Mafic rocks from Erinpura gneiss terrane in the Sirohi region: Possible ocean-floor remnants in the foreland of the Delhi Fold Belt, NW India

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A small isolated mafic body occurs to the south of Sirohi near village Daba within the Neoproterozoic Erinpura Granite in the southern sector of the Proterozoic Delhi Fold Belt in NW India. This mafic body occurs close to a 100 m wide NE–SW trending shear zone (Daba Shear Zone) which overprints the felsic rock fabrics. Further south, a small mafic body near village Kui was also sampled which forms the southern limit of the Phulad Ophiolite Suite which is a 300 km long major NE–SW trending lineament, described as Western Margin Fault. Some of the lithological components of the Daba mafic body show locally preserved magmatic fabric but completely transformed mineralogies under lower amphibolites facies metamorphic conditions where two-stage deformation has been inferred. Magnetic fabric analysis underlines a general correspondence of structural elements in both felsic and mafic lithologies. Binary correlations of Zr with other high field strength elements underline fractionation as the main process in the evolution of Daba and Kui rocks. Geochemical characteristics indicate subalkaline tholeiitic basalt affinity for these mafic rocks. The trace element characteristics, such as enriched LIL elements, high Th, absence of negative Nb anomalies and depletion in compatible elements in Daba samples suggest an enriched mantle source and lower degree of melting. The trace and rare earth element characteristics for Kui (Th anomaly, Nb–Ta trough and less spiked patterns, flat REE trends) indicate derivation from a refractory mantle source affected by fluids derived from subduction. Distinct differences in trace and REE characteristics between Daba and Kui can be interpreted in terms of different stages of ophiolite development.

1. Introduction

The NW Indian terrane archives a well-documented record of Precambrian geology, from Archean basement and overlying Proterozoic Fold Belts (Gupta *et al* 1997) to the Eocambrian Marwar Basin (Pareek 1984; Pandit *et al* 2001) (figure 1a). The oldest rock unit in this region

is the 3.3 to 2.5 Ga Banded Gneiss Complex which forms the basement for the Proterozoic supracrustal Aravalli and Delhi fold belts (Roy and Kröner 1996; Wiedenbeck *et al* 1996). These Proterozoic sequences have undergone green-schist to amphibolite facies metamorphism and show evidence of multiple deformation episodes between 1.8 and 1.4 Ga (Roy and Jakhar 2002). The southern

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Figure 1. (a) Simplified geological map of NW India showing major Precambrian units and ophiolite occurrences along the Western Margin Fault (WMF). Map adapted from Heron (1953), Gupta *et al* (1980), Roy and Jakhar (2002) and Just *et al* (2011). (b) Lithostratigraphic map (adapted from Roy and Sharma 1999) showing occurrence of the Daba mafic body within Erinpura granite terrane around Sirohi (SW Rajasthan). Sampled section along NW–SE traverse is also shown.

sector of the Delhi Fold Belt (DFB) represents a Grenvillian age (~ 1 Ga) arc terrane which also corresponds with the period of amalgamation of crustal blocks to form the Rodinia supercontinent (Dalziel 1991; Meert and Torsvik 2003; Li *et al* 2008). The western margin of the DFB is defined by a linear zone of ductile shearing (Ghosh *et al*

1999), named as Western Margin Fault (WMF) which is interpreted as a Proterozoic suture (Gupta *et al* 1980).

Occurrence of isolated outcrops of mafic–ultramafic rocks (peridotite – gabbro–pyroxenite, gabbro–norite, anorthosite and sheeted dykes) along a 300 km long and 20–50 km wide zone

along the WMF further substantiate the status of this lineament as a major structure (suture zone?). These mafic-ultramafic rocks have been identified as remnants of 'ophiolite', named as Phulad Ophiolite Suite (POS – Gupta *et al* 1980). The Sm–Nd isochron age of 1024 ± 78 Ma (Volpe and Macdougall 1990) for the Ranakpur diorites from the POS is in general agreement with coeval arc magmatism in this terrain (987 ± 6 Ma, Deb *et al* 2001; 968.3 ± 1 Ma, Pandit *et al* 2003). The WMF, also called Phulad Shear Zone in this southern sector of Delhi Fold Belt, is characterized by distinctly vertical stretching lineations (Ghosh *et al* 1999) and the kinematics is identified as a transpressional setting (Sengupta and Ghosh 2004). This fault zone also bears evidence of reactivations, however, their timing has not been constrained so far (Biswal *et al* 2004; Sarkar and Biswal 2005). The terminal stage of Delhi orogeny is marked by felsic magmatism [late syn- to post-orogenic granites and granodiorite, named 'Erinpura Granite' (Heron 1953)], ubiquitous in the southern sector of the Delhi Fold Belt and its western foreland. The Erinpura Granite is an ensemble of variably deformed granite and granite gneisses (Gupta *et al* 1997) which bears evidence of anatexis and shearing (Just *et al* 2011). The Erinpura thermal event is also noted as isotopic resetting in the ophiolites and Delhi Fold Belt arc sequences (Volpe and Macdougall 1990).

Within the Erinpura granite terrane, a small mafic body occurring to the south of Sirohi town was reported by Roy and Sharma (1999) from the village Daba (figure 1b). This isolated mafic

body is juxtaposed to a NE-trending shear zone (Daba Shear Zone) within the Erinpura granite terrain. The Daba mafic rocks, for which no petrographic or geochemical data are available so far, occur to the west of the reported mafic-ultramafic rocks of the Phulad Ophiolite Suite (Gupta *et al* 1980). Geochemical characteristics of the Phulad mafic rocks identify them as ocean floor and low-K tholeiites (Volpe and Macdougall 1990; Khan *et al* 2005). The Daba mafic rocks are genetically unrelated to the Erinpura Granites or the Delhi Supergroup metasediment hosts. These mafic rocks need to be evaluated for petrogenetic aspects and for a possibility whether they represent remnants of an ocean floor, analogous to the Phulad Ophiolite Suite exposed in the same Neoproterozoic terrane.

We have studied the area around Daba in the southern Delhi Fold Belt (figure 1a, b) and the results are presented in this paper. The aim of the paper is:

- to infer the deformation kinematics of the shear zone in Daba and its relationship with mafic and felsic rocks through geological characterization, and
- geochemical evaluation of the mafic rocks from Daba and Kui for petrogenetic interpretation and possible correlation with POS.

For this purpose we have sampled the Daba Shear Zone ($24^{\circ}50.459'E$: $72^{\circ}51.061'E$) along a NW–SE traverse and documented the field data (figures 1b, 2). In addition, mafic rock samples from Kui

Figure 2. Map showing sample locations and orientations of structural elements in the studied section across the Daba Shear Zone (DBZ). (a) Foliations, and (b) lineations.

(24°27. 696'N: 72°48.205'E) representing the southern part of POS (Biswal *et al* 2004; Khan *et al* 2005) were also collected and analyzed for comparison with the Daba mafic rocks.

2. The Daba mafic body

The Daba mafic body is traceable over a distance of 3 km within the Erinpura Granite terrane in the south of Sirohi (figure 1b, see also Roy and Sharma 1999). The 860–830 Ma Erinpura Granite terrane (Choudhary *et al* 1984; Just *et al* 2011) was uplifted after the Delhi orogeny and formed the basement for sedimentation of pelitic and carbonate sequences of the Sirohi Group (figure 1b). The age of these sediments is not properly constrained; however, they are overlain by volcano-sedimentary sequence called Sindreth Group in which felsic volcanics have been precisely dated at 767 Ma (zircon U–Pb) by van Lente *et al* (2009). Erinpura Granite and Sirohi Group rocks share a common deformation history, characterized by NE–SW trending foliations and map-scale fold structures in the so called ‘Sirohi Belt’ (Roy and Sharma 1999). Shear bound slivers of Sirohi Group taper towards the south, however, the southern boundary is not well defined due to sand cover and lack of rock exposures. In SE continuation of the Sirohi belt some outcrops can be seen to the east of village Daba (south of Sirohi) where a >100 m wide zone with NE–SW trending vertical foliations has been identified as a shear zone and named as Daba Shear Zone (DSZ).

We undertook a NW–SE traverse (figures 1b, 2) beginning with coarse grained non-sheared Erinpura

granite-gneiss through its sheared and mylonitized counterparts. The non-sheared granite-gneiss shows incipient migmatitization and localized anatexis (figure 3) as compared to large-scale partial melting seen in the area further north-east (Just *et al* 2011). At the contact between sheared Erinpura Granite (felsic mylonites) and Daba mafic body, a thin band (few dm) of garnet mica-schist occurs.

Figure 3. Field photographs showing fabric transformation of host anatectic Erinpura granite gneiss into mylonitic and ultra-mylonitic shear fabrics in the Daba Shear Zone.

Figure 4. (a) Daba mafic rock showing alternate plagioclase-rich and hornblende-rich bands defining a pronounced foliation. (b–c) Photomicrographs showing features of shear deformation that can be used to infer the kinematics of the shear zone; (b) sigmoidal fabrics and development of shear planes in mafic and felsic parts; and (c) asymmetric wings indicating synkinematic recrystallisation of hornblende clasts during shearing.

The Daba mafic rocks show megascopic variation from massive to foliated types wherein the generally steep foliations show meter-scale anastomosing pattern around the more rigid massive parts. Cm-scale features of intense shearing are seen only in the feldspar-rich parts. In the sheared felsic rocks subhorizontal stretching lineations (figure 2b) are defined by elongated quartz and feldspar grains. Shear-induced rotation of porphyroclasts and development of s-c fabrics have been considered for kinematic analyses of the shear movement. These features are seen in the felsic mylonites and ultramylonites as well as in the feldspar-rich zones within the mafic rocks (figure 4a). There kinematic analysis identifies the shear zone as a zone of dextral strike-slip movement. Deformation conditions can be inferred from the microstructures and stability of mineral phases present. Major mineral phases in the felsic mylonites are plagioclase, K-feldspar, quartz and biotite. Feldspar is often fractured and shows features of low-temperature plasticity, such as undulose extinction, furthermore deformation twinning and marginal recrystallisation (core-mantle structures) have been recognized. Deformation induced exsolution (perthitic structures) can be seen in K-feldspar. Quartz is completely recrystallized through a predominant subgrain rotation. Stretching lineations are also locally seen in the sheared feldspar-rich parts of mafic rocks. This is marked by the tails of recrystallized hornblende (figure 4b, c). Earlier formed brownish-green hornblende, with fine inclusions along the cleavage planes and larger inclusions of sphene, is seen recrystallizing into clear green hornblende during deformation (figure 4c). Asymmetric tails of newly formed green hornblende indicate shear facilitated recrystallization. Stability of biotite in felsic and green hornblende in mafic rocks indicate deformation under lower amphibolite facies metamorphic conditions.

Massive, non-sheared parts of the Daba mafic rocks show gabbroidic appearance and locally a megacrystic type is seen (figure 5a). This variety consists of large (cm size) equigranular, megacrysts (>75%) of hornblende set in a groundmass consisting of sericitized plagioclase, hornblende and epidote (figure 5b). Relict pyroxene cores mantled by hornblende, allow its nomenclatures as meta-pyroxenite. Hornblende is also present as the main mineral in the medium- and fine-grained types. The Daba mafic rocks comprise hornblende, chlorite, actinolite, sericitized plagioclase and epidote, indicating obliteration of primary magmatic mineralogy. Two stages of alteration can be inferred from petrographic analysis. In the first stage sericitization of plagioclase and transformation of pyroxene into green-brown hornblende occurred. An overprint under retrograde temperature conditions

Figure 5. (a) Photograph of meta-pyroxenite showing equigranular, subhedral mafic minerals set in a finer-grained felsic rich groundmass. (b) First stage alteration in Daba metapyroxenite seen as alteration of pyroxene into green-brown hornblende. Relict pyroxene can still be seen. (c) Transformation of brown-green hornblende into actinolite during second stage of alteration.

during the shear deformation is indicated by the synkinematic growth of inclusion-free green hornblende which marks the second stage of deformation. This later stage of retrogression under the influence of fluids was, most likely, channelized along the shear zone.

Figure 6. (a) Field photograph showing magmatic appearance of mafic rocks at Kui. (b) Photomicrograph of Kui mafic rock showing thermally equilibrated hornblende grains during amphibolites facies metamorphism.

In Kui area, further south, the mafic rocks occur as minor bodies within the metasediments of Delhi Supergroup rocks and both the sediments and the mafic rocks have been co-folded during subsequent deformation and metamorphism (Biswal *et al* 2004). The samples from Kui show magmatic appearance, locally with gabbroidic texture (figure 6a) and have completely transformed mineralogy which is now represented by hornblende and sericitic plagioclase. The mineral grain boundaries are straight (figure 6b) indicating thermal re-equilibration under amphibolite facies metamorphism generally recorded in this part of the DFB. These rocks do not show any evidence of shearing or second stage alteration which is prominently seen in Daba rocks.

The felsic and mafic rocks do not show a coherent pattern in the orientation of structural elements (foliation, lineation); in the latter these features are hardly detectable (figure 2a, b). The mafic rocks show more random orientations as compared to well-defined foliation in the felsic rocks in the shear zone. The plunge of lineations in the shear zone is sub-horizontal while it is highly variable (5° to 62°) in case of mafic rocks. The magnetic fabric orientations (anisotropy of magnetic susceptibility–AMS) (Hrouda 1982, 1993; Borradaile and Henry 1997; de Wall *et al* 2001) were analyzed to substantiate the structural data and for a better evaluation of the DSZ in terms of relationship between mafic rocks and the shear overprint.

3. Magnetic fabric characteristics

For the AMS analyses, oriented hand samples were collected in the field and were drilled in the lab for standard cylinders (2.5 cm in diameter and 2.1 cm

in height). Seven samples from the mafic and eight samples from the felsic rocks were analyzed. The AMS data are provided in table 1. The method uses the directional difference in induced magnetization for fabric characterization. Magnetic susceptibility is measured in low AC-fields (in 300 A/m, 920 Hz) where a linear relationship between magnetic field and magnetization is realized. AGICO kappabridge KLY-4S was used for the measurements, which is of high sensitivity (10^{-8} SI) and determines the AMS by measurements in 64 positions for each of three orthogonal sections of the sample. These measurements are used for calculation of the 2nd order tensor of magnetic susceptibility, expressed by an ellipsoid with orthogonal principal axes $\kappa_{\max} > \kappa_{\text{int}} > \kappa_{\min}$.

The Daba felsic rocks (Erinpura Granite) have low magnetic susceptibility (53 to 330×10^{-6} SI) wherein paramagnetic mica is the predominant magnetic phase. The bulk magnetic susceptibility for the mafic rocks is generally higher and in the range of 300 to 18200×10^{-6} SI. Most of the samples are paramagnetic with hornblende as the predominant magnetic phase while a contribution of ferri-magnetic phase, identified as magnetite, is seen in the sample D/15 (table 1). The principal axes of the AMS ellipsoids were plotted in the Schmidt net projection. The long axis of the AMS ellipsoid, $\kappa_{\max}$, is referred to as the magnetic lineation while the short axis, $\kappa_{\min}$, indicates the pole of the magnetic foliation. Further details about the method are given in Tarling and Hrouda (1993). The magnetic fabrics in the felsic rocks reflect a preferred orientation of mica (i.e., biotite) whereby the magnetic lineation is mainly related to the rotation of mica laths around stretched clasts (Siegesmund *et al* 1995). In the mafic rocks, the magnetic lineation is in the direction of the hornblende mineral

Table 1. Volume susceptibility (κ_{mean} in 10^{-6} SI units) and magnetic fabric orientation of felsic and mafic rocks from the Daba Shear Zone. Declination (Dec) and Inclination (Inc) of the magnetic lineation (κ_{max}) and pole to magnetic foliation (κ_{min}) are listed. For location of samples please refer to figure 2.

Specimen	κ_{mean}	Dec κ_{max}	Inc κ_{max}	Dec κ_{min}	Inc κ_{min}
Mafic rocks					
D-1-1	301	166	46	71	4
D-1-2	364	165	57	72	2
D-1-3	322	349	19	81	4
D-11-2	254	19	11	288	8
D-11-2-1	255	17	9	108	2
D-11-2-2	297	19	27	287	5
D-12-1	566	242	14	148	17
D-12-2	574	252	30	155	12
D-13-1	612	206	4	113	30
D-13-1	609	207	7	114	30
D-13-2	658	224	22	128	15
D-14-1	975	57	22	307	40
D-14-2	1007	53	20	304	41
D-14-3	978	39	15	296	39
D-15-1	18220	220	3	314	46
D-15-2	7777	41	9	307	21
D-15-3	1021	220	1	119	86
D-16-1	904	284	51	25	9
D-16-2	939	293	15	25	6
Felsic rocks					
DA-1-2-1	170	32	12	301	7
DA-1-2-2	150	33	11	302	7
DA1-1	166	212	10	120	12
DA1-2	149	214	31	116	13
DA1-3	154	216	27	119	14
D-3B-1-1	269	248	76	138	5
D-4-1-1	333	221	62	313	2
D-4-1-2	223	228	51	325	5
D-4-2-1	275	237	28	147	2
D-4-2-2	266	232	42	139	3
D-5-1	53	215	4	120	46
D-5-2	59	22	7	119	45
D-5-3	70	26	3	118	41
D-6-1	87	22	15	112	1
D-6-2	71	23	7	113	2
D-7C-1	92	37	18	127	1
D-7C-2	85	34	24	128	9
D-7D-1	99	207	57	305	5
D-7D-2	106	209	69	302	2
D-9-1	81	207	10	298	7
D-9-2	95	26	2	296	5
SR11-1	75	12	2	103	27
SR11-2	90	188	7	94	24

lineation which has also been reported from some other settings (e.g., de Wall *et al* 2001). The magnetic fabric can be interpreted as preferred growth of hornblende grains during fabric recrystallization under the applied stress.

Magnetic foliation and magnetic lineation for mafic and felsic rocks of the Daba Shear Zone are compared in figure 7 in which κ_{max} as well as κ_{min} show a grouping and indicate predominantly NE–SW trending foliations and subhorizontal to moderately

Figure 7. Comparison of magnetic foliations and lineations in the felsic and mafic rocks in Daba Shear Zone. Orientation of magnetic fabrics in Schmidt net projection for the two rock types (sheared Erinpura Granite and mafic rocks). (a) Presentation of foliation, and (b) lineation parameters. Squares: $\kappa_{\max}$, triangles: κ_{int} , dots: $\kappa_{\min}$.

Table 2. Major (wt% oxide) trace and rare earth element (in ppm) analyses of the Daba and Kui mafic rocks. Major elements analyzed by XRF; trace elements for D-14, Py and Kui – 3 by XRF and trace and REE for the rest by ICP-MS. Some critical elemental ratios are also presented. Amph: amphibolites, MG: meta gabbro, MetPx: meta pyroxenite.

	Daba							Kui		
	D-1B	D-12	D-14	D-15	D-16	PY	Db-2	Kui-1	Kui-2	Kui-3
	Amph	Amph	MG	Amph	Amph	MetPx	MetPx	Amph	Amph	Amph
Oxides (wt%)										
SiO ₂	55.60	49.50	41.70	39.80	42.60	45.50	45.40	44.30	46.00	44.50
TiO ₂	1.04	1.14	2.68	2.95	1.99	1.91	1.73	1.71	1.20	1.72
Al ₂ O ₃	11.66	9.01	10.78	12.48	16.28	9.24	15.54	15.61	12.29	15.83
Fe ₂ O ₃	9.38	8.30	13.70	15.41	13.39	10.05	9.29	13.71	15.83	13.68
MnO	0.15	0.17	0.21	0.20	0.23	0.17	0.15	0.20	0.23	0.19
MgO	7.78	12.51	11.11	10.33	6.70	11.69	7.96	7.56	9.55	7.44
CaO	8.39	16.49	15.76	14.86	12.35	18.31	13.61	13.05	12.10	12.53
Na ₂ O	4.54	1.15	1.79	1.76	2.99	1.64	2.39	1.68	1.45	1.75
K ₂ O	0.71	0.39	0.98	1.07	1.57	0.50	1.00	0.47	0.49	0.63
P ₂ O ₅	0.13	0.15	0.73	0.90	0.82	0.20	0.13	0.27	0.03	0.32
LOI	0.64	1.21	0.78	1.03	1.09	0.49	2.10	0.87	0.80	1.22
Sum	100.02	100.02	100.22	100.79	100.01	99.70	99.30	99.40	99.90	99.80
Trace elements (in ppm)										
Ni	105	102	66	49	41	133	104	57.9	82.1	55
V	200	283	384	488	321	392	324	398	377	376
Cr	292	436	81	51	73	217	74	261	438	329
Co	39	41	59	53	40	47	48	45.3	53.8	53
Ga	18	14	14	16	40	12	17	14.2	15.7	17
Zr	103	114	132	147	162	121	154	166	76	102
Sr	572	589	639	942	1559	506	1024	129	75.8	134
Rb	12	14	10	8	43	6	28	11.8	12.7	28
Sc	26	76	–	41	30	70	–	49.3	40.7	–
Y	15	14	37	28	26	21	23	39.5	27.6	50
Nb	28	15	27	23.4	33	15	18	4.21	4.44	7
Ba	331	349	706	637	685	342	402	129	100	194
Hf	2	1.9	3	3.1	2.5	2.9	–	2.68	1.8	–
Ta	4.3	0.8	5	1.3	1.5	0.9	–	0.29	0.21	–
Pb	3.5	6.6	<4	2.9	6	3.6	–	3.39	2.89	–
Th	5.7	1.1	<2	1	1.7	0.5	–	0.58	0.65	–
U	5.7	0.4	–	0.1	0.4	0.1	–	0.18	0.18	–

Table 2. (Continued).

	Daba							Kui		
	D-1B	D-12	D-14	D-15	D-16	PY	Db-2	Kui-1	Kui-2	Kui-3
	Amph	Amph	MG	Amph	Amph	MetPx	MetPx	Amph	Amph	Amph
Rare Earth Elements (in ppm)										
La	15.7	17.2	25	38.3	48.3	20.4	–	12.7	12.4	–
Ce	33.4	38.1	–	88.4	102	50.5	–	25.7	20.9	–
Pr	3.7	5	–	11.9	12.7	6.9	–	3.3	2.5	–
Nd	14.6	20.7	–	52	51.3	29.6	–	14.9	10.5	–
Sm	2.9	4.3	–	9.8	8.5	6	–	4.3	3.1	–
Eu	0.8	1.3	–	2.9	2.6	1.9	–	1.4	1.2	–
Gd	2.5	3.5	–	7.9	6.5	5.3	–	5.7	3.7	–
Tb	0.4	0.4	–	1.1	0.9	0.7	–	1.0	0.6	–
Dy	2.5	2.9	–	6.2	5.3	4.4	–	7.3	5.0	–
Ho	0.5	0.6	–	1.2	1.1	0.9	–	1.6	1.0	–
Er	1.5	1.3	–	2.8	2.7	2.2	–	4.7	3.1	–
Tm	0.3	0.2	–	0.4	0.4	0.3	–	0.7	0.5	–
Yb	2.1	1.2	–	2.3	2.4	1.9	–	4.8	3.2	–
Lu	0.3	0.2	–	0.3	0.3	0.3	–	0.7	0.5	–
ΣREE	81.2	96.9		225.5	245	131.3	0	88.6	68.3	
Nb/Y	1.87	1.07	0.73	0.84	1.27	0.71	0.78	0.11	0.16	0.14
Zr/Nb	3.68	7.60	4.89	6.28	4.91	8.07	8.56	39.43	17.12	14.57
Th/Yb	2.71	0.92	–	0.43	0.71	0.26	–	0.12	0.20	–
Sc/Y	1.73	5.43	–	1.46	1.15	3.33	–	1.25	1.47	–
CaO/Al ₂ O ₃	0.72	1.83	1.46	1.19	0.76	1.98	0.88	0.84	0.98	0.79

plunging lineation in both the lithological units. However, for the mafic rocks, the magnetic fabric axes are more scattered than in the felsic ones. This is the most pronounced pattern for magnetic foliation. While the $\kappa_{\min}$ axes for felsic rocks yield a well defined cluster to indicate parallel, vertical NE–SW trending foliations, flat to vertical projections of the magnetic foliation poles are realized in the mafic rocks. Two samples (D/1 and D/16), which are from the westernmost part of the sampled area in Daba (figure 2) plot as an outlier and show clear variance in the foliation and lineation orientation (table 1). The magnetic fabric analysis further substantiates that both the rock types have undergone the same shear deformation. Strain is concentrated in the quartzo-feldspathic rocks and structures in the mafic rocks are more variable and partially cryptic in nature.

4. Geochemistry

4.1 Analytical methods

We have analyzed seven mafic rock samples from the Daba Shear Zone and three from Kui area (figure 1a). Major oxides and some trace element compositions (Cr, Co, Ni, Zn, Zr, Sr and Rb) were measured on fused pellets by Philips PW 2400

X-ray fluorescence spectrometer. Rare earth elements and some other trace elements (V, Nb, HF, Y, Ta, Sc, Th, Ga, Ba, Pb) were analyzed by Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA ICP-MS), at the GeoZentrum Nordbayern, University of Erlangen, Germany. For ICP-MS analysis each pellet was ablated five times along ~ 900 μm long lines with a repetition rate of 20 Hz, a crater size of 40 μm and a scan speed of 40 $\mu\text{m/s}$. The laser energy was 0.51–0.71 mJ (~ 40 – 56 J/cm² energy density) following the method prescribed in Brätz and Klemm (2002). Reported accuracies are up to 5% for major and trace elements and up to 7% for rare earth elements. For loss on ignition (LOI) estimation, the dry sample powders were heated in an oven for eight hours and the difference in mass was calculated as the ‘volatiles’ or LOI. The geochemical data on Daba and Kui mafic rocks are given in table 2.

4.2 Major and trace element geochemistry

The Daba mafic rock samples show a large variation in SiO₂ which ranges from 39.8 to 49.5% except sample D1b, which has anomalous high value of 55.6%. The high silica content is most likely a result of fine felsic intercalations (thin feldspar-rich bands) present in the sample. TiO₂

Figure 8. Geochemical discrimination of Daba and Kui mafic rocks (major oxides as wt% and trace elements as ppm). (a) SiO_2 – Zr/TiO_2 diagram (Winchester and Floyd 1977) showing classification as sub-alkaline basalt. (b) Y–Zr discrimination diagram (Barrett and MacLean 1994) showing well defined tholeiitic affinity (high Y/Zr) for Kui samples while Daba samples are transitional to slightly calc-alkaline. (c) TiO_2 – Y + Zr – Cr trilinear diagram showing tholeiitic trend for Daba and Kui mafic rocks (trend lines after Davies *et al* 1979).

contents vary from 1.01 to 2.98% and MgO from 6.7 to 12.51%. CaO, Na_2O and K_2O contents are highly variable and range from 8.39 to 18.31%, 1.15 to 4.54% and 0.39 to 1.57%, respectively, which can be attributed to their variable mobilization during post-crystallization processes. Considering the moderate-to-high Fe_2O_3 contents, the rocks can be called as tholeiites to high Mg tholeiites. The Kui samples are more homogenous in terms of elemental concentrations such as SiO_2 (44.3 to 46%), TiO_2 (1.20 to 1.73%), MgO (7.44 to 9.55%), CaO (12.10 to 13.61%), Na_2O (1.45 to 1.75%) and K_2O (0.47 to

0.63%) and show some overlap with Daba samples. The Daba samples have moderate-to-high concentrations of HFS elements, such as Zr, Y and Nb, which vary from 103 to 162 ppm, 15 to 37 ppm and 15 to 27 ppm, respectively. Kui samples have similar Zr, higher Y and lower Nb abundances as compared to Daba rocks. Such distinctions are spelled out in significant differences in the critical trace elemental ratios (table 2).

Since the rocks are deformed and variably altered, some of the elements especially alkalis, alkaline earths and large ion lithophile elements may have been mobile and may not represent pristine compositions. Moderate to low LOI values (2.1 to 0.49%) preclude any large-scale alteration effect. In case of basic rocks the REE, HFSE (Ti, Zr, Y, Nb, Hf, P, Th, etc.) and transition metals (Sc, V, Cr) are considered generally immobile during low temperature alteration processes (Camire *et al* 1995; Kerrich *et al* 1998) and can be used for petrogenetic interpretations. Considering the stability fields of mineral assemblages it seems likely that the Daba and Kui rocks may have undergone up to lower amphibolite facies metamorphism. Therefore, the geochemical trends have been evaluated against Zr and only the relatively immobile elements have been considered for classification and petrogenetic interpretations. The Kui samples have low Nb/Y ratios (<1) and indicate tholeiitic affinity while Daba samples (~ 1) show a little overlap with alkaline rocks (Pearce and Gale 1977). The samples were plotted in the immobile elements based classification diagrams (figure 8). In the SiO_2 – Zr/TiO_2 classification diagram of Winchester and Floyd (1977) all the samples classify as sub-alkaline basalt except the sample (D1-B) which plots in the field for andesite on account of higher silica (figure 8a). In the Y–Zr discrimination diagram (Barrett and MacLean 1994) the Kui samples define a tholeiitic affinity (high Y/Zr) while Daba samples are transitional to slightly calc-alkaline (figure 8b). The tholeiitic character of the samples is clearly depicted in the TiO_2 –Y+Zr–Cr diagram of Davies *et al* (1979) where all the samples plot along a tholeiitic trend (figure 8c). This diagram is based on immobile elements and can discriminate tholeiitic and calc-alkaline trends analogous to conventional AFM diagram.

To understand the elemental behaviour during crystallization, some critical major and trace elements were plotted against Zr (figure 9), which is highly immobile and incompatible, and can proxy for MgO in evaluating fractionation process. Geochemical data for other areas of Phulad Ophiolite, from Phulad–Barr–Jetgarh sector (Volpe and Macdougall 1990) and for northern, central and southern sectors (Khan *et al* 2005, using complete dataset provided by the authors) are also shown

Figure 9. Bivariate diagrams showing behaviour of some critical elements against Zr in Daba and Kui mafic rocks. Normal fractionation trends are discernible in inverse correlation of Zr with Cr (a) and MgO (b) while a covariance is seen in Zr–TiO₂ (c) and Zr–Nb (d) pairs. The behaviour of Fe₂O₃ is erratic, however, a faint covariance with Zr can be seen (e). For comparison fields of Phulad–Barr–Jetgarh of Volpe and Macdougall (1990) and different sectors of Phulad Ophiolite Suite of Khan *et al* (2005) have also been shown.

as respective fields onto the bivariate plots (figure 9). Stray samples were not considered while drawing the fields for Volpe and Macdougall (1990) and Khan *et al* (2005). The Daba and Kui samples show a general correspondence with the Phulad–Barr–Jetgarh samples (figure 9a–e). Notwithstanding the alteration effects, the Daba and Kui samples define normal fractionation trends, demonstrated as inverse correlation between Zr–Cr (figure 9a), Zr–MgO (figure 9b) and covariance between Zr–TiO₂ (figure 9c) and Zr–Nb (figure 9d) pairs. Behaviour of Fe₂O₃ is rather erratic, although a faint covariance with Zr is discernible in case of Daba samples (figure 9e). A positive correlation between Zr and Y is already shown in figure 8(b). Such correlations of Zr with other elements indicate derivation of these rocks through fractional crystallization process. A regular decrease in CaO/Al₂O₃ with progressive fractionation

indicates that olivine and pyroxene were the main crystallizing phases (table 2).

The primitive mantle normalized multi-element spider diagrams for Daba mafic rocks show positive Ba anomaly, minor peak for Sm and negative anomalies for Th and Hf (figure 10a). The odd sample (D/16), however, shows higher abundance levels of LILE elements and peaks for Th and Ta. The Kui samples show much lower enrichment levels for LILE and LREE (~20) and flat patterns towards the compatible element end of the diagram (figure 10b). The patterns show peaks for LILE elements (K, Rb, Ba) and La, negative Th anomaly and characteristic Nb–Ta trough. Although, both the datasets show enrichment in LILE and LREE, notable differences in the enrichment levels, shape and pattern underline distinct source characteristics for the Daba and Kui samples. The Daba patterns show a similarity with the E-type MORB

Figure 10. Primitive Mantle normalized trace element and chondrite normalized REE diagrams for Daba and Kui samples (normalizing values after Sun and McDonnough 1989). Trace element spider-diagrams for Daba (a) and Kui (b) showing enrichment in LIL elements and Nb anomaly in Kui samples. Note higher levels of enrichment and slope towards compatible end members in case of Daba (a) while Th anomaly and Nb–Ta trough can be seen in case of Kui data (b). Chondrite normalized REE patterns for Daba (c) and Kui (d) samples showing distinct patterns. Note a significant LREE enrichment and fractionated pattern for Daba samples (c) while Kui samples define insignificant LREE enrichment and flat HREE pattern (d).

while Kui samples show continental signatures and patterns in calc-alkaline rocks (Wilson 1989). The differences are further outlined in the chondrite normalized REE patterns (figure 10c, d). The Daba patterns show steep slopes and significant LREE enrichment, indicated by La abundances 66 to 204 times the chondrite and $(\text{La}/\text{Sm})_{\text{N}} \sim 3$ to 3.5 (figure 10c). Absence of any noticeable Eu anomaly further supports the contention that plagioclase was not a major fractionating phase. Such patterns are clearly distinct from the N-MORB, which are characterized by LREE depletion. Although REE are generally immobile, crustal metamorphism and anatexis may lead to enriched LREE trends. Such a possibility seems unlikely in the light of observed negative Th anomalies because crustal melts would also result in associated Th enrichment. Although Kui samples have prominent Nb negative anomaly, in the absence of corresponding LREE enrichment, this can be regarded as an intrinsic characteristic and not related to any post-crystallization modifications. Depleted HREE $[(\text{La}/\text{Lu})_{\text{N}} 5.61 \text{ to } 17.25]$ patterns suggest garnet as a refractory phase in the source of these rocks. Residual garnet would result in HREE depletion due to their preferential retention (Wilson 1989). If partial melting is fairly extensive ($>10\%$) the REE should not be fractionated from each other during melting and therefore the elemental ratios of critical REE (La/Sm, La/Yb, Ce/Yb and La/Ce) should reflect the ratios in the mantle source (e.g., Rollinson 1993). However, only light REE are truly incom-

patible and thus only La/Ce ratio is likely to be diagnostic of the source composition (Wilson 1989; Torres-Alvarado *et al* 2003). The Kui REE patterns are almost flat with a minor LREE enrichment $[(\text{La}/\text{Sm})_{\text{N}} = 1.7 \text{ to } 2.4]$ and unfractionated HREE trends. Such patterns indicate relatively higher degree of melting as compared to the Daba samples.

5. Discussion and interpretation

The data presented in the preceding sections characterize the Daba mafic body as a shear bound (strike-slip kinematics) ensemble of mafic rocks with subalkaline affinity. The strain is highly localized within the felsic rocks (mylonitized Erinpura Granite) and in garnet mica schist along the contact with mafic body. Within the magmatic body the shear deformation is seen only at few places, especially in feldspar rich parts. This strain partitioning gives an overall unstrained appearance to the mafic rocks which generally do not show any field evidence of deformation. However, the magnetic fabric study has underlined a general correspondence of structural elements in both the lithologies and thus identifies the magmatic textures as shear relicts. Despite the preserved magmatic texture, both the Daba and Kui mafic rocks have completely transformed mineralogies. While in the Kui rocks a single stage fabric re-equilibration under amphibolite facies conditions is recognized, the Daba rocks

show at least two phases of fabric transformation (amphibolite facies and lower amphibolite to greenschist facies), wherein the second stage is related to the shear deformation.

Fluid mobilization during shearing and lower amphibolites facies metamorphism can potentially affect the geochemical characteristics including relatively immobile elements. Crustal fluids can induce prominent Nb negative anomalies. In the present case, the geochemical signatures do not seem to be significantly modified as shown in consistent REE patterns, absence of Ce anomaly (Polat and Hofmann 2003) and well-defined fractionation trends. Good binary correlations of Zr with other HFSE underline fractionation as the main process in the evolution of Daba and Kui rocks (figure 9). The Primitive Mantle normalized patterns for Daba and Kui are distinct from each other and show consistency within both the groups (figure 10a, b). Enrichment in LREE, K, Rb, Ba and Th and depletion in Nb are considered typical continental signatures, characteristic of oceanic or within plate settings which are enriched in incompatible elements (Wilson 1989). Such characteristics of Kui samples indicate a significant 'continental' signature. Such patterns can also result from interaction with subduction fluids, from sediment mixing or due to crustal fluids during metamorphism. The Daba rocks show much higher degree of LREE enrichment, however, any crustal input seems unlikely on account of prominent Th and Rb depletion and absence of any negative Nb anomaly. These features can be interpreted as inherited from an enriched lithospheric mantle source.

To evaluate possible contribution from mantle source and the subduction component, Pearce (1983), Pearce and Peate (1995) proposed M/Yb–Nb(Ta)/Yb plots where M is an incompatible element of interest. The diagrams are based on the assumption that subduction-related enrichment in 'M' would result in displacement of the data from the 'mantle array'. More recently, Pearce (2008) has demonstrated the suitability of Th–Nb and Ti–Yb plots in evaluating subduction/non-subduction character and melting depth and temperature, respectively. In these diagrams majority of ocean floor basalts plot within a diagonal MORB–OIB array in the Nb/Yb–Th/Yb plot. Daba and Kui samples plot in two distinct fields in this diagram (figure 11a), corresponding to E-MORB and N-MORB, respectively. The Kui samples are marginally displaced above the array while Daba samples plot along a dispersion axis oblique to the array. Such trends indicate a subduction or continental margin setting. In the TiO₂/Yb–Nb/Yb diagram, the N-MORB affinity for Kui and E-MORB for Daba are shown

Figure 11. Tectonic discrimination and source characterization of Daba and Kui mafic rocks (Pearce 2008). (a) Nb/Yb–Th/Yb, and (b) TiO₂/Yb–Nb/Yb diagrams showing distinct mantle sources for Daba and Kui samples.

(figure 11b) on account of higher Nb and TiO₂ abundances in the latter.

Differences in mantle source characteristics between Daba and Kui samples cannot be explained in terms of mantle heterogeneity which seems unlikely on such a micro scale. These characteristics, however, can be explained through different stages of ophiolite development as detailed in Shervais (2001). Most of the tectonic models for ophiolite formation and evolution propose that ophiolites generally form during early stages of subduction of oceanic lithosphere (Stern and Bloomer 1992; Shervais 2001). Mafic rocks of Phulad Suite are juxtaposed with shallow water sediments in the east followed by platform sediments and then continental slope sediments in the further east indicating gradual thickening of the crust from west to east and an eastward subduction (Khan *et al* 2005). We relate the development of Daba and Kui mafic rocks to this eastward subduction and

propose a model that envisages influx of fluids from the subducting slab into the mantle wedge to initiate melting of the lithospheric mantle to produce LILE enriched melts (Daba rocks). A lower degree of melting is also indicated by highly LREE fractionated patterns. This explains the E-MORB characteristics of Daba samples where enrichment can be related to the addition from fluids. Enrichment in LILE (K, Rb, Cs, Ba) and LREE and depletion in HFSE (Ti, Nb, Ta, Hf) in response to aqueous fluids expelled during subduction are common characteristics of subduction zone ophiolites (see Shervais 2001, for a review). Depletion in HFSE can be caused by larger fractions of partial melting. Further flow of new MORB-source asthenosphere into the wedge beneath the extending lithosphere would initiate melting of previously depleted, 'refractory', asthenosphere (stranded within the zone of melting) under increasing flux of subduction related fluids. Consequently the melts are strongly depleted in HFSE (Ti, Nb, Ta, Hf) and HREE compared to oceanic basalts. Large flux of slab-derived melts required to lower the solidus in the refractory mantle would also result in addition of LILE and LREE, reflected in LILE enriched and HFSE depleted patterns (Shervais 2001). The undifferentiated and flat REE patterns, anomaly for Th and Nb-Ta trough, etc., in Kui rocks can be explained through higher degree of melting of the 'refractory' asthenospheric mantle. This model also explains the Zr/Nb variability (table 2) between Daba and Kui samples, possibly resulting from selective enrichment in Zr. However, this model is valid for ophiolites not affected by post crystallization modifications. The $(\text{Gd/Yb})_n$ of ≥ 1 for Daba and Kui indicate that the mantle source was at a depth of garnet stability (Hirschmann and Stolper 1996).

Distribution of POS mafic-ultramafic rocks along the western margin and in the foreland of the DFB seems to be largely controlled by the major NE-SW trending shear system of the WMF. The Daba Shear Zone shows a similar structural trend and also marks the southern extension of a bundle of shear zones that have been recognized in the Sirohi area (Roy and Sharma 1999). On a larger scale this shear system is most likely a consequence of late-Neoproterozoic (775 ± 26 Ma, Just *et al* 2011) transpression in the foreland of the DFB. This implies a significant structural imprint along the western margin of the DFB following the Erinpura thermal event (~ 850 Ma), the latter regarded as a late syn-orogenic to post-orogenic phase of the Delhi orogeny. Tectonic significance of this deformation event is still not known and the structural relationship between Daba Shear Zone and the POS is also inconclusive, for which efforts are underway.

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