

Formation and tectonic evolution of the Cretaceous–Jurassic Muslim Bagh ophiolitic complex, Pakistan: Implications for the composite tectonic setting of ophiolites

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Abstract

The Muslim Bagh ophiolitic complex Balochistan, Pakistan is comprised of an upper and lower nappe and represents one of a number of ophiolites in this region which mark the boundary between the Indian and Eurasian plates. These ophiolites were obducted onto the Indian continental margin around the Late Cretaceous, prior to the main collision between the Indian and Eurasian plates. The upper nappe contains mantle sequence rocks with numerous isolated gabbro plutons which we show are fed by dolerite dykes. Each pluton has a transitional dunite-rich zone at its base, and new geochemical data suggest a similar mantle source region for both the plutons and dykes. In contrast, the lower nappe consists of pillow basalts, deep-marine sediments and a *mélange* of ophiolitic rocks. The rocks of the upper nappe have a geochemical signature consistent with formation in an island arc environment whereas the basalts of the lower nappe contain no subduction component and are most likely to have formed at a mid-ocean ridge. The basalts and sediments of the lower nappe have been intruded by oceanic alkaline igneous rocks during the northward drift of the Indian plate. The two nappes of the Muslim Bagh ophiolitic complex are thus distinctively different in terms of their age, lithology and tectonic setting. The recognition of composite ophiolites such as this has an important bearing on the identification and interpretation of ophiolites where the plate tectonic setting is less well resolved.

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1. Introduction

The tectonic setting in which ophiolites originally formed is generally regarded to be either at a mid-ocean ridge or associated with a subduction zone (either a back-arc basin or the arc itself). The ophiolite definition originally published by the Penrose Conference participants in 1972 reflects the consensus that ophiolites are fragments of ocean lithosphere formed at mid-ocean ridges by sea-floor spreading (Anonymous, 1972). However, geochemical

studies of ophiolites have subsequently challenged this view. Miyashiro (1973) was the first to suggest that the Troodos massif was formed in an island arc and questioned the hypothesis of a mid-ocean ridge setting for ophiolite genesis. Miyashiro's (1973) paper has initiated a long-lasting, and continuing, debate about the tectonic environment of formation of ophiolites (e.g. Pearce et al., 1984; Boudier and Nicolas, 1985; Shervais, 2000; Nicolas and Boudier, 2003; Pearce, 2003; Hawkins, 2003; Shervais et al., 2004). Many models of supra-subduction zone ophiolites have been developed (e.g. Pearce, 2003) and these have marked some of the key advances in our understanding of modern ophiolite analogues. Distinguishing between the different possible tectonic settings of ophiolites has proved problematic

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given that some fully developed ophiolites (such as the Troodos and Oman massifs) have subduction zone geochemistry but the structure of a mid-ocean crust with no associated arcs, or overlying arc-derived sediments.

In Pakistan, the Bela, Muslim Bagh, Zhob, Waziristan and Khost ophiolite complexes are located at the western edges of the Indian plate, and mark its boundary with the Eurasian plate (Fig. 1). The Muslim Bagh ophiolitic complex, located in the Zhob valley (Fig. 2) northeast of Quetta, is one of the best-exposed ophiolites in Pakistan. It was first studied by Vredenberg (1901) and is a part of the western ophiolite belt (comprising the ophiolites of Bela, Muslim Bagh, Waziristan and Khost) that represents the boundary between the Indian plate and the adjacent Afghan continental block (Fig. 1) (Mahmood et al., 1995; Gnos et al., 1997). The ophiolite extends for more than 100 km between Gawal and the southwest of Qila-Saifulah. The regional geology of the Muslim Bagh area was mapped at a scale of 1:253,440 by the Hunting Survey Corporation (Jones, 1960) and was recognised as an ophiolite complex by Rossman et al. (1971) and later by Ahmad and Abbas (1979). Mahmood et al. (1995) suggested a mid-ocean ridge origin for the Muslim Bagh ophiolite, whereas Siddiqui et al. (1996) proposed that it formed in a back-arc basin environment. The ophiolite consists of an upper and a lower nappe: the upper nappe is composed of ultramafic rocks intruded by gabbros plutons and dolerite dykes, while the lower nappe comprises a basalts and sediments overlain by a *mélange* of ophiolitic rocks (Fig. 2).

On the basis of new field observations and geochemical data, we show that there is a clear feeder relationship between the dolerite dykes and gabbro plutons of the Muslim Bagh ophiolitic complex. Our study also reveals that this ophiolite has characteristics of both supra-subduction zone and mid-ocean ridge settings, suggesting formation

in several different tectonic environments. These findings have implications for the interpretation of other ophiolite complexes which may also have been formed in several different tectonic settings.

2. Regional tectonic evolution

The tectonic evolution of the Indian Ocean commenced during the break-up of Gondwanaland. In the first stage, between 157 and 118 Ma, Madagascar and greater India rifted from Africa (Fig. 3a), (Cochran, 1988; Gnos et al., 1997; Peters, 2000). The lower ophiolitic nappe of Muslim Bagh formed during this period of oceanic spreading (Sawada et al., 1992; Kojima et al., 1994) and paleomagnetic data reveal that it formed at a latitude of 27°–34°S (Khadim et al., 1992; Yoshida et al., 1992b). Portions of this ocean floor are still preserved in place in the Mozambique, west Somali and possibly the north-Somali basins. Accreted remnants of ocean crust of equivalent age are also preserved in northwestern Australia (Veevers et al., 1985; Cochran, 1988). Mesozoic fragments of this ocean floor may also exist along the western side of the Indian plate (Gnos et al., 1997), however, these are covered by several kilometres of continental detritus derived from the Indus and Bengal fans.

In the second stage, between 87 and 65 Ma, an oceanic spreading centre (the Mascarene–Madagascar basin) developed as the Indian plate rifted from Madagascar plate (Fig. 3b), (Storey et al., 1995; Plummer, 1996). This rifting and associated rotation of the Indian plate resulted in transpression along its northwestern edge, and possibly in the formation of both east-dipping and west-dipping subduction zones. The geological evidence for these two subduction zones is discussed in detail in Plummer (1996), Gnos et al. (1997) and Peters (2000). Part of the westward-dipping subduction zone is preserved in the metamorphic sole rocks of the Muslim Bagh and Bela ophiolitic complexes (Mahmood et al., 1995; Gnos et al., 1997; Khan et al., 1999).

Intra-oceanic subduction initiated in the Late Cretaceous at the northwestern leading edge of Indian plate (Fig. 3b) and ophiolites were obducted onto the northern and western edges of the Indian plate around the time of the Cretaceous–Tertiary boundary (Searle, 1983; Mahmood et al., 1995; Plummer, 1996; Gnos et al., 1997). The consumption of oceanic crust and emplacement of ophiolites during the closure of Neo-Tethys occurred not only north of India, but also along two or more subduction zones between Afro-Arabian plate and Indian plate. This subduction and ophiolite emplacement is evidenced by the formation of metamorphic soles beneath the western ophiolitic belts of Pakistan and eastern Oman in addition to *mélanges*, high grade metamorphic rocks and large-scale faulting and folding (e.g. Powell, 1979; Gnos et al., 1997; Khan et al., 1999).

Dercourt et al. (1993) argued for the presence of a single subduction zone (the Kohistan island arc and back-arc

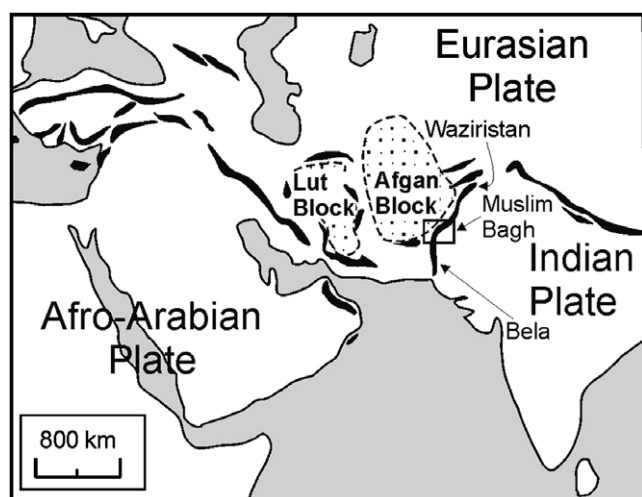


Fig. 1. Regional map showing the Alpine suture zones between the Afro-Arabian, Indian and Eurasian plates (based on Gansser, 1964 and Mahmood et al., 1995). Note that the boundaries between major continental blocks are marked by ophiolite belts.

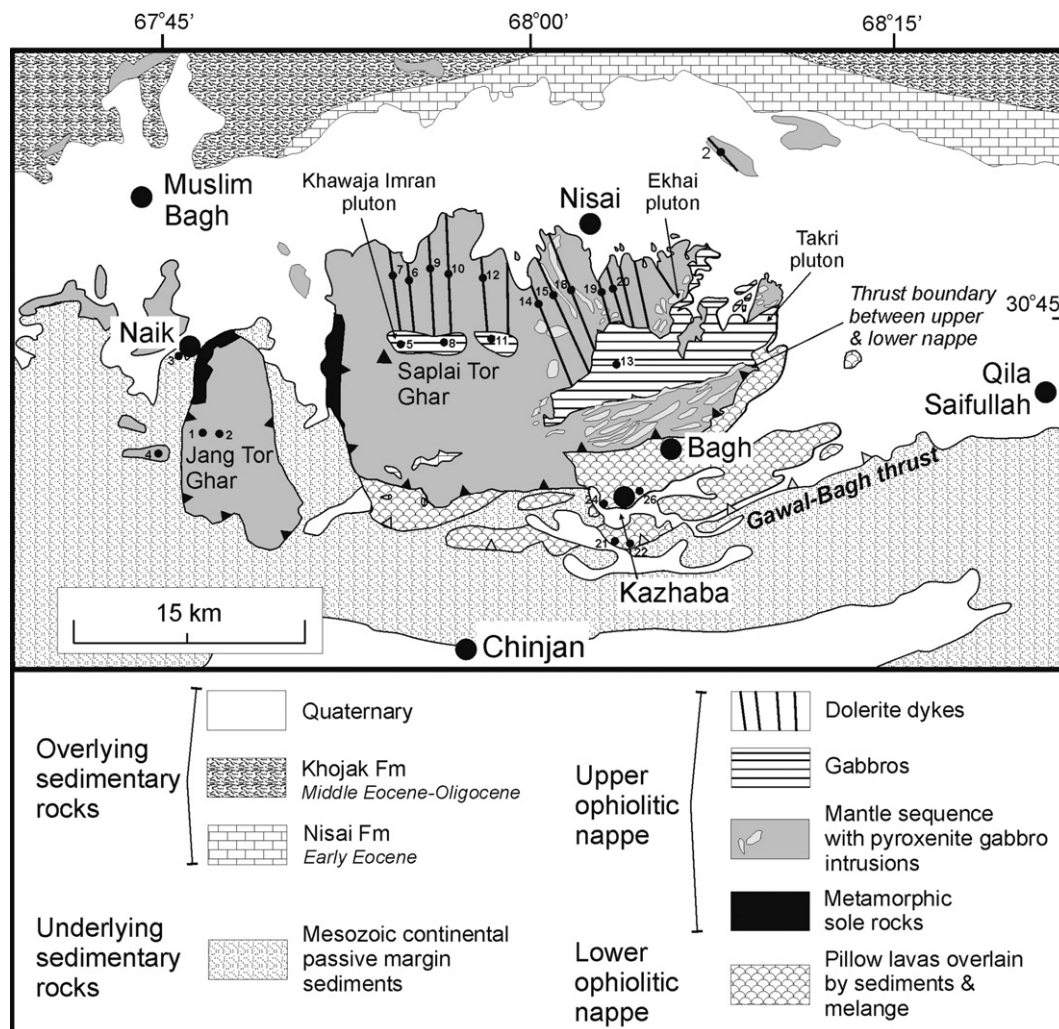


Fig. 2. Geological map of the Muslim Bagh ophiolite showing the location and lithology of the upper and lower nappes. Also shown are the sample locations which are described in more detail in [Electronic Appendix A](#).

basin; Tahirkheli, 1982; Searle et al., 1999) along the southern margin of Eurasia. However, the presence of ophiolites on the edges of eastern Arabia (Gnos et al., 1997) and western Indian plate, clearly demonstrates that the boundary between these two plates was not only transcurrent but was also temporarily convergent in places (Powell, 1979; Gnos et al., 1997), with the result that associated subduction zones were only relatively short-lived features. Such subduction zones probably would not have formed back-arc basins, since full back-arc basin development with rifting and magma generation requires a long-lived (>10 m.y.) subduction zone (Pearce, 2003; J.A. Pearce personal communication 2007). The regional tectonic setting of the western boundary of the Indian plate was therefore more likely to have resulted in the formation of a nascent-arc and a fore-arc rather than a mature back-arc basin.

Consumption of Tethyan oceanic crust along these intra-oceanic subduction zones during the Late Cretaceous and early Tertiary (Fig. 3c) eventually led to the collision of the Indian and Eurasian continents in the Early Eocene and the final emplacement of these Tethyan ophiolites onto

the Indian continental passive margin (Allemann, 1979; Tapponnier et al., 1981; Patriat and Achache, 1984; Gnos et al., 1997; Khan et al., 1999). The ophiolites that had accreted along the northern edge of the Indian plate were directly involved in continental collision (Searle, 1983) and so have been dismembered and tectonised into extensive mélanges (e.g. Kazmi and Jan, 1997). In contrast, the ophiolites of the western suture zone (Bela, Muslim Bagh, Zhob, Waziristan and Khost) docked with the Afghan continental block along a transform fault and so were not directly involved in this collision process (Gnos et al., 1997). Consequently, these ophiolites are much less dismembered and display much clearer structural relations.

3. Field relations, petrography and tectonic emplacement of the Muslim Bagh ophiolitic complex

The area chiefly covered by this study is shown in Fig. 2, along with the sample locations. A more detailed description of the field relations and petrography of each sample is given in [Electronic Appendix A](#).

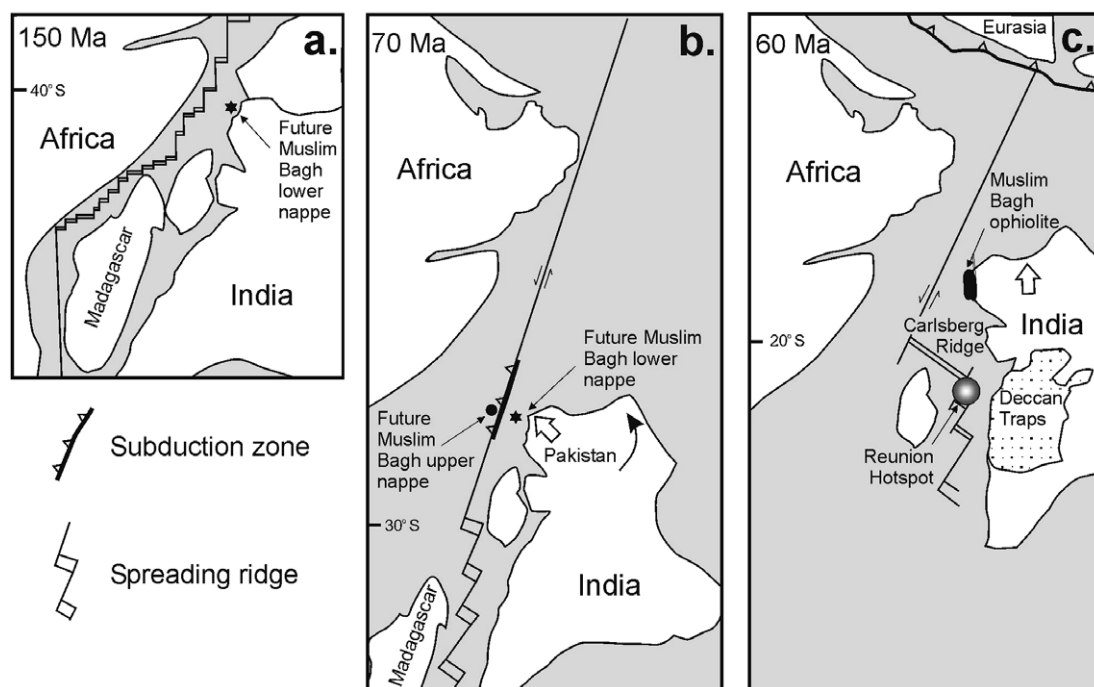


Fig. 3. Plate tectonic reconstructions for the evolution of the western Indian Ocean the late Jurassic to the early Tertiary (after Scotese et al., 1988). See text for more details.

3.1. Upper ophiolitic nappe

The upper nappe of the Muslim Bagh ophiolitic complex is located in the northwestern part of the complex. The Saplai Tor Ghar, Jang Tor Ghar and Khanozai massifs (the Khanozai massif is located 40 km west of the Jang Tor Ghar massif and is not shown in Fig. 2) are all part of the upper nappe, which mainly consists of mantle sequence rocks, including harzburgite, dunite and lherzolite (Mahmood et al., 1995; Siddiqui et al., 1996). A significant characteristic of this nappe is that it contains many isolated gabbro plutons emplaced within the ultramafic rocks, as well as having an abundance of dolerite dykes crosscutting the mantle sequence and apparently feeding many of the isolated mini-magma chambers represented by the gabbro plutons. However, this significant aspect of these dolerite dykes has not been recognised in previous studies. Economically, important chromite bodies, which are presently exploited on a large-scale in the region, are hosted by dunites. These chromites are found in the form of lenses, pods and layers that are up to 2 m thick and in places they extend laterally for several thousand metres. The age of this upper nappe is partially constrained to the latest Cretaceous by an Ar–Ar age of 68.7 ± 1.8 Ma from the main gabbro pluton in the Takri area (Mahmood et al., 1995).

The base of this nappe is marked by metamorphic sole rocks (Munir and Ahmad, 1985; Mahmood et al., 1995), which demarcate the main boundary between the lower and upper nappes (Fig. 2).

3.1.1. Subophiolitic metamorphic sequence

Metamorphic sole rocks are generally regarded to form during the inception of oceanic subduction (e.g. Boudier et al., 1988; Hacker, 1990; Hacker and Mosenfelder, 1996; Searle and Cox, 1999; Wakabayashi and Dilek, 2003).

The metamorphic sole along the base of the Muslim Bagh upper nappe records the early history of oceanic detachment (Mahmood et al., 1995) and is discontinuously present below the upper ophiolitic nappe. In many areas this discontinuity is due to intense shearing associated with emplacement which has broken up the original sequence and resulted in imbrication and the formation of a *mélange*, e.g. in the Saplai Tor Ghar and Khanozai areas. The *mélange* also contains blocks and fragments of basalts, metamorphosed to amphibolite and greenschist facies (both with serpentinised margins) which range in size from a few cm to several tens of metres across. Significantly, high pressure metamorphic rocks, found associated with some large-scale ophiolites (e.g. the Oman ophiolite; Nicolas, 1989) are not found in the Muslim Bagh area.

Well-exposed metamorphic sole rocks lie beneath the northwestern part of the Jang Tor Ghar massif (Fig. 2). The series starts at the contact with peridotite–mylonites and garnet–amphibolites and grades downwards into amphibolites and epidote–amphibolites or actinolite–schists with intercalated calcite marble layers. In the lower part of the metamorphic sole, the amount of quartz increases and garnet–biotite–gneisses along with biotite–schists are found with decreasing metamorphic grade. The lowest exposed layers of the metamorphic sole consist

of muscovite (sericite)–chlorite–schist with marble bands. Metamorphic sole rocks beneath the Saplai Tor Ghar and Khanozai massifs are lithologically similar, although much less complete.

Above the metamorphic sole rocks, a mylonitised peridotite layer is found which consists of a banded dunite and harzburgite sequence. This unit grades continuously upwards into a sequence of harzburgite, with concordant and discordant dunite bodies (see below). The mylonitised basal peridotite shows an emplacement direction from WSW to ENE (Mahmood et al., 1995) and Ar–Ar isotopic dating of amphiboles from the metamorphic sole has yielded an age of 70.7 ± 5.0 Ma (Mahmood et al., 1995).

3.1.2. Harzburgite

The Saplai Tor Ghar, Jang Tor Ghar and Khanozai massifs are mainly composed of serpentinitised harzburgites. However, the Jang Tor Ghar massif also contains a significant amount of lherzolite. The harzburgite consists primarily of orthopyroxene (bronzite) and olivine (Siddiqui et al., 1996). The olivine is partially to completely replaced by antigorite and iddingsite, and orthopyroxene is mostly replaced by antigorite, bastite and chlorite. The harzburgite has been 50–60% serpentinitised.

3.1.3. Dunite

The basal part of the mantle sequence consists of alternating harzburgite and dunite bands, with the olivine-rich layers representing 30–40% of the volume. This banded unit ranges from 200 to 1000 m thick (Mahmood et al., 1995) and grades upwards into a sequence of harzburgite with concordant and discordant dunite bodies. Above this banded unit, the upper section of the mantle sequence is dominated by dunites with economically important chromite layers which show partial-to-complete serpentinitisation. These chromite bodies are several metres thick and extend laterally for several thousand metres.

3.1.4. Wehrlites

Wehrlites also occur in the transition zone (Fig. 5) and show concordant to discordant layering which varies in thickness from 2 mm to 2–3 cm. The rocks display recrystallisation of clinopyroxene and intense deformation of olivine. In addition to occurring as concordant to discordant layers, wehrlite also is found as minor intrusions several metres across; e.g. at the base of Takri pluton. Field observations reveal that these intrusions are rooted in the transition zone and intruded into the gabbro pluton (Fig. 5). Significantly, wehrlites are not found within the mantle section.

The wehrlites are medium to coarse grained and show a granular and porphyroclastic texture. Mineralogically, they consist of olivine (45–65%), clinopyroxene (20–30%), chrome spinel (2–3%) and Fe–Ti oxides (2%). The rocks are partially to highly altered, with olivine commonly altered to antigorite and clinopyroxene to green hornblende.

3.1.5. Dolerite dykes

One of the most interesting features of the upper ophiolitic nappe of Muslim Bagh is the abundance of dolerite dykes cross-cutting the mantle sequence rocks (Fig. 4d). These dykes range in size from 1 to 100 m across and appear to feed many isolated mini-magma chambers (gabbro plutons). The dolerite dykes trend $\sim 160^\circ\text{N}$ and are mainly found in the Saplai Tor Ghar massif with a smaller number in the Jang Tor Ghar and Khanozai massifs (Fig. 2). The dykes possess chilled margins and have locally thermally metamorphosed their surrounding mantle rocks. The cross-cutting relationship and chilled margins suggest that the mantle rocks were significantly cooler at the time of the emplacement of the dolerite dykes. In places, these dykes contain up to four-metre-wide blocks of peridotites. The dykes run essentially parallel to each other and in places have been deformed into boudinage structures. Some dykes reach up to half to a kilometre across as they are followed up-sequence and in the centre of these thickest dykes the rocks show a gabbroic texture.

Mineralogically, most of the dolerites consist of plagioclase (>50%), augite (15–30%), hornblende (25%), calcite (2–4%) and Fe-oxides (1–2%). However, the mineralogy is variable and in some dolerites consists of plagioclase (45–55%), hornblende (40–45%), augite (2–6%) and Fe-oxides less than (2%). The clinopyroxene is partially to completely altered to green to dark green/brown hornblende and chlorite. Secondary calcite and epidote are present in the fractures and veins. Plagioclase is variably altered to sericite and in some rocks the all plagioclase is altered to sericite.

Field observations reveal that as the base of the gabbro pluton is approached, the dolerite dykes become less apparent and a transition zone develops between the top of dykes and the base of the gabbro. At the top of the zone of abundant dolerite dykes there is often a zone of harzburgite impregnated with interstitial gabbro. Moving upward, nearer the base of the gabbro, these harzburgites grade into layers of dunite, wehrlite and clinopyroxene with layers of gabbro (Figs. 4a and 5). Dunite steadily decreases towards the base of the pluton, and alternating layers of clinopyroxene and gabbro, or wehrlite and gabbro, become much more common. Such a transition zone is found at the base of each gabbro pluton in the Muslim Bagh area, however, it is most obvious at the base of the largest pluton in the Takri area where the zone is ~ 1000 m thick. The transition zone varies from 20 to 500 m thick in the other smaller plutons. Although compositionally similar to the Moho transition zone (cf. Boudier and Nicolas, 1995) the localised occurrence of these rock types and their structural position within the ophiolite make it unlikely that they represent the Moho transition zone. Field evidence reveals that no dykes cross-cut the gabbro plutons, nor are the gabbros observed to cut the dolerite dykes. Both of these lines of evidence imply that the gabbros and dolerites formed at a similar time and suggests a petrogenetic link between the gabbros and the dolerites.

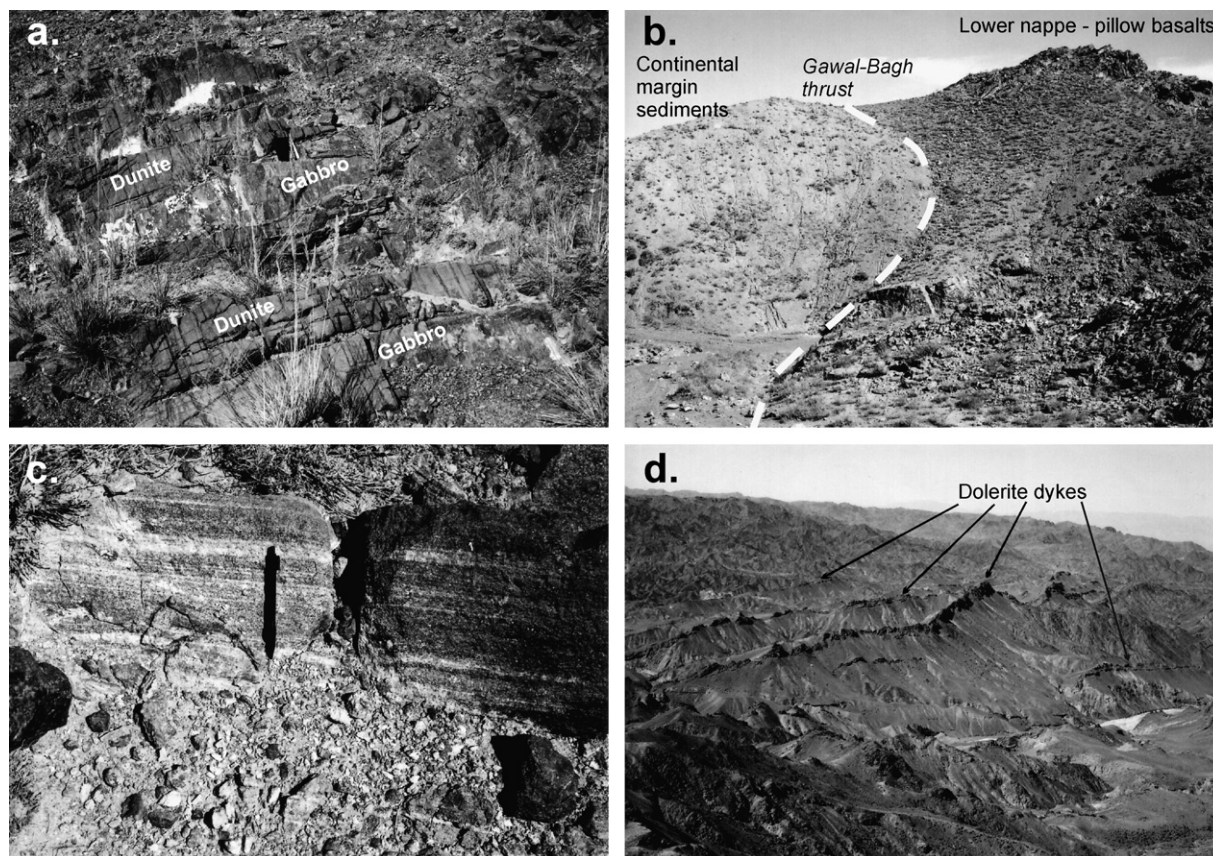


Fig. 4. Field photographs showing (a) alternate layering of dunite and gabbro in the transition zone, between the dolerite dykes and gabbro plutons of the upper nappe; (b) thrust zone between the Muslim Bagh ophiolite and continental sediments; (c) layering of plagioclase- and clinopyroxene-rich bands in one of the gabbro plutons from the upper nappe; (d) dolerite dykes running parallel to each other in the Saplai Tor Ghar massif.

3.1.6. Gabbro plutons

The main gabbro pluton is located in the southeast of the Saplai Tor Ghar massif (Fig. 2). Ahmad and Abbas

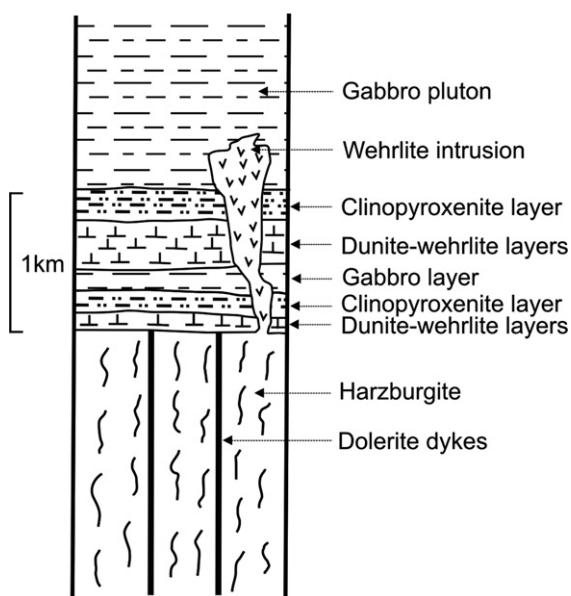


Fig. 5. Schematic diagram illustrating the alternate layers of dunite, wehrlite, clinopyroxenite and gabbro in the transition zone between the top of the dolerite dykes and the base of the gabbro plutons. See text for more details.

(1979), Mahmood et al. (1995) and Siddiqui et al. (1996) described the pluton as a sequence of oceanic crustal rocks composed of a gabbroic section with sheeted dykes. The gabbroic section of the Muslim Bagh ophiolitic complex in the Saplai Tor Ghar massif is 4–5 km wide by 1 km thick and is characterised by bands of gabbro, pyroxenites and wehrlite (Fig. 4) (Mahmood et al., 1995). Our detailed mapping has revealed that this pluton is an isolated gabbro body, unlike gabbroic rocks of oceanic crust (Nicolas, 1989). Similar, isolated gabbro plutons are relatively common in the Saplai Tor Ghar Massif and in the Khanozai area. Each gabbro pluton can clearly be seen to be fed by a suite of dolerite dykes.

In the Takri area, the main gabbro pluton has yielded an Ar–Ar age of 68.7 ± 1.8 Ma (Mahmood et al., 1995) and takes the form of a synform 4 km in diameter, which is asymmetrically rimmed by a dunite-rich zone, and consists of layered, foliated and isotropic gabbros (Mahmood et al., 1995).

The second largest gabbro pluton which is found in Khawaja Imran (Fig. 2) is ~3–4 km long and 0.5–1.0 km wide and also displays layering and foliation. The gabbro plutons of the Ekhai, Sra-Salwat and Khanozai areas (outside the area of Fig. 2) are ~1–2 km long and 0.5–1 km wide and show similar features to the Khawaja Imran pluton. The gabbro plutons are all found around the same

structural level in the mantle sequence rocks, but none of these gabbros appear to have formed a well-developed sheeted dyke complex, rather all that is found in the field at the top of these gabbro plutons are the poorly developed roots of sheeted dykes. This suggests that the supply of magma was relatively low, probably due to minimal rifting and extension.

The gabbros consist of layered, foliated and rare isotropic gabbros. The dominant rock types are olivine gabbro, which occurs in layers near the base of the intrusion, and gabbro containing only a small amount of olivine which predominates at a higher level. The layering is best developed near the base of each intrusion and is characterised alternating layers of predominantly plagioclase and clinopyroxene $\pm$ olivine that range in thickness from one to several centimetres with sharp boundaries between the layers.

The olivine gabbros consist of plagioclase (60–70%), clinopyroxene (20–25%), olivine (5–20%) and Fe-oxides (1–4%) and the average crystal is 2–3 mm. The olivine gabbros are variably altered: in some samples plagioclase has been partially altered to sericite and olivine to serpentine; whereas in other rocks olivine and plagioclase are relatively unaltered and the only clinopyroxene is partially altered to brown-to-green hornblende. Texturally, the rocks display magmatic deformation while the feldspars show moderate orientation, however mechanical twinning (tapering) is rarely found. The olivine has not recrystallised, but many grains exhibit dislocations.

Mineralogically, the olivine-poor gabbros consist of plagioclase (60–70%), clinopyroxene (20–30%), orthopyroxene (2–3%) and Fe-oxides (<2%) with small amounts of olivine. Some gabbro plutons also contain up to 20% primary hornblende in the form of large euhedral to subhedral crystals, in addition to >50% plagioclase, thus indicating the hydrous nature of these magmas. The plagioclase is generally fresh, but clinopyroxene is partially to completely altered to brown-to-green hornblende, tremolite, and chlorite, while the volumetrically minor olivine is partially altered to serpentine.

Texturally, the rocks show evidence of solid state deformation which varies from granular, to porphyroclastic to mylonitic textures. The granular texture is characterised by the recrystallisation of clinopyroxene into a mosaic of ~ 0.5 mm polygonal crystals. The plagioclase shows abundant mechanical twinning and recrystallisation. This texture is developed at the expense of the primary texture indicating solid state deformation at high temperature, within the stability conditions of clinopyroxene (Mahmood and Khan, 1999). The porphyroclastic texture, typically displays an average grain-size of 0.5 mm and the minerals commonly possess irregular lobate margins. The plagioclase crystals are in irregular form and mechanical twinning, along with undulose extinction is very common. In places these porphyroclastic textures are marked by a significant reduction of grain-size from 1 to 0.1 mm, depending on the intensity of deformation.

In contrast, the mylonitic texture is characterised by both the recrystallisation of plagioclase into a mass of smaller crystals of significantly reduced crystal size (<0.1 mm) and the development of amphibole rims on aligned clinopyroxene porphyroclasts. This type of texture indicates increased stress under high-to-moderate temperature (Mahmood and Khan, 1999).

3.1.7. Clinopyroxenites

Concordant to discordant layers of clinopyroxenite, from a few centimetres to decametres thick, are present in the transition zone between the top of dolerite dykes and the base of gabbro (Fig. 5). Mineralogically, these consist of >90% clinopyroxene, with subordinate olivine (5–10%), orthopyroxene (2–5%), and Fe-oxides less than (4%). The clinopyroxene is partially altered to brown hornblende and olivine partially altered to serpentine. The rocks display a granular texture and have two populations of clinopyroxene crystals: primary crystals a few millimetres in size, and polygonal neoblasts which are <1 mm.

3.2. Lower ophiolitic nappe

3.2.1. Mélange

The mélange which occupies the base of the upper nappe and top of the lower nappe is well exposed northwest of Bagh village (Fig. 2). The mélange is about 1 km thick and contains blocks which are several metres to 100 m in diameter. These blocks have been tectonically derived from both over-thrusting and underlying rocks during the emplacement of the upper nappe on the lower nappe. The included blocks consist of serpentinised mantle rocks, gabbro, basalt, garnet–amphibolite, amphibolite and greenschist, along with mudstone, radiolarian chert, limestone, and shale (Mengal et al., 1996; Siddiqui et al., 1996).

3.2.2. Basalts overlain by sediments

This unit, which is about 1 km thick, is well exposed in the Bagh area and consists mostly of imbricated sheets of pillow basalts with a subordinate amount of massive lava and volcanic breccia (Munir and Ahmad, 1985; Sawada et al., 1992). These tholeiitic basalts are unconformably overlain by a sedimentary sequence of reddish-brown bedded radiolarian cherts and micritic limestone which grades up-succession into siliceous shale and mudstone (Mengal et al., 1996). The sediments constrain the minimum age of the underlying basalts to Jurassic since they contain marine microfossils which range in age from Jurassic to Early Cretaceous [predominantly Berriasian to Hauterivian (145.5–130.0 Ma); Kojima et al., 1994].

Alkaline igneous rocks have been found to intrude the lower nappe (McCormick, 1991) in the Kazhaba and Naik areas (Fig. 2). These rocks consist of basanite, tephrite, phonotephrite, picritic and kimberlitic rocks with minor trachybasalt, and alkali intrusions ~ 300 m across in the Naik area and ~ 100 m across in the Kazhaba area. In several places these alkaline magmas have intruded into wet

hyaloclastite mudstones and have formed amygdaloidal pillow structures (Siddiqui et al., 1996). The geochemistry and petrogenesis and age of these rocks will be discussed more extensively in another paper.

3.3. Tectonic emplacement

The Muslim Bagh ophiolitic complex shows two stages of tectonic emplacement; intra-oceanic thrusting followed by emplacement onto the continental margin. The intra-oceanic thrusting occurred along a several hundred metres thick shear zone, represented by the metamorphic sole rocks beneath the upper nappe, which also mark the main boundary between the upper and lower nappes. These metamorphic sole rocks record the initial obduction which commenced at ~70 Ma, and structural evidence from the basal peridotite–mylonite zone shows that the emplacement direction was from WSW to ENE (Mahmood et al., 1995). The final emplacement of the two nappes onto the continental margin is marked by the west-dipping Gawal-Bagh thrust zone (Fig. 2) which is found between the Muslim Bagh ophiolitic complex and the continental sedimentary rocks (Fig. 4b).

In the first stage of thrusting, the upper nappe was pushed over the adjacent oceanic lithosphere. Following this event, the thrust zone propagated east–northeast with time (Mahmood et al., 1995). Imbricated structures in the lower nappe confirm that its thrusts and folds are related to east-directed emplacement onto the Indian continent. Our field observations reveal that during the final stages of emplacement, the thinned continental passive margin sediments (Late Triassic Wulgai Formation) were partially subducted beneath the Muslim Bagh ophiolitic complex most likely by slab pull (cf. Shervais, 2000). Following tectonic emplacement and erosion of ophiolite, these passive margin sediments were exposed in several places, for example, in the southwest of Muslim Bagh town and north of Hamrani village. The intense deformation of the Wulgai Formation attests to this choking of the subduction zone. After the final emplacement, the continental shelf developed again and the Early Eocene Nisai Formation and Middle Eocene to Oligocene Khojak Formation were deposited over the ophiolite (Allemann, 1979; Qayyum et al., 1996a) (Fig. 2).

4. Geochemistry

4.1. Analytical methods

Following removal of weathered surfaces the samples were crushed in a jaw crusher and powdered using an agate Tema mill. Two grams of sample powder were then heated in a porcelain crucible to 900 °C for 2 h to determine the loss on ignition. Major and trace element abundances were analysed using a JY Horiba Ultima 2 inductively coupled plasma optical emission spectrometer (ICP-OES) and a Thermo X7 series inductively coupled plasma mass

spectrometer (ICP-MS) at Cardiff University, United Kingdom. The ignited powders were prepared for analysis by fusion of 0.1 g $\pm$ 0.0005 of sample with 0.4 g $\pm$ 0.0005 lithium tetraborate flux in a platinum crucible on Claisse Fluxy automated fusion system. The mixture was then dissolved in 30 ml of 10% HNO₃ and 20 ml of de-ionised water. After the sample was fully dissolved, 1 ml of 100 ppm Rh spike was added and the solution was made up to 100 ml with de-ionised water. ~20 ml of this solution was run on the ICP-OES to obtain the major element abundances. 1 ml of the solution was added to 1 ml of Tl and 8 ml of 2% HNO₃ and analysed on the ICP-MS to obtain the trace element abundances (Table 1). Accuracy and precision of the data were checked using international reference materials BIR-1 and JB-1a, (Table 2) and by running three of the samples from this study in each of the analytical runs. Data for the gabbros, dolerites and basalts are presented in Table 1. The extensive hydrothermal alteration of many of the samples has significantly mobilised the large ion lithophile elements such as Rb and Ba leading to considerable scatter on geochemical diagrams. Consequently, these elements have been excluded from the following discussion in favour of relatively immobile elements.

4.2. Upper nappe dolerites

The Muslim Bagh dolerites range from 3.6 to 13.3 wt% MgO, with the majority of samples containing 4–7 wt% MgO (Table 1). Sample 2003–1 contains 13.3% MgO and in thin section has significantly more altered olivine than most of the other dolerites. This sample was collected close to the margin of the dyke and its anomalously high olivine content suggests that it accumulated olivine and is likely to have formed by in situ sidewall crystallisation. Although the Ni content of this dolerite is significantly lower (84 ppm) than one might expect for a sample containing over 13 wt% MgO, this can be explained by the alteration of olivines which appears to have leached Ni from the rock (cf. Hill et al., 2000). A peculiar feature of many of these dolerites (and indeed some of the gabbros from Muslim Bagh) is their high CaO contents with associated lower SiO₂ contents. These elevated CaO values can be explained by the occurrence of secondary calcite and epidote in veinlets and in interstitial alteration patches in many of these rocks. A broad, but distinct positive correlation between loss on ignition and CaO content (not shown) confirms this explanation. It is likely that this alteration has also modified the alkali contents of the rocks and this is confirmed by a significant amount of scatter on the alkali–silica diagram (Fig. 6e). In view of the alteration which these rocks have undergone, our discussion of their tectonic setting will focus on the relatively immobile high-field strength and rare Earth elements and not the more mobile large ion lithophile elements such as Rb, Ba and K. The consistency of the MORB-normalised trace element patterns for the Muslim Bagh dolerites (Fig. 6b) particularly with respect

Table 1
Major and trace element data for representative samples of the Muslim Bagh ophiolite

Sample Rock type	2003–1 Dolerite	2003–2 Dolerite	2003–4 Dolerite	2003–7 Dolerite	2003–9 Dolerite	2003–10 Dolerite	2003–12 Dolerite	2003–14 Dolerite	2003–15 Dolerite	2003–18 Dolerite	2003–19 Dolerite	2003–20 Dolerite	2003–5 Gabbro	2003–6 Gabbro	2003–8 Gabbro	2003–11 Gabbro	2003–13 Gabbro	2003–16 Gabbro	2003–21 Sheet flow	2003–22 Pillow lava	2003–24 Sheet flow
SiO ₂ (wt%)	36.88	40.17	40.71	49.76	54.18	44.25	52.25	39.75	43.28	42.78	53.60	40.60	45.89	49.63	53.35	50.24	34.64	52.77	49.00	49.27	48.49
TiO ₂	0.49	0.48	1.11	1.29	1.25	0.88	1.25	0.83	0.79	0.89	1.47	0.79	0.24	1.06	0.12	1.69	0.62	1.12	0.92	0.84	0.62
Al ₂ O ₃	13.63	10.23	15.24	13.89	14.34	13.74	13.86	12.81	14.02	13.72	13.55	10.42	16.61	14.92	2.14	14.58	11.97	14.54	14.04	13.74	14.84
Fe ₂ O ₃ (t)	13.79	9.39	13.31	11.32	11.03	9.42	11.52	9.10	9.45	9.27	11.82	9.20	7.00	10.04	5.72	13.07	7.81	10.96	10.90	9.44	7.69
MnO	0.18	0.17	0.21	0.17	0.18	0.14	0.18	0.14	0.15	0.16	0.17	0.19	0.14	0.16	0.11	0.20	0.12	0.17	0.17	0.15	0.13
MgO	13.33	7.61	4.07	2.59	3.69	5.11	3.10	4.54	5.25	6.25	3.62	10.90	10.82	7.60	15.87	4.00	4.54	4.54	8.42	9.96	6.41
CaO	17.74	23.42	20.70	10.89	6.51	23.31	9.29	25.45	20.80	21.38	8.74	25.36	18.59	9.11	19.13	8.63	22.75	6.92	10.73	10.86	12.07
Na ₂ O	0.22	2.83	0.25	4.95	4.90	0.28	4.97	0.19	1.46	0.78	4.80	0.01	0.66	3.01	0.09	3.16	0.35	4.44	2.92	2.87	3.88
K ₂ O	0.02	0.02	0.06	0.54	0.49	0.05	0.34	0.06	0.03	0.02	0.17	0.01	0.05	0.52	0.04	0.33	0.03	0.60	0.30	0.12	0.10
P ₂ O ₅	0.23	0.24	0.84	0.32	0.23	0.22	0.33	0.09	0.38	0.07	0.34	0.33	0.18	0.28	0.13	0.10	0.25	0.44	0.27	0.17	0.20
LOI	3.16	5.10	4.09	3.54	2.69	4.19	2.96	5.00	5.28	4.51	2.21	2.98	1.10	3.29	2.27	2.08	19.29	2.98	2.98	3.27	5.77
Total	99.67	99.66	100.60	99.26	99.50	101.60	100.05	97.95	100.89	99.83	100.49	100.79	101.28	99.62	98.98	98.08	102.36	99.48	100.64	100.68	100.19
Sc (ppm)	79.2	44.5	37.5	28.9	32.6	33.9	33.2	32.0	35.9	37.8	31.0	34.6	65.5	35.6	106.8	33.8	24.5	31.1	44.3	42.1	36.5
V	508	229	356	320	287	279	364	243	239	235	357	287	203	245	172	389	154	234	286	249	188
Cr	212	47	9	4	25	57	15	58	32	120	7	50	59	59	1224	24	585	61	148	331	438
Co	70	39	34	30	30	37	33	30	35	33	34	26	35	35	50	36	36	30	49	42	37
Ni	84	142	41	84	55	44	29	30	34	106	18	31	57	50	608	26	215	36	77	87	121
Zn	48	58	61	158	191	26	63	48	44	37	77	5	5	40	0	67	27	99	50	32	19
Ga	8.9	3.0	14.7	15.6	16.3	13.1	14.1	11.2	11.1	14.6	4.9	10.5	15.7	2.2	16.8	22.3	16.3	12.8	12.7	10.1	
Sr	18	22	226	182	107	37	266	42	76	35	64	27	222	289	11	192	32	63	183	145	253
Y	4.8	14.3	30.9	29.0	31.9	21.5	31.0	19.4	19.2	22.7	30.9	20.4	5.3	24.9	1.8	24.0	15.8	31.5	21.9	20.0	16.5
Zr	2	25	91	84	99	48	82	38	46	42	91	48	19	64	7	64	29	85	44	42	27
Ba	12.0	8.3	42.7	73.4	47.7	15.6	103.0	27.6	12.6	9.2	23.5	10.2	14.2	113.8	10.4	97.8	11.3	84.4	19.5	27.0	28.8
Nb	0.09	0.35	7.63	2.52	1.88	3.14	1.68	2.31	0.98	1.34	0.76	2.96	0.89	0.11	0.12	1.99	1.23	3.11	0.69	0.70	0.46
La	0.04	0.69	12.32	3.40	3.27	3.95	2.44	3.24	1.80	3.13	2.15	4.28	2.22	0.17	0.20	3.24	2.00	5.70	1.44	0.95	0.76
Ce	0.19	2.58	26.37	11.03	9.68	12.11	7.06	10.38	6.21	7.64	7.00	12.50	6.75	0.78	0.59	9.81	5.78	16.95	4.63	3.93	2.79
Pr	0.04	0.49	3.35	1.79	1.60	2.04	1.18	1.73	1.06	1.24	1.22	2.09	1.11	0.18	0.10	1.59	0.92	2.78	0.90	0.78	0.57
Nd	0.39	2.82	13.59	8.81	7.91	10.12	6.01	8.52	5.37	6.15	6.19	10.35	5.50	1.24	0.51	7.69	4.46	12.86	4.95	4.40	3.25
Sm	0.23	1.09	3.46	2.80	2.58	3.32	1.98	2.75	1.82	1.92	2.08	3.24	1.85	0.56	0.20	2.48	1.42	3.72	1.82	1.66	1.27
Eu	0.15	0.48	1.10	1.14	0.98	1.09	0.69	1.03	0.53	0.67	0.82	1.03	0.73	0.26	0.08	1.07	0.52	1.03	0.67	0.64	0.52
Gd	0.46	1.54	3.98	3.54	3.23	4.11	2.57	3.67	2.47	2.51	2.78	4.25	2.43	0.78	0.27	3.26	1.95	4.34	2.52	2.36	1.85
Tb	0.10	0.31	0.72	0.65	0.61	0.78	0.48	0.67	0.46	0.47	0.52	0.77	0.46	0.15	0.05	0.59	0.36	0.75	0.48	0.45	0.37
Dy	0.81	2.17	4.93	4.44	4.07	5.27	3.32	4.62	3.17	3.14	3.56	5.27	3.23	1.03	0.35	4.05	2.47	5.11	3.41	3.15	2.60
Ho	0.17	0.44	0.98	0.88	0.80	1.04	0.65	0.91	0.63	0.62	0.69	1.03	0.65	0.20	0.07	0.78	0.49	1.01	0.69	0.64	0.52
Er	0.51	1.39	3.04	2.68	2.41	3.20	2.01	2.88	1.96	1.91	2.13	3.20	1.96	0.58	0.19	2.41	1.52	3.06	2.06	1.93	1.62
Tm	0.08	0.22	0.49	0.42	0.37	0.50	0.31	0.45	0.30	0.30	0.33	0.49	0.32	0.09	0.03	0.37	0.23	0.49	0.34	0.31	0.26
Yb	0.51	1.48	3.45	2.85	2.55	3.45	2.15	3.13	2.10	2.04	2.29	3.38	2.13	0.55	0.16	2.54	1.59	3.17	2.26	2.06	1.71
Lu	0.07	0.23	0.52	0.44	0.38	0.53	0.33	0.46	0.30	0.30	0.33	0.49	0.32	0.08	0.03	0.37	0.23	0.46	0.33	0.30	0.26
Hf	0.06	0.82	2.35	2.04	2.47	1.36	2.12	1.10	1.28	1.18	2.34	1.37	0.13	1.75	0.20	1.68	1.03	2.08	1.19	1.16	0.83
Ta	0.01	0.02	0.34	0.16	0.20	0.10	0.15	0.08	0.08	0.06	0.19	0.06	0.00	0.15	0.00	0.15	0.15	0.18	0.05	0.04	0.03
Th	0.01	0.10	2.38	0.44	0.34	0.48	0.25	0.41	0.24	0.32	0.18	0.42	0.33	0.01	0.02	0.35	0.20	0.49	0.06	0.05	0.04
U	0.02	0.04	0.68	0.17	0.17	0.08	0.13	0.07	0.09	0.04	0.13	0.11	0.02	0.15	0.03	0.15	0.12	0.12	0.03	0.04	0.01

Table 2
Measured and certified values for international reference materials JB-1a and BIR-1

	JB-1a (meas)	JB 1a (cert)	BIR-1 (meas)	BIR-1 (cert)
SiO ₂ (wt%)	52.59	52.16	47.38	47.70
TiO ₂	1.27	1.30	0.99	0.97
Al ₂ O ₃	14.21	14.51	15.22	15.40
Fe ₂ O ₃ (t)	8.98	9.10	11.59	11.30
MnO	0.14	0.15	0.17	0.18
MgO	7.76	7.75	9.84	9.70
CaO	9.42	9.23	13.71	13.40
Na ₂ O	2.75	2.74	1.59	1.81
K ₂ O	1.29	1.42	0.00	0.03
P ₂ O ₅	0.26	0.25	0.04	0.03
Sc (ppm)	28.0	27.9	46.0	43.0
V	189	206	331	319
Cr	400	415	386	391
Co	36.4	39.5	53.0	52.0
Ni	139	140	166	166
Zn	77	82	78	72
Ga	17.0	18.0	15.7	15.3
Sr	426	443	102	109
Y	23.55	24.0	16.5	15.6
Zr	137	146	14	14
Ba	493	497	10	7
Nb	24.16	27.00	0.48	0.55
La	37.55	38.10	0.59	0.62
Ce	65.24	66.10	1.89	1.92
Pr	7.40	7.30	0.37	0.37
Nd	25.62	25.50	2.43	2.38
Sm	5.10	5.02	1.07	1.12
Eu	1.47	1.47	0.53	0.53
Gd	4.64	4.54	1.76	1.87
Tb	0.67	0.69	0.34	0.36
Dy	3.94	4.19	2.51	2.51
Ho	0.71	0.72	0.55	0.56
Er	2.06	2.18	1.67	1.66
Tm	0.32	0.31	0.25	0.25
Yb	2.06	2.10	1.68	1.65
Lu	0.30	0.32	0.25	0.25
Hf	3.29	3.48	0.55	0.58
Ta	1.52	1.65	0.04	0.04
Th	8.39	8.80	0.02	0.03
U	1.62	1.57	0.02	0.01

to Th and Nb, demonstrates that despite the alteration and obvious major element mobility which these rocks have undergone, these trace elements have retained a coherent magmatic signature.

With the exception of Nb, which shows a slight-to-moderate negative anomaly, and Th, which has a significant positive anomaly, the MORB-normalised multi-element plots of the Muslim Bagh dolerites have essentially flat patterns (Fig. 6b). The more trace element-depleted nature of sample 2003–1 confirms its earlier interpretation as containing cumulate olivine. Although elevated Th and depleted Nb are consistent with the formation of these rocks in a supra-subduction zone setting, comparison of these rocks with modern-day arc tholeiites from a well-established subduction system (e.g. the Lesser Antilles) shows that the Muslim Bagh dolerites have a much less pronounced enrichment in Th and depletion in Nb, and

so have a weaker subduction signature (Fig. 6b). This subduction signature is further confirmed by the Nb/Yb vs. Th/Yb diagram (Fig. 6d) which shows that almost all the dolerite dykes of the Upper Muslim Bagh nappe fall in the compositional field of arc-related rocks – well above the field of depleted mid-ocean ridge-derived basalts.

4.3. Upper nappe gabbros

Like the dolerites the gabbros are variably altered by secondary processes and contain calcite and epidote bearing veinlets and interstitial material, resulting in some samples having elevated CaO and lower SiO₂ than would ordinarily be expected of a gabbro. The samples possess a similar range in MgO content to the dolerites ranging from 4.0 to 15.8 wt% (Table 1). The gabbros, however, possess a significantly wider range of incompatible trace element contents than the dolerites, a feature which is most likely due to olivine accumulation in magma chambers, since the two most incompatible trace element-depleted samples (2003–5, and 2003–8) also have the highest MgO (Table 1) and contain the most olivine. Despite this wider range in elemental abundance the gabbros generally possess a very similar chemical signature to the dolerites in that they possess flat MORB-normalised trace element patterns with positive and negative Th and Nb anomalies, respectively, and overlapping incompatible trace element ratios. (Fig. 6a and d). This confirms field observations that the dolerite dykes were feeders of the gabbro plutons and that together they represent a suite of subduction-related rocks. Evidence for a subduction-related origin for these gabbros is also shown by the presence of primary hornblende in some of the samples.

There is however, a significant range in incompatible trace element ratios which are influenced by subduction-related processes (e.g. Th/Yb and Nb/Yb; Fig. 6d) within both the gabbros and the dolerite dykes. The variation in these ratios is unlikely to be due to the accumulation of olivine, since these elements are approximately equally incompatible in olivine, furthermore the two samples which most likely represent cumulates, 2003–5 and 2003–8, possess have similar incompatible element ratios to the more evolved samples. This therefore implies that the mantle wedge source region of these rocks was markedly heterogeneous. Furthermore, it is noticeable that a one of the dolerites plots just within the MORB-array (Fig. 6d), and many of the other dolerites and gabbros plot only slightly outside the field of MORB compositions. This lack of, and reduced, subduction signature suggests in these rocks suggests that the arc system may well have been relatively immature.

4.4. Lower nappe basalts

These Jurassic pillow basalts and sheet flows have a composition typical of mid-ocean ridge basalts (Table 1): they display tholeiitic major element chemistry with a relatively restricted range in MgO contents (6–10 wt% MgO),

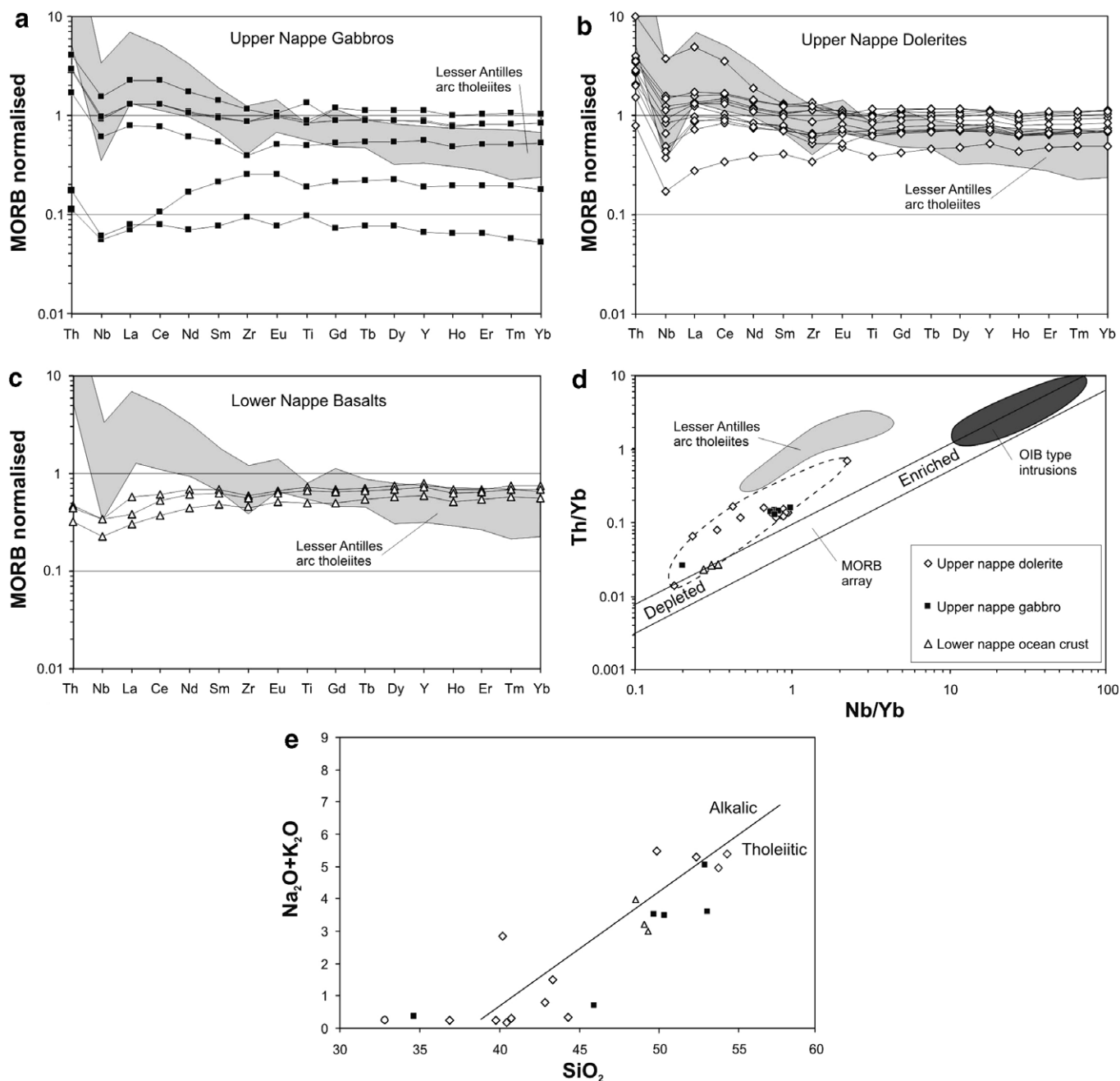


Fig. 6. (a–c) N-MORB-normalised (Sun and McDonough, 1989) multi-element plots, showing representative samples from the upper and lower nappes; (d) Th/Yb–Nb/Yb diagram (after Pearce and Peate, 1995); (e) alkali-silica diagram (tholeiitic–alkalic divide from Miyashiro, 1978). Data sources: OIB type intrusions intruding the lower nappe (M. Khan, unpublished data); lesser antilles arc tholeiites (Thirlwall et al., 1994, 1996; Woodland et al., 2002; Zellmer et al., 2003).

and possess a MORB-normalised trace element pattern which is markedly depleted in the most incompatible elements (Fig. 6c). Although these samples have slightly elevated Th values resulting in a small negative Nb anomaly this cannot be regarded as evidence for a subduction-related origin since the rocks are very depleted, and even the Th content of these rocks, although elevated is still less than average MORB. With such depleted magmas any addition of a Th-enriched component from a subduction zone would result in much more elevated Th and indeed LREE than are observed in these rocks. This point is borne

out by the compositions of (a) the upper nappe dolerites from this study, which contain a small subduction component and (b) arc tholeiites from the present-day lesser Antilles (Fig. 6c).

Further support for a mid-ocean ridge origin is provided by the Nb/Yb vs. Th/Yb diagram (Fig. 6d) which shows that the basalts of the lower Muslim Bagh nappe plot at the depleted end of the MORB array. This evidence provides support for the view that the basalts of the lower nappe were generated at a mid-ocean ridge, well away from the influence of any subduction zone.

5. Discussion

5.1. Origin of the Muslim Bagh ophiolitic complex

Two models have been proposed for the tectonic setting of the Muslim Bagh complex: a supra-subduction origin in a back-arc basin (Siddiqui et al., 1996) and a mid-ocean ridge origin (Mahmood et al., 1995), and these will be reviewed in this section.

A wide range of ophiolites and related rocks can be formed in fore-arc terranes. These may be derived both from crust formed outboard of the trench and emplaced in the fore-arc, and from in situ injection of basic magma into the accretionary complex (Dewey, 1976; Lytwyn et al., 1997). Shervais (2000, 2004) proposed that supra-subduction zone ophiolites are mostly of fore-arc origin and that back-arc basins are less important in the search for ophiolitic analogues with subduction characteristics. Dewey and Bird (1971) argued that the presence or absence of an island arc could be used to discriminate between a mid-ocean and back-arc basin origin for ophiolite complexes, since a back-arc basin must be associated with an arc. Additionally, Hawkins (2003) has proposed that arc-derived clastic sediments on an ophiolite may be another key indicator of its original tectonic setting.

It is significant that (a) the Muslim Bagh ophiolitic complex is not apparently associated with an arc and (b) arc-derived sediments do not overlie the complex which was only covered by shallow marine Eocene limestone, *after* final tectonic emplacement onto the Indian continental margin (Allemann, 1979). These observations led Mahmood et al. (1995) to propose that the Muslim Bagh ophiolitic complex formed at a mid-ocean ridge with the upper ophiolite nappe representing a slow-spreading mid-ocean ridge system and the lower nappe consisting of *mélange*.

The evidence for slow mid-ocean spreading was based on the lherzolite present in the Jang Tor Ghar massif and the occurrence of what was interpreted to be oceanic crust. Mahmood et al. (1995) proposed that the gabbro pluton of the Takri area (Southeast of Saplai Tor Ghar) formed at a mid-ocean ridge. However, mid-ocean ridge-generated oceanic crust consists of a gabbroic section (layered gabbro, foliated gabbro and isotropic gabbro), mafic sheeted dyke complex with pillow lavas and associated sediments (Nicolas, 1989). In contrast, as has been shown, the Muslim Bagh upper nappe, particularly around the Saplai Tor Ghar massif, possesses only isolated gabbro bodies, and a sheeted dyke complex and pillow lavas with associated sediments are clearly absent.

It is possible that the pre-existing oceanic crust of the upper nappe was eroded before or during tectonic transportation and emplacement onto the Indian continent. However, the evidence from other Tethyan ophiolites (e.g. Troodos and Oman) which preserve complete oceanic crustal sequences, strongly suggest that such erosion during transportation and obduction is relatively insignificant. It is therefore unlikely that the upper layers of the Muslim

Bagh ophiolitic complex were removed by this process. Another possibility is that the top-most crustal layers of the upper nappe were eroded *after* obduction onto the Indian continental margin. However, if erosion occurred after tectonic emplacement then the continental margin sediments (the Early Eocene Nisai formation) deposited on the oceanic crust should also be eroded. Significantly, the Nisai formation was deposited directly on the mantle rocks and this clearly indicates that when the upper nappe emplaced on the continental margin it did not possess sheeted dykes or pillow lavas. Therefore, the most likely scenario given the evidence outlined above, is that emplacement of the upper nappe occurred without pre-existing oceanic crust and was only comprised of mantle rocks along with the subduction-related isolated gabbro plutons and their feeder dykes. Similar occurrences of mantle rocks and gabbros have been reported along present-day spreading centres, e.g. at 15°N on the Mid-Atlantic Ridge (Canat et al., 1997).

Neither the geochemistry nor the structure of the gabbros and dolerite dykes are consistent with a sea floor spreading origin. As has been discussed, subduction initiated ~71 Ma, whereas gabbro plutons in this subduction zone formed around ~69 Ma. There is therefore a relatively small time gap between subduction initiation and the formation of dolerite dykes and gabbro plutons, implying relatively rapid formation of the arc-derived rocks of the Muslim Bagh complex. The explanation for this rapid formation may lie in the fact that movement at the western margin of the Indian plate was mainly transform/transcurrent, and only temporarily convergent. Thus, there was probably no back-arc basin, which requires a long-lived subduction zone (Pearce, 2003) and is almost always associated with a mature island arc system with significant volcanic edifices.

We therefore propose that the dolerite dykes and gabbro plutons formed in the over-riding plate above a subduction zone, and ultimately became the Muslim Bagh upper nappe (Fig. 7). The magmatism did not cause rifting, nor the development of an extensive sheeted dyke complex above the gabbro plutons. As has been noted above, even the largest pluton intruding the Muslim Bagh upper nappe (the Takri pluton) shows only the poorly developed roots of a sheeted dyke complex and it is clear that the magmas solidified as hypabyssal intrusions (nascent-arc rocks). This suggests, along with the geochemical evidence that the gabbros and dolerite dykes of the upper nappe formed in a short-lived 'nascent-arc' setting.

5.2. Muslim Bagh: a composite tectonic setting ophiolite?

The Muslim Bagh ophiolitic complex consists of two nappes of different age, lithology and tectonic setting. The upper nappe is a supra-subduction zone ophiolite, whereas the lower nappe formed at a mid-ocean ridge (and hotspot) during the separation of the Indian plate from the African plate. Thus the Muslim Bagh ophiolitic

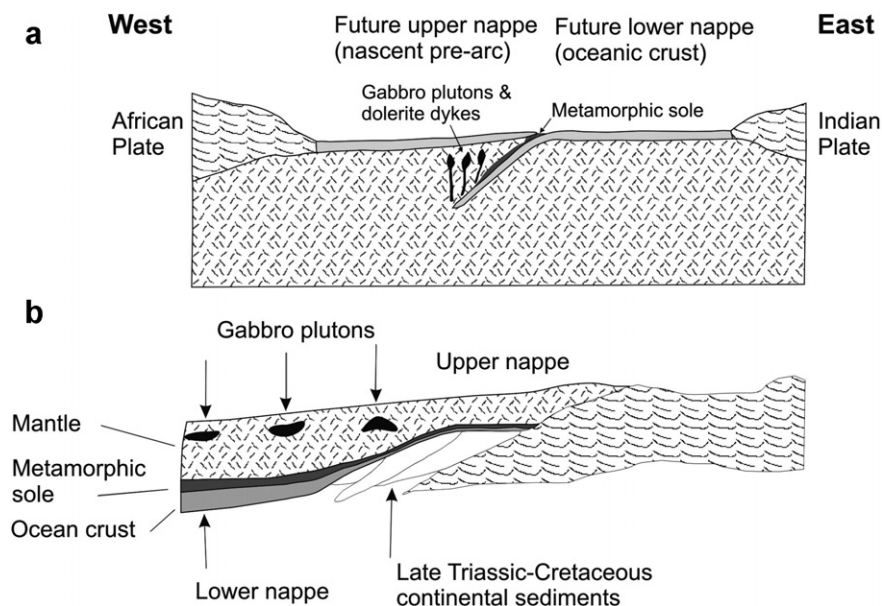


Fig. 7. Schematic crustal cross sections showing (a) the upper ophiolitic nappe being generated in a nascent-arc subduction setting and, (b) the upper and lower nappes both emplaced on Indian continental margin sediments.

complex has characteristics of both supra-subduction zone and mid-ocean ridge settings. Most current classification schemes for the origin of ophiolites propose either a supra-subduction zone or a mid-ocean ridge setting. The ophiolitic complex at Muslim Bagh does not fall into either classification and clearly is derived from several tectonic settings and so can be regarded as an ophiolite of composite tectonic origin.

It has been proposed that some ophiolites have been derived from a 60 to 100 km wide belt of typical oceanic lithosphere which was in existence prior to island arc inception, and was trapped between the trench and the arc system at the onset of underthrusting (Karig, 1982; Leith, 1984 and Geary et al., 1989). Although Pearce (2003) has suggested that this crust need not be trapped and could be lost by trench erosion or development of a second subduction zone, the results of our study clearly indicate that this old trapped oceanic lithosphere can survive and is the first part of the ophiolite to be emplaced onto the continent.

Furthermore, if we assume that the old oceanic lithosphere is destroyed during collision then the metamorphic sole rocks should also be lost. These sole rocks formed during the inception of intra-oceanic subduction, which would have been welded below the old oceanic lithosphere at the time accretion (Boudier et al., 1988; Hacker, 1990; Searle et al., 2003). However, the presence of these sole rocks below many ophiolites (e.g. Nicolas, 1989) demonstrates that the leading edge of old oceanic lithosphere is often not tectonically eroded and can result in an ophiolite sequence with characteristics of a both mid-ocean ridge and supra-subduction zone ophiolite.

Other examples of ophiolitic complexes with a composite tectonic origin are found in the Philippines, California, Japan and Cuba. The Zambales ophiolite of the Philippines

consists of Eocene arc (or back-arc ocean crust) and pre-existing Cretaceous oceanic lithosphere (Encarnacion et al., 1993; Geary et al., 1989; Yumul et al., 2000). The ophiolites of the western Sierra Nevada foothills in California include Jurassic arc-derived rocks and pre-existing Paleozoic–Early Mesozoic oceanic lithosphere (Dilek et al., 1990). Cuban ophiolites also display evidence of several tectonic settings. Cobiella-Reguera (2002) showed that the northern ophiolite belt of Cuba consisted of Upper Jurassic–Neocomian age oceanic lithosphere fragments (mid-ocean ridge origin) and back-arc basin associated with Aptian–Albian volcanic arc rocks. Geochemical data for the northern ophiolitic belt also suggests that part of it contains supra-subduction zone signatures (Proenza-Fernandez, 1997) while other parts possess N-MORB-type and oceanic plateau signatures (Ando et al., 1996; Iturralde-Vinent et al., 1996; Kerr et al., 1999).

The above examples clearly demonstrate that these ophiolites have both supra-subduction zone and mid-ocean ridge characteristics, suggesting formation in several tectonic settings. This type of ophiolite has been termed “Sierran-type ophiolites” by Dilek (2003) in his classification of ophiolites.

6. Conclusions

1. The exposures of the Muslim Bagh ophiolitic complex show three different magmatic stages which originated in different tectonic settings. The first stage represents mid-ocean ridge-related basalts of the lower nappe which formed in the Late Jurassic to Late Cretaceous during separation of the Indian and African plates. The second stage is characterised by the intrusion of

hotspot-derived rocks into the pre-existing oceanic crust during the northward movement of the Indian plate. The third stage consists of the formation of dolerite dykes and gabbro plutons of the upper nappe. Field observations show that dolerite dykes were feeders of the gabbro plutons. This is confirmed by the geochemical similarity between the dolerite dykes and the gabbros, which all possess a clear geochemical signature of subduction.

2. The absence of sheeted dykes and pillow lavas in the Muslim Bagh upper nappe may indicate a low magma supply rate and supports the contention that these gabbro plutons formed in a short-lived subduction zone with minimal associated rifting and extension.
3. The Muslim Bagh ophiolitic complex shows two stages of emplacement, (1) intra-oceanic emplacement of the upper nappe onto the lower nappe at a nascent subduction zone, which is marked by the metamorphic sole rocks and (2) final emplacement onto the Indian continental margin which is marked by the Gawal-Bagh thrust between the ophiolite and continental sediments.
4. The Muslim Bagh ophiolitic complex has characteristics of both supra-subduction zone and mid-ocean ridge settings, and is also intruded by hotspot-derived magmas. The Muslim Bagh 'ophiolite' clearly formed in several tectonic settings and can be described as a composite tectonic origin ophiolite. It is possible that ophiolites with composite tectonic settings, like the Muslim Bagh ophiolitic complex, may be more common than hitherto realised, and thus we would advocate a cautious approach in the interpretation of the tectonic setting of older ophiolites.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.jseae.2007.04.006](https://doi.org/10.1016/j.jseae.2007.04.006).

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