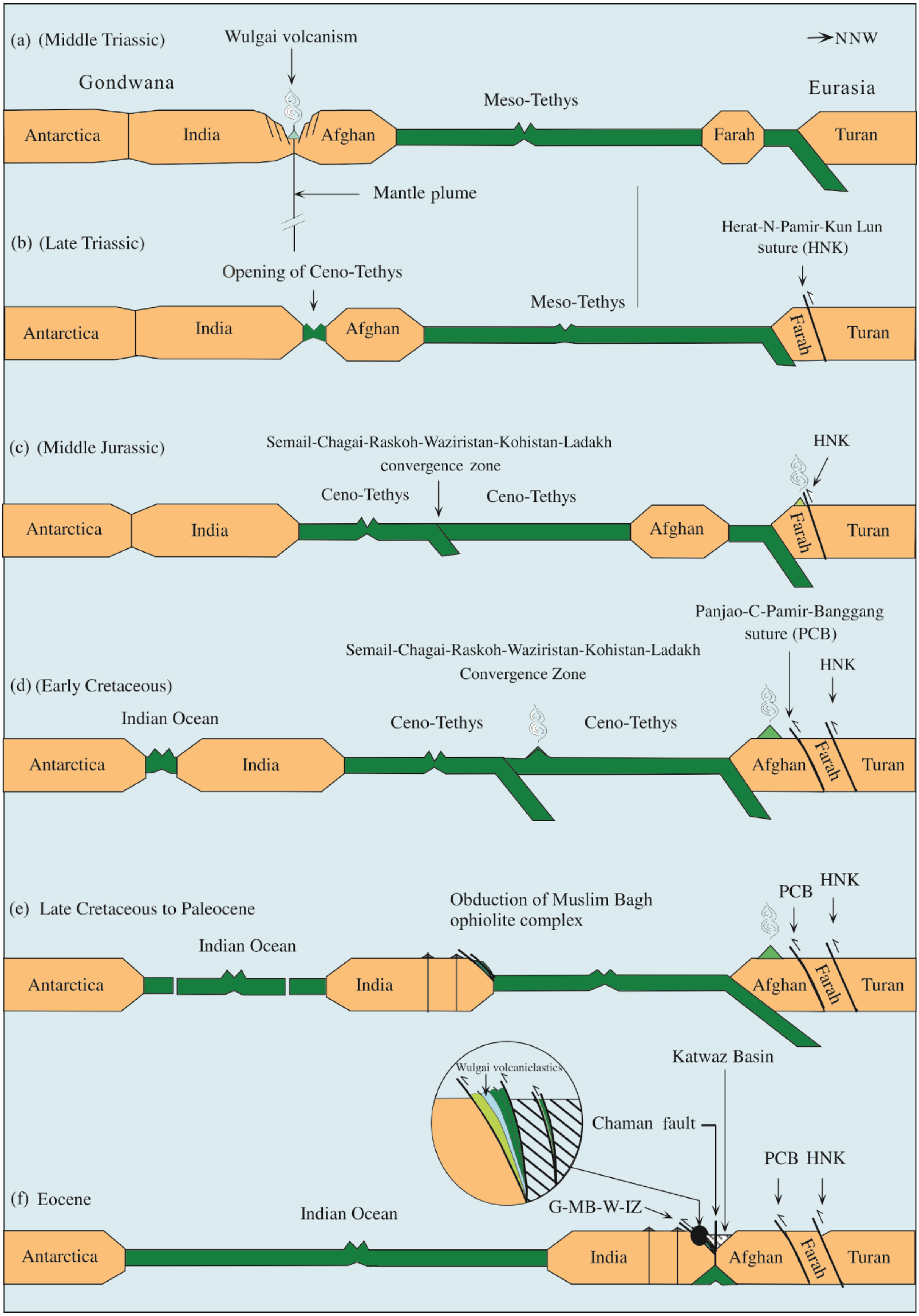

Figure 8. Tectonic reconstructions showing the Middle Triassic to Pliocene history of Ceno-Tethys Ocean floor, Indian continent and Indian Ocean floor (based on the data from Siddiqui et al., 2016, 2012; Rehman et al., 2011; Zaman and Torii, 1999; Metcalfe, 1995; Brookfield, 1993; Treloar et al., 1993; Boulin, 1990, 1988; Stöcklin, 1989; Sengör et al., 1988).

5 CONCLUSIONS

The petrogenetic study of the Middle Triassic volcaniclastic rocks strongly suggests that these rocks belong to mildly to strongly alkaline intra-plate volcanic rock series.

The parent magma of these rock suites was generated by about 10%–15% partial melting of an enriched mantle source. Their low $Mg^{\#}$ and low Cr, Ni and Co contents suggest that the parent magma of these volcaniclastic rocks were not primary mantle melts but fractionated in an upper crustal magma chamber, en-route to eruption.

It is suggested that this Middle Triassic intra-plate volcanism may represent mantle plume activity related to the Late Triassic rifting of micro-continental blocks including Afghan, Iran, Karakorum and Lhasa from the northern margin of the Gondwana.

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