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Hybrid Mafic Dykes from Delwara Shear Zone, Mt. Abu, NW India

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Abstract: Mafic dykes intrude the composite Mt. Abu granite batholith as a minor and the last phase of magmatism. The dykes are sub-vertical, variable in width and visibly compact, however, features of alteration and shearing can be seen. The dykes occurring within the recently identified and described, Delwara Shear Zone (DWSZ), from the western margin of the Mt. Abu batholith are intensely to moderately sheared and intricately mixed with the host granitoids. The mafic dykes occurring within the shear zone bear evidence of assimilating the host granitoids during their ascent, seen as relicts, streaks and sub-rounded K-feldspar clasts in mafic dykes. The hybridization has resulted in unusual geochemical signatures of the mafic dykes such as higher silica levels, erratic and high incompatible trace element abundances and lack of any systematic trends. Mixing line calculations on the mafic dyke samples reveal between 30 to 60% felsic input into the mafic dykes. Mafic dykes outside the shear zone in the Mt. Abu are meter scale in width and generally free of felsic inclusions owing to small volumes of mafic melts. Large volume of mafic melts are required for assimilating up to 60% felsic component which has been identified as approximately 100 m wide zone within the DWSZ. Shearing has played an important role in providing the channel ways and for sustained high temperatures to allow such hybridization.

Keywords: Mafic dykes, Delwara Shear Zone, Geochemistry, Hybridization, Mixing line calculation, Mt. Abu, Rajasthan.

INTRODUCTION

Mt. Abu, the highest elevation in the Aravalli mountain region in NW India, is a granitic batholith located in the southwestern part of Rajasthan state (Fig. 1). It is a composite granitic body with two megascopically distinguishable textural variants (gneissic and mildly deformed ones) that show further variations within each group. The granites were intruded by rhyolitic dykes during the later stages of granite emplacement while the terminal phase of magmatism is represented by the intrusion of mafic dykes. The Mt. Abu granitoids were conventionally described as part of the post-Delhi Erinpura granite suite (Heron 1953; Gupta et al., 1997), however, in a recent study, de Wall et al. (2012) have proposed grouping of Mt. Abu granitoids (all textural varieties) with the Malani magmatism on the basis of close geochemical similarities. This contention has further been substantiated by Ashwal et al. (2013) who reported 965 ±5 Ma (zircon; U – Pb) ages for both the textural variants of Mt. Abu granites, placing them coeval with the Malani Igneous Suite (770 – 750 Ma, (Torsvik et al., 2001; Gregory et al., 2009). The granites and rhyolitic dykes of Mt Abu were earlier studied by Singh and Joshi (2005) and Singh (2007) who provided general geochemical characteristics. Mafic dykes occur all over the Mt Abu batholith but have not been studied so far, probably on account of being volumetrically insignificant petrologic/magmatic entity. This paper focuses on the mafic dykes occurring within the Delwara Shear Zone (DWSZ), a high strain zone recently described by de Wall et al. (2012) from the western periphery of Mt. Abu. The mafic dykes in the DWSZ have conspicuous lighter colour index as compared to the mafic dykes elsewhere in the batholith and also have unusual presence of sub-rounded K-feldspar xenocrysts. The geochemical characteristics of DWSZ mafic dykes have been studied and the possibility of these features being a result of hybridization effect of assimilation of granite host has been evaluated and discussed in this paper. Relative proportion of felsic input in individual sample has also been estimated using mixing calculations.

NEOPROTEROZOIC TECTONOMAGMATISM IN SW RAJASTHAN

The Grenvillian (1 Ga) subduction event and associated collision of Marwar and Bundelkhand–Aravalli cratons mark the initiation of Neoproterozoic tectonics in NW India,

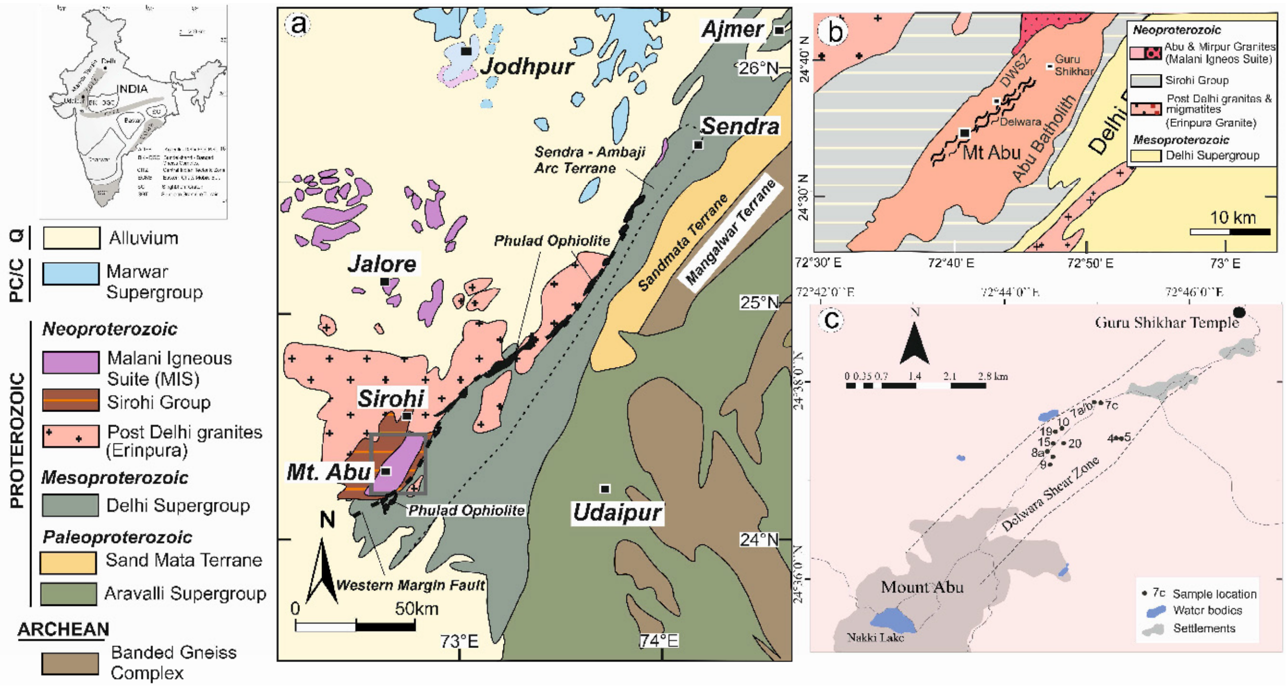

Fig.1. (a) Simplified lithostratigraphic map of the Aravalli-Dehli Fold Belts within the tectonic framework of NW India (adapted from Heron, 1953; Gupta et al., 1997). The box refers to the area in 'b'. **(b)** Map showing geological setting of Mt. Abu and surrounding areas. The Delwara Shear Zone (DWSZ) is indicated in the map. **(c)** Map showing sampling sites within the DWSZ. Sample numbers tied to Table 1. In addition, map of India showing major Precambrian terranes and tectonic features is also shown.

with well documented ophiolite development along the suture (Phulad Ophiolite Suite – Gupta et al., 1997), calc-alkaline rhyolites (990±6 and 987±6.4 Ma -Deb et al., 2001) and granites (968 ±1Ma – Pandit et al., 2003) along a linear zone in the Sendra – Ambaji sector (Fig. 1). This collision also initiated the deformation of the Mesoproterozoic Delhi sediments, described as the Delhi orogeny. A late-orogenic magmatic event with respect to the Delhi orogeny is known as Erinpura Granite (Heron, 1953) that is manifested in granite emplacement in the southern segment of the Delhi fold belt and further west in the Marwar craton. The Erinpura granite encompasses variably deformed granitic bodies emplaced during the 873 – 800 Ma time span (Choudhary et al., 1984; van Lente et al. 2009, Just et al 2010, Pradhan et al., 2010).

The 770 – 750 Ma (Torsvik et al., 2001; Gregory et al. 2009), predominantly felsic Malani magmatism (Malani Igneous Suite, MIS e.g. Bhushan and Chandrasekharan, 2002) covers a large part of the Marwar terrane in south-western Rajasthan (Fig. 1). This magmatic event began with outpouring of predominantly felsic (at places bimodal) lavas (rhyolite and ignimbrite) followed by emplacement of peraluminous (Jalore type) and peralkaline (Siwana type) granites. The granite emplacement was followed by the intrusion of cogenetic felsic dykes while the terminal magmatism is marked by intrusion of mafic dykes and dyke swarms. Geological considerations and paleomagnetic data allow grouping of mafic dykes with the main Malani magmatic event (Bhushan, 1995; Gregory et al., 2009). This contention has also been confirmed in a recent study by Meert et al. (2013) who proposed 752 Ma (zircon U – Pb) age for mafic dykes from a site east of Jodhpur. The MIS represents a distinct and younger magmatic event as compared to the Erinpura granite which is well supported by the field observations, such as the rhyolitic dyke (MIS) intrusions into Erinpura granite at Siyana (40 km NW of Sirohi) and Balewa (NW of Barmer; Pandit et al., 1999).

The Mt. Abu Batholith

Located along the southwestern margin of the Delhi Fold Belt, the NE trending, oblong, Mt. Abu batholith (~125 km^2) marks the eastward extension of the MIS (Fig. 1). The batholith comprises peripheral granite gneiss (augen gneisses) component and compact pink granite occurring in the central part. Gupta et al. (1997) described the pink granite as 'undeformed', and on this notion, correlative with the Malani Igneous Suite while the deformed variety was associated with the Erinpura granite on account of deformation (gneissic fabric). The gneissosity is prominent in the western part of the batholith within the

NE-SW trending Delwara shear zone (de Wall et al., 2012). Based on similarities in magnetic fabric and geochemical characteristics between both deformed and undeformed granites, de Wall et al. (2012) inferred that both the granitoid types are comagmatic, related to a single thermal event and part of the Malani magmatism on account of close geochemical similarity with the peraluminous Jalore type granites of the MIS. Nearly concordant, 765 ± 5 Ma U – Pb ages of both Mt. Abu augen gneiss and pink granite further underline that the two varieties are coeval with the MIS (Ashwal et al., 2013). Rhyolitic dykes intrude the granite and represent a later phase of felsic magmatism in Mt Abu. Lobate contacts of these dykes with the host granites indicate dyke intrusion into still hot granitic magma. In contrast, mafic dykes have sharp contacts (Fig. 2a, b) with the host granitoids and also mark the terminal magmatic event in the Mt Abu batholith and the neighbouring Malani granites, e.g. the Mirpur Granite (de Wall et al 2010). The mafic dykes (~5 cm to ~3 m wide) are sub-vertical and show predominately NW-SE in the central and western parts and E-W in the northern part of the batholith. The dykes are dark greenish in colour and apparently massive (Fig. 2a). However, on a mesoscopic scale, these show features of shearing, alteration and development of thin laminations.

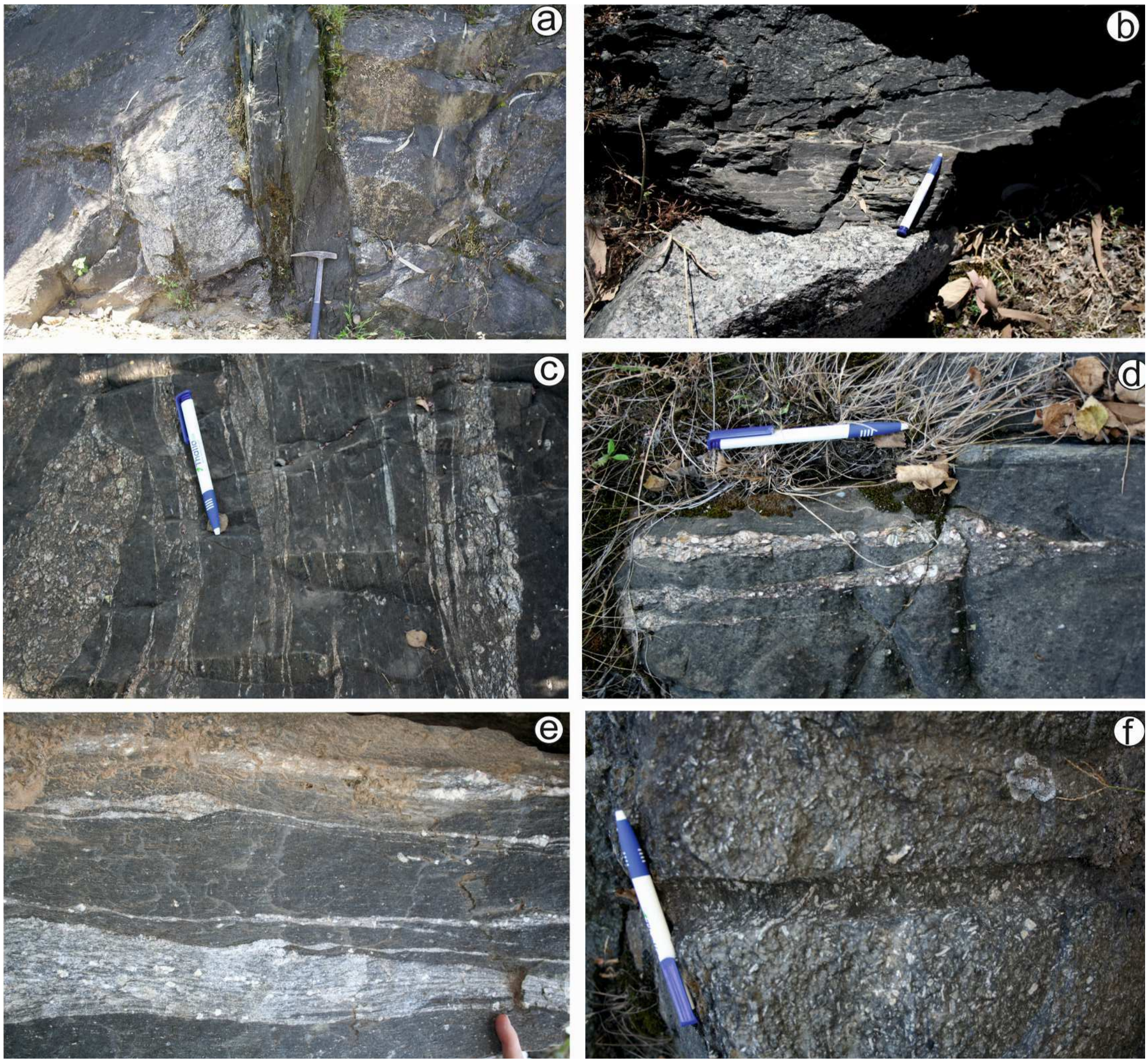

Fig.2. Field photographs showing megascopic features of the mafic dykes in Mt. Abu. **(a)** Mafic dyke from outside the DWSZ shown as an example of general appearance of mafic dykes in Mt. Abu. **(b)** Mafic dyke from DWSZ showing a sharp contact with the host granite and shearing effect. **(c)** Lit par lit intrusion of mafic dykes into the granite in the DWSZ. **(d)** Felsic interfolial fold within mafic dyke showing shearing assisted assimilation. Remnant feldspar as clasts can be seen within the mafic matrix. **(e)** Solid state deformation of felsic and mafic bands in high strain zones of the DWSZ. **(f)** Mafic dyke showing magmatic fabric and disseminated mafic components in a less strained region of the DWSZ.

Table 1. Geochemistry of mafic dykes from the Delwara Shear Zone in Mt. Abu showing major oxides as wt % and trace elements in ppm. Major oxides and some trace elements (V, Cr, Co, Ni, Zr, Sr and Rb) were analyzed by XRF while rest of the trace elements and Rare Earth Elements were analyzed by ICP-MS. Some important elemental ratios are also given. Sample locations given in Fig. 1c.

	Ma6-19*	Del-4	Del-5*	Del-7a*	Del-7b1*	Del-7b2	Del-8a	Del-9*	Del-10
SiO_2	50.3	59.4	60.4	59.3	51.3	53.2	57.7	59	54.5
TiO_2	2.52	1.44	1.92	1.13	1.38	1.75	2.01	1.93	2.22
Al_2O_3	15.72	15.06	13.23	13.44	19.43	15.54	13.44	14.74	14.17
Fe_2O_3	12.11	7.14	10.08	12.78	9.16	12.94	11.21	9.06	10.65
MnO	0.17	0.12	0.14	0.25	0.16	0.22	0.16	0.12	0.15
MgO	4.13	2.03	1.76	0.49	1.32	1.55	1.9	2.1	3.11
CaO	7.34	7.21	3.8	3.97	7.66	4.86	4.78	3.8	5.22
Na_2O	3.14	3.8	2.35	3.84	4.31	3.37	2.77	3.29	2.56
K_2O	2.75	1.82	4.77	2.06	2.54	3.55	4.47	4.00	3.83
P_2O_5	0.57	0.33	0.7	0.36	0.92	0.95	0.78	0.51	0.57
LOI	0.97	0.74	0.74	1.18	1.25	1.29	0.42	0.84	2.72
Total	**99.6**	**99.0**	**99.9**	**98.7**	**99.4**	**99.2**	**99.6**	**99.4**	**99.7**
Trace elements (in ppm)									
Sc	30.8		22.23	46.28	24.43				
V	190	162	121.5	9.92	33.8	24	154	140	165
Cr	89	36	19.28	6.05	7.11	2	7.93	27.9	51
Co	43	21	18.25	5.02	9.76	14	24.2	22.3	28
Ni	15	21	13.2	19.95	7.76	5	39.8	29.4	9
Ga	30	30	32.5	36.18	31.3	30	31.3	29.1	22
Rb	188	71	283.75	119.25	87.5	125	265	280	227
Sr	235	266	181	151	519.25	303	179	170	226
Y	48.9	50	54	127.25	59.4	96	71.1	50.2	60
Nb	19.2	15	27.1	73.15	29.85	34	30.9	21.3	21
Ba	434	319	1153	577.75	899.25	1458	938	574	666
La	48.9		68.73	116	58.9				
Ce	100		127.75	248.75	127.25				
Pr	12.3		15.13	31.25	16.43				
Nd	52.2		64.05	131.25	71.9				
Sm	11.5		13.05	28.13	15.33				
Eu	3		3.25	5.78	5.65				
Gd	10.8		12.33	26.95	13.95				
Tb	1.5		1.8	4.09	2				
Dy	9.9		10.83	26.83	12.28				
Ho	1.9		2.12	5.25	2.31				
Er	5.4		5.65	14.65	5.98				
Tm	0.8		0.8	2.19	0.83				
Yb	5		5.13	14.38	5.57				
Lu	0.7		0.76	2.12	0.83				
Hf	9.1		13.8	54.13	15.08				
Ta	1.4		1.38	4.2	1.69				
Pb	16	27	29.93	20.15	11.43	19	45.7	29.5	26
Th	11.3	47	11.35	19.05	5.96	9	24.2	24.7	25
U	0.8	5	1.01	3.49	0.96	3	3.3	1.82	4
Zr	369	264	566	2039	570	935	543	378	370
Nb/La	0.39		0.39	0.63	0.51				
Th/La	0.23		0.17	0.16	0.10				
Nb/U	24.00	3.00	26.83	20.96	31.09	11.33	9.36	1.82	5.25
Nb/Th	1.70	0.32	2.39	3.84	5.01	3.78	1.28	0.86	0.84
(La/Sm)N	2.75		3.40	2.66	2.48				
(Tb/Lu)N	1.46		1.61	1.31	1.64				

In the DWSZ the mafic dykes are sheared and intricately mixed with the host granites (Fig. 2b-e). Localized high strain zones show features of partial assimilation of sheared granite and presence of sub-rounded K-felsdspar clasts while still-preserved magmatic fabric can be seen in the dykes in relatively low strain areas (Fig. 2f). Megascopic features indicate assimilation of variable proportions of host granitoids during shearing assisted dyke intrusions. These dykes were sampled south of Guru Shikhar across the DSWZ along an approximately 1 km transect, representing good rock exposures in the widest part of the shear zone. Sample locations are shown in the Fig. 1c.

Geochemistry of Mafic Dykes i n the Delwara Shear Zone

Whole rock major and some trace element compositions (V, Cr, Co, Ni, Zn, Zr, Sr and Rb) were determined using fused pellets by X-ray fluorescence spectrometer (Philips 1480). Rare Earth Elements and some other trace elements (Nb, HF, Y, Ta, Sc, Th, Ga, Ba, Pb) were analysed using Thermo Elemental Inductively Coupled Plasma Mass Spectrometer (ICP-MS) at the GeoZentrum Nordbayern, Germany following Brätz and Klemd (2002). Geochemical data are presented in Table 1; reported accuracies are within 5% for major and trace elements and up to 7% for REE.

Mafic dykes (Fig. 1c; Tab. 1) within the shear zone, show a significant and unusual spread in silica content (50.3 to 60.4%) and some other major oxides. Notable variations, considering the limited areal extent of samples, are seen in MgO (0.49 to 4.13%), K_2O (1.82 – 4.77%) and CaO (3.97-7.66%) that show multifold variations within the total data set. The trace element variations are even more conspicuous (Table 1). The Zr (264 – 935 ppm with a lone sample having 2039 ppm), Y (48.9 to 127) and Nb (15 to 30.9 ppm) concentrations are highly variable and significantly higher than expected for the magmatic rocks with equivalent silica levels. Such geochemical characteristics cannot be explained through any known magmatic process. In the conventional geochemical discrimination schemes these rocks would classify as basalt to basaltic andesite to andesite, on account of SiO_2 content ranging between 50.3 and 60.4%. Even in the relatively immobile elements based Zr/TiO_2 – Nb/Y classification scheme majority of samples erroneously plot in the andesite field and few straddle across the andesite – rhyodacite – rhyolite fields.

To evaluate geochemical variations further, some critical major oxides and trace elements were plotted against Zr which is a relatively immobile element that can be used as proxy for fractionation process (Fig. 3). The sample with anomalously high Zr (Del 7a; Zr = 2039 ppm) was excluded. The diagram shows absence of systematic variations in major

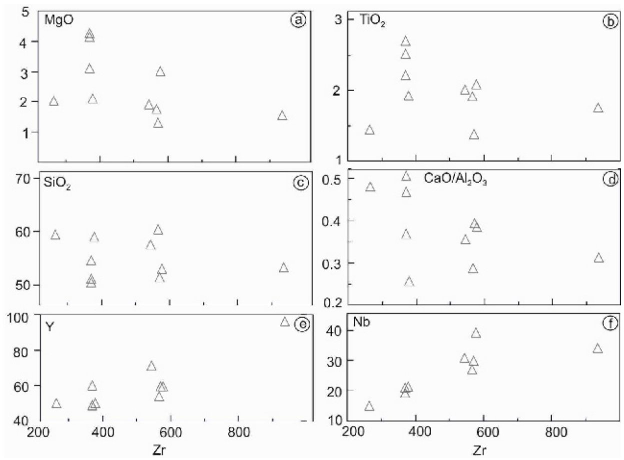

Fig.3. Bivariate plots showing geochemical characteristics of some major and trace elements in relation to Zr. Major oxides (SiO_2, TiO_2, MgO, CaO and Al_2O_3 are shown as wt% while Zr, Y and Nb are in ppm.). Note a general lack of systematic trends in major oxides (a-d) and feeble covarianve in case of trace elements (e-f).

oxide phases (MgO, TiO_2, SiO_2 and CaO/Al_2O_3) although some inverse correlation can be seen (Fig, 3 a-d). Both Y and Nb show much higher abundances for the given silica levels and some positive correlation with Zr (Fig. 3 e, f).

Multi-element spider diagrams are useful in providing an overview of the trace element behaviour and can be interpreted in terms of source characteristics and process. The primordial mantle normalized (Sun and McDonnough, 1989) spider diagram patterns for the sheared dykes (Fig. 4a) are consistent and indicate their derivation from a common source and process. Fields of mafic dyke samples from outside the shear zone have also been shown on the diagram for comparison. The spiderplots indicate prominent negative anomalies for Nb, Sr and Ti and peaks for Zr and La, which are typical crustal signatures. Incidentally, the patterns for the samples outside the shear zone also show similar characteristics but with relatively lower enrichment and depletion levels. The enhanced trace element abundances can be attributed to input from granite host with high trace element concentrations (de Wall et al., 2012).

The chondrite normalized REE diagram (normalization data after Sun and McDonnough, 1989) for the mafic dykes from the shear zone show significant LREE enrichment (La ~ 200 to 500 times chondrite), moderate LREE slopes $[(La/Sm)_N$ between 2.5 and 3.4] and relatively depleted HREE with sub-horizontal to slightly concave upwards HREE slopes (Fig. 4b). Moderate to small negative Eu anomaly is seen except in sample Del 7a. The LREE enriched patterns indicate a source rich in incompatible elements while negative Eu anomalies suggest plagioclase removal.

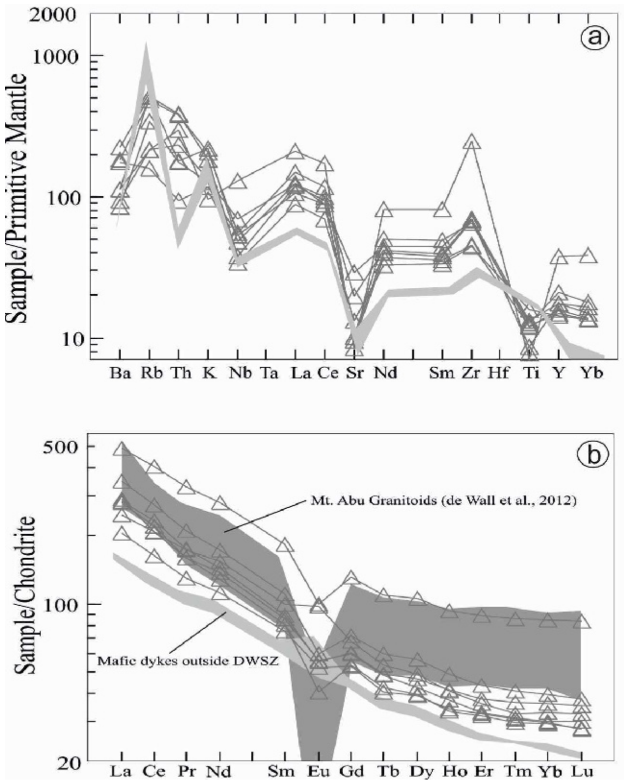

Fig.4. (a) Primordial mantle normalized (after Sun and McDonnough, 1989) multi- element spiderplots showing negative Nb, Sr and Ti anomalies and prominent peaks for Zr and Rb (typically crustal features) in the mafic dykes from DWSZ. **(b)** Chondrite-normalized (after Sun and McDonnough, 1989) REE diagram for mafic dykes from DWSZ showing significantly LREE enriched and rather flat HREE patterns with moderate to low negative Eu anomalies. Field for the mafic dykes from outside the shear zone (type Mt. Abu) and Mt.Abu granitoids (de Wall et al., 2012) are also shown as potential end members.

The LREE enriched patterns and moderate to high Ce/Yb ratios suggest either an enriched lithospheric mantle source or a result of assimilation of crustal rocks. The light REE are truly incompatible and thus only La/Ce ratio is likely to be diagnostic of the source composition (Wilson, 1989; Torres-Alvarado et al., 2003). The trends for Mt Abu granitoids (de Wall et al., 2012) and dyke samples outside the shear zone have also been shown onto the diagram. We envisage that the observed REE patterns in the mafic dykes from shear zone can be produced by mixing variable proportions of the two end members (granite and mafic dyke composition from outside the shear zone).

Considering the field observations, such as variable degree of assimilation of granitic host during dyke intrusion and concomitant shearing, presence of K-feldspar and albitic clasts within mafic dykes, the geochemical signatures can be interpreted in terms of hybridization resulting from assimilation of granitic host by the rising mafic melts. Nonlinear and erratic geochemical relationships rule out any fractionation or partial melting process. To validate this contention the samples were subjected to Mixing line test and the results are discussed in the following section.

Mixing Test

Mixing Test (as detailed in Castro et al., 1990) was performed on the mafic dyke samples from DWSZ to evaluate the mixing of granitic material and to quantify the fraction of felsic input. The mixing test is based on the assumption that the end-member compositions for felsic and mafic rocks have mixed in variable proportions to give rise to the hybrid types. For mixing test the average composition of Mt. Abu granitoids (N = 9; de Wall et al., 2012) was considered as the felsic end-member while mafic dyke AB_20 with high MgO and low SiO_2, located outside shear zone, was considered as the mafic end-member. The difference in the individual major oxide values between felsic and mafic end members was calculated for each sample (*see* Castro et al., 1990, for details) and the results are shown in Table 2. The calculated values were plotted against the difference between hybrid and mafic end members that

Table 2. Calculated difference in the individual major oxide values between felsic and mafic end members for the hybrid type mafic dykes

	mean granite	mean dyke Ab_20	mixed - mafic									felsic-mafic
			Del 4	Del 5	Del 7b1	Del 7a2	Del 8a	Del 9	Del 10	Del 11	Ma6_19	
SiO_2	73.30	39.50	19.90	20.90	19.80	13.70	18.20	19.50	15.00	13.40	10.80	33.80
TiO_2	0.25	2.56	-1.12	-0.64	-1.43	-0.81	-0.55	-0.63	-0.34	-0.47	-0.04	-2.31
Al_2O_3	12.52	13.74	1.32	-0.51	-0.30	1.80	-0.30	1.00	0.43	2.81	1.98	-1.22
Fe_2O_3	2.46	14.89	-7.75	-4.81	-2.11	-1.95	-3.68	-5.83	-4.24	-4.32	-2.78	-12.43
MnO	0.04	0.22	-0.11	-0.08	0.03	0.00	-0.06	-0.10	-0.07	-0.06	-0.05	-0.18
MgO	0.16	7.00	-4.97	-5.24	-6.51	-5.45	-5.10	-4.90	-3.89	-3.99	-2.87	-6.84
CaO	0.97	8.27	-1.06	-4.47	-4.30	-3.41	-3.49	-4.47	-3.05	-1.91	-0.93	-7.30
Na_2O	3.04	1.17	2.63	1.18	2.67	2.20	1.60	2.12	1.39	2.66	1.97	1.87
K_2O	5.61	6.23	-4.41	-1.46	-4.17	-2.68	-1.76	-2.23	-2.40	-3.38	-3.48	-0.62
P_2O_5	0.05	0.53	-0.20	0.17	-0.17	0.42	0.25	-0.02	0.04	-0.06	0.04	-0.48

result in a linear array of data points. The slope of the regression curve defines the relative proportion of the felsic component. The mixing test shows that the mafic dykes from the Delwara shear zone have assimilated between 30 and 60% felsic component (Table 3). The data show good to moderate R^2 values, ranging between 0.86 and 0.98. Regression curves for the samples Ma_6_19 and Del_5, which show the lowest (30%) and the highest (60%) calculated felsic input, respectively, are shown as examples for data evaluation and interpretation (Fig. 4a,b).

Interpretation and Conclusions

Mafic dykes in the Mt. Abu are generally basaltic in composition with alkaline to sub-alkaline affinity, however, geochemical characteristics of dykes from the DWSZ do not represent features resulting from crystal fractionation. These characteristics seem to be derived by incorporation of variable proportions of host granite, which has imparted erroneously 'intermediate' geochemical signatures to these samples. The SiO_2 content ranges from >50 to ~60% in dykes from the DWSZ in contrast to <50% for those outside the shear zone. This can be explained through assimilation of felsic material (granitic host) which has been estimated to range between 30 and 60%. The mafic dykes in the Mt. Abu region in general are up to meter scale in width, which would cool rather quickly and therefore not capable of assimilating such large proportions of felsic material as that would require much larger volumes of mafic melt. Approximately 100 m wide zone of intense shearing has been identified in the DWSZ where such large volume of the mafic melt was channelized through the shear planes and a relatively high temperature was maintained by ongoing shearing to facilitate digestion of significant volumes of the granitic host. Partly digested remnants of the granite could still be seen as streakes, enclaves and sub-rounded feldspar clasts within sheared mafic dykes. Hybridization of mafic melt is reflected in geochemical signatures which lack any systematic trend. We rule out the possibility of mafic and felsic magma mixing on account of rheological incompatibility between the two. The mafic dykes were emplaced under high temperature conditions, and coupled with the low viscosity, were capable of assimilating the granitic hosts. Mafic dykes represent the terminal magmatic activity in the Mt Abu following the emplacement and crystallization of granite. The age data on some analogous mafic dykes from the Malani Igneous Suite show a time gap of ~15 million years between granite emplacement and mafic intrusions in other parts of the MIS (Meert et al., 2013). This leads to two possible interpretations; (i) the time gap between granite and dyke intrusion was smaller than seen elsewhere in the MIS in general or (ii) the eastern corridor of the MIS (Mt. Abu – Sirohi region; de Wall et al., 2014) remained tectonically active for a much longer period.

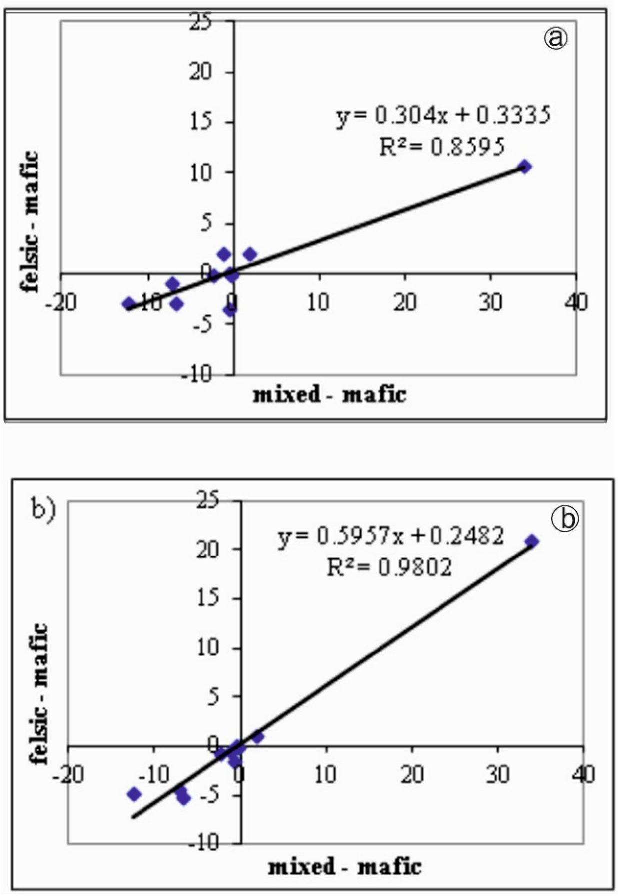

Fig.5. Regression curves showing results of Mixing Tests (after Castro et al., 1990) for the mafic dyke samples a) Ma_6_19 and b) Del_5, samples showing the least and the maximum felsic input, respectively, among the DWSZ mafic dykes. X-axis: difference of mixed and mafic-magma, Y-axis: difference of felsic and mafic magma.

Table 3. Estimated felsic component (in %) for individual mafic dykes from DWSZ. The correlation coefficient (R^2) and slope of the regression curve are also given

Sample	R^2	Slope	Felsic component (%)
Del_4	0.9331	0.5815	58
Del_5	0.9802	0.5957	60
Del_7b1	0.8989	0.5556	56
Del_7a2	0.8791	0.3933	39
Del_8a	0.9664	0.5154	52
Del_9	0.9778	0.5699	57
Del_10	0.9690	0.4350	44
Del_11	0.8901	0.3916	39
Ma6_19	0.8595	0.3040	30

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