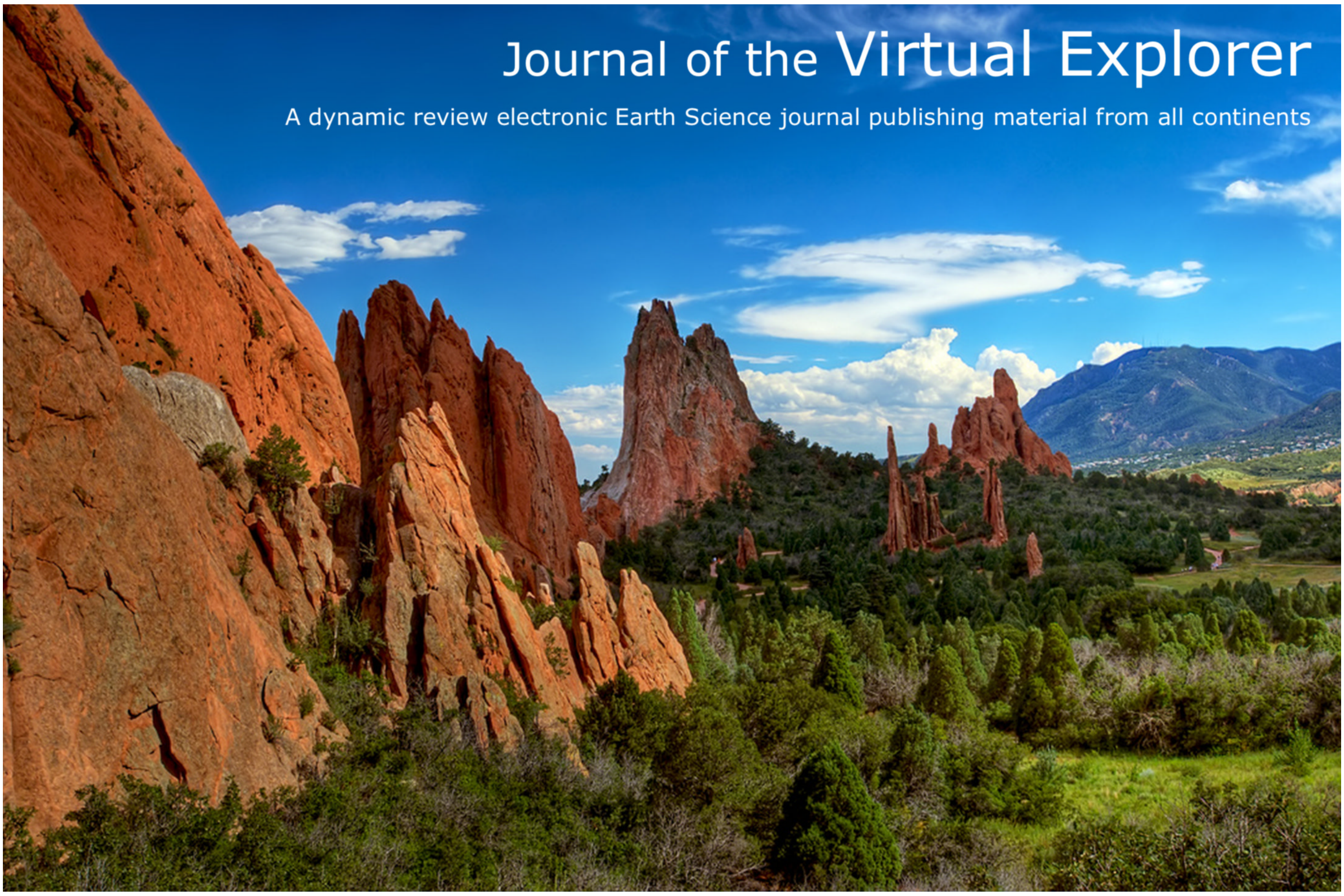

Discovery of a Neo-Tethyan ophiolite in Northern Iran: Evidence for its formation at a slow–spreading center

M. Salavati, A. Kananian, M. Noghreian, A. Darvishzadeh, A. Samadi Soofi

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Abstract: The Southern Caspian Sea ophiolite complex (SCO) is an almost complete oceanic lithospheric section including from bottom to top, layered ultramafic cumulates, layered gabbros, isotropic gabbros, sheeted dike and basaltic lavas with a pelagic limestone cap yielding an Late Cretaceous age.

Layered ultramafic cumulate rock is composed of clinopyroxenite, wehrlite, dunite and massive- to layered-mafic cumulate rocks consisting of gabbro and norite. Disaggregated, this ophiolite complex includes a small sheeted dike complex and a preponderance of pillow lavas over sheet flows in the volcanic section. Geological observations such as the absence of well-developed layered gabbro, the presence of pyroxenite dikes, the presence of small pockets of sepentenized dunites, the absence of well-developed dike complex, the absence of chromatic pods, well-developed extended point source volcanism onto pillow lavas, the presence of gabbro pegmatoidic dikes in layered and isotropic gabbro suggest that the SCO is a lherzolite ophiolite type (LOT) and was formed in a slow-spreading center.

The available field and geochemical data on SCO (the presence of highly magnesian clinopyroxene (Mg# =81-90), homogeneous composition of clinopyroxene, absence of zoning in clinopyroxene and low Mg# in coexisting olivine, the geochemical data for the volcanic, mafic–ultramafic cumulate rocks and REE features (Nb,Ti and Zr negative anomalies)) show that this ophiolite complex was formed in medium- to high-pressure from the basaltic magma in a subduction-related marginal basin such as an island arc/suprasubduction zone tectonic setting.

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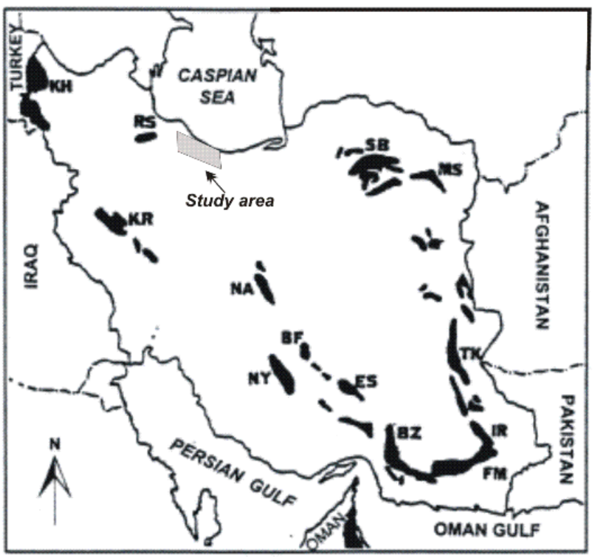
Introduction

Iranian ophiolites are part of the Tethyan ophiolites of the Middle East. They link the Middle Eastern and Mediterranean Hellenides–Dinarides ophiolites (e.g. Turkish, Troodos, Greek and East European) to more easterly Asian ophiolites (e.g. Pakistani and Tibetan) (Shojaat *et al.*, 2003). Tethyan evolution in Iran and neighboring Turkey, Oman and Baluchistan is very complex and hard to work out.

The main tectonic elements of Iran and the locations of the major Iranian ophiolites are depicted in Figure 1. Geographically, the Iranian ophiolites have been divided into four groups (Takin, 1972; Stocklin, 1974; McCall, 1997; Hassanipak and Ghazi, 2000 and Shojaat *et al.*, 2003): (i) ophiolites of northern Iran along the Alborz range, (ii) ophiolites of the Zagros Suture Zone, including the Neyriz and Kermanshah ophiolites, which appear to be coeval with the Oman (Samail) ophiolite emplaced onto the Arabian continental margin, (iii) unfragmented ophiolites of the Makran accretionary prism which include the complexes of Band-e-Zeyarat/Dar Anar and Remeshk/Mokhtar Abad, and (iv) ophiolites and colored melanges that mark the boundaries of the central Iranian microcontinent (CIM), including Shahre-Babak, Nain, Baft, Sabzevar and Tchehel Kureh ophiolites. The CIM is composed of the Yazd, Posht Badam, Tabas and Lut blocks.

Figure 1. Distribution of the ophiolite belts in Iran



Distribution of the ophiolite belts in Iran after Emami *et al.* (1993), and location of the SCO area. Main Iranian ophiolite complexes: BZ: Band-e-Ziyarat (also called Kahnuj complex). KM: Kermanshah. NA: Nain. NY: Neyriz. SB: Sabzevar. SHB: Shar Babrak. THL: Torbat Hydariyah. TK: Tchehel Kureh

The Alborz range of northern Iran is a region of active deformation within the broad Arabia–Eurasia collision zone (Allen *et al.*, 2003). It is an active orogenic belt that contains a number of ophiolites, which suggests that the continental collision between Arabia and Eurasia occurred along the Alborz Suture Zone. On the southern coast of Caspian Sea, in Northern side of Alborz range, two ophiolite sequences are reported: 1) Asalem-Shanderman (Talesh) ophiolite in Paleozoic (Berberian, 1983 and Eftekharnejad *et al.*, 1993); and, 2) Southern Caspian Sea ophiolite complex (SCO) in Mesozoic (Salavati, 2000).

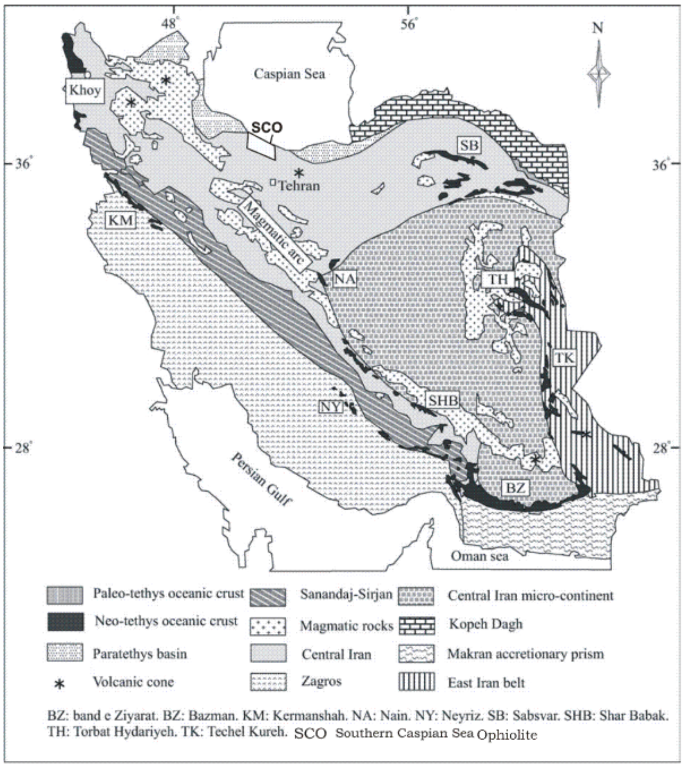
The results of most of the petrological and geochemical studies on the Iranian ophiolites show mid-ocean ridge basalt (MORB) and island arc tholeiite (IAT) affinities with a harzburgite mantle that indicate a HOT type ophiolite (Desmons and Beccaluva, 1983; McCall and Kidd, 1981; Wampler *et al.*, 1996; Ghazi *et al.*, 1997; Hassanipak and Ghazi, 1996a: Ghazi and Hassanipak, 1999a). Also some LOT ophiolite type are reported in Iran such as Upper Cretaceous Khoy ophiolite (Khalatbari-Jafari *et al.*,2006).

In this paper with the results of petrological and geochemical studies of the Southern Caspian Sea ophiolite and comparison SCO with other famous world ophiolites, we attempt identification of SCO ophiolite type, and suggest a possible tectonic formation for this ophiolite within the context of the Neo-Tethyan tectonic reconstruction models of Iran and the Middle Eastern region.

The Southern Caspian Sea ophiolite complex

The Southern Caspian Sea ophiolite complex is located in the north part of the Iranian Guilan province (Figure 2).

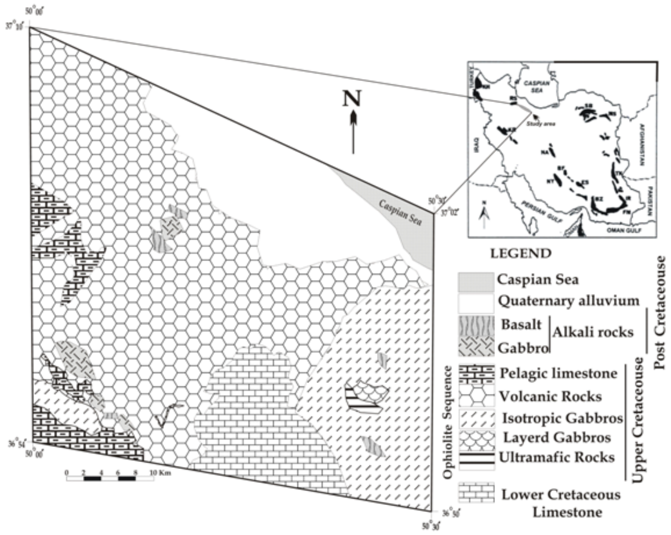
Figure 2. Location of the SCO ophiolites in Iran



Location of the SCO ophiolites with respect to the main ophiolite belts in Iran (in black), and to the main geological formations of Iran. Adapted from the 'Magmatic Map of Iran' at 1/1,000,000, compiled by M.E. Emami, M. Mir Mohammad Sadegi and S.J. Omrani (1993, Geological Survey of Iran) (Emami *et al.*, 1993), and from the 'Sedimentary-structural map of Iran' by A. Aghanabati (2004).

The SCO occurs as lense body that has NNW-SSE trend and is one of the best-preserved oceanic crustal remnants of the Mesozoic Iranian ophiolites (Figure 3).

Figure 3. The geological map of the SCO

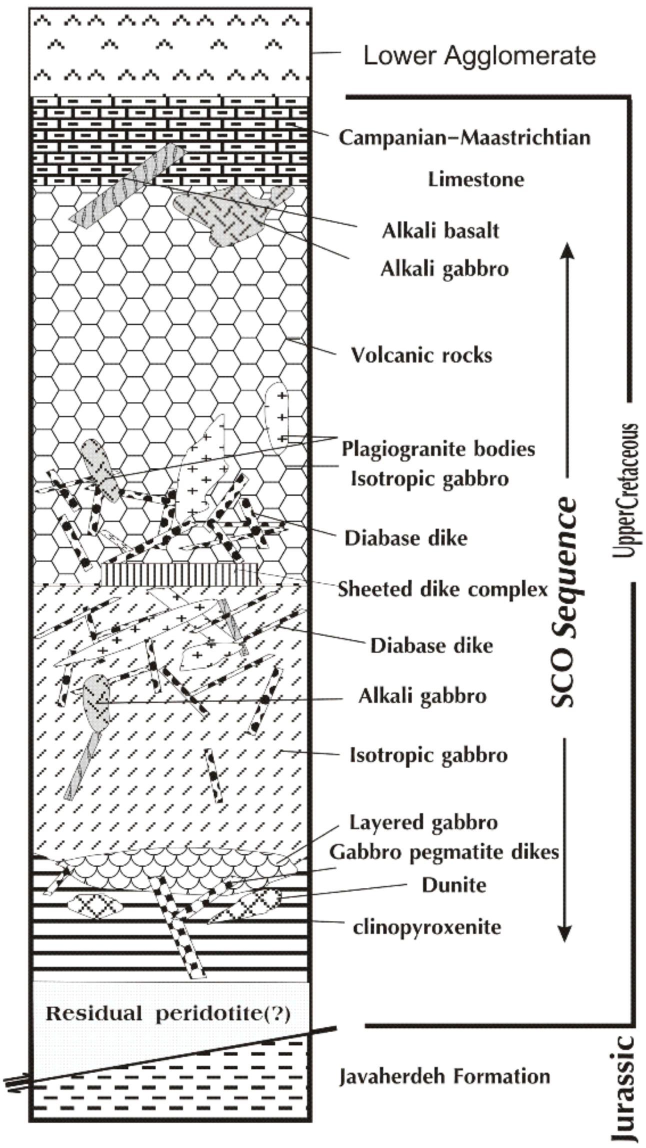


The geological map of Southern Caspian Sea ophiolite, showing the main geological unit of SCO.

The study of different parts of SCO ophiolite was difficult because of poor accessibility and dense rain forest. The full suite of ophiolite lithologies is present only on the southern coast of the Caspian Sea in the East Guilan. Detailed maps are shown in (Figure 3).

The study of schematic stratigraphic columns of the SCO show that the SCO is almost a complete oceanic lithospheric section (Figure 4) including, from bottom to top (east to west): ultramafic cumulates (dunite, wherlite, olivineclinopyroxenite and clinopyroxenite), layered gabbros, isotropic gabbros, sheeted dike complex and basaltic pillow lavas (Figure 3) covered by Campanian-Early Maastrichtian limestone bearing fossils of Globotruncana. Pelagic sedimentary rocks contain upper Cretaceous fossils that indicate an upper Cretaceous age for the formation of the pillow basalts, the final phase of the formation of the oceanic crust.

Figure 4. Stratigraphic columns of the SCO.



Schematic reconstructed ophiolite stratigraphy of the SCO.

a) Ultramafic cumulate rocks

The cumulate ultramafic sequence in the SCO is well exposed in the eastern part of the region along the roads between Syahkalrood and Javaherdasht and between Ramsar and Javaherdeh, whereas the basaltic volcanic unit is exposed in almost all areas (Figure 3).

Unfortunately, mantle rocks (lherzolite and/or harzburgite) cannot be found in this ophiolite complex. It seems that the mantle parts of this ophiolite are not outcroped and only crustal parts of SCO ophiolite can be observed. Ultramafic rocks of the SCO comprise a wide variety of dunites, wherlite, olivine-clinopyroxenite and pyroxenites. The SCO ultramafic sequence covers only 10% of the area of the ophiolite in SCO (Figure 3), and generally, pyroxenite is more abundant than dunite. Dunite occurs as lenses or thick layers within pyroxenites. It seems that this part is the base of gabbroic units. At the top of this unit gabbroic magma is intruded as dikes.

b) Layered to massive gabbro

The gabbroic complex is composed of different types of lithology (massive gabbro, layered gabbro). The thickness of each rock type is highly variable. The layered gabbro has varied thickness in each layer ranging from a few centimeters to 80 centimeters.

c) Sheeted dike complex—sheet flows to pillow lavas

At the top of isotropic gabbroic unit, the transitional zone from upper gabbro to sheeted dike complex is very clear and it is represented only in eastern study area. The complete sequence of sheeted dike complex is not found.

In the bottom of extrusive units a transitional zone between diabase dikes and pillow lavas is observed that gradually converts to pillow lava units.

The width of the dikes ranges from 10-20 cm, with the color varying from brown through green to yellowish green. Although the rocks have undergone low-grade greenschist-facies metamorphism as a result of ocean floor metamorphism, fresh plagioclase and clinopyroxene can still be identified. The dominant texture is intersertal to intergranular. Baking and chilling is present, although a preferential direction of chilling is absent.

Volcanic rocks are the most widespread rock-type in the SCO ophiolite (Figure 3). The volcanic rocks occur as pillow lava, massive lava and pillow breccias, and cover almost 80% of the ophiolite area, typically forming rounded hills and topographic high. In volcanic units the pillow forms are dominant and are more abundant than the other forms (the ratio of pillow lava to sheet lava is 90 to 10), indicating a slow-spreading center (Juteau and Maury, 1999). Sometimes sedimentary beds were found between the lava indicating a gap in volcanism. The pillow pieces have various sizes ranging from 10cm to 15 meters in diameter. Pillows show complete zonation from surface to core generally with a clear chilled margin. Similar to what is noted in the dike complex, the pillow lavas and sheet flows have plagioclase and clinopyroxene with textures ranging from intersertal through intergranular to spherulitic.

At their top, pillows have a carbonate or hyaloclastic breccias matrix. The volcanic unit capped by Upper Cretaceous pelagic limestones contains the following Campanian-Early Maastrichtian micro faunas: Globotruncana stuari, Globotruncana elevata, Globotruncana covanata, Globotruncana conica and Globotruncana calcarata. The limestone unit has a N110E strike with 25 dip toward southeast.

Both pillow and sheet lavas have vesicular texture and quartz, chlorite, calcite and epidote fills the vesicles.

Andesite to trachy-andesite dikes or small subsurface bodies crosscut volcanic unit and limestone. In addition, plagiogranite dikes or veins crosscut pillow unit. Gabbroic dikes with highly variable thicknesses up to 4 m were found in the volcanic unit.

Ophiolite complexes are generally metamorphosed as a result of ocean floor metamorphism. Volcanic components always suffer burial metamorphism and intense hydrothermal alteration commonly attributed to ocean floor metamorphism. Most SCO rocks show alteration of primary mineral assemblages, with varying degrees of low-grade metamorphism. Secondary mineral assemblages are generally heterogeneous and patchily distributed, even on the scale of a single thin section. Secondary mineral assemblages in the SCO rocks (from basalt to gabbro/cumulate) represent metamorphic facies ranging from zeolite to greenschists. The metamorphic grade increases downward through the ophiolite succession and reaches greenschist facies in the cumulate rocks.

Lastly all rocks of SCO are capped by agglomerate that is younger than the SCO.

Geochemistry (Whole rock and mineral geochemistry)

The Southern Caspian Sea ophiolite have a mainly tholeiitic nature although some rocks have alkaline nature. Available geochemical data show that the volcanic to hypabyssal rocks exhibit transitional Mid-Ocean Ridge basalt-island arc tholeiite signatures. Salavati (2000) showed that most of the volcanic–hypabyssal rocks are tholeiitic. MORB-like and alkaline basalt rocks are also recognized (Salavati, 2000). The tholeiitic (Zr/Y=3.5-5.5; Ti/V=19-35) and MORB-like (Zr/Y=6-8; Ti/V=76-85) volcanic rocks occur as pillow lavas and sheet flows which are megaclasts within the SCO (Salavati, 2000). The ultramafic have pyroxene with high Mg# (Mg/Mg $^{+}Fe^{2+}$) within a range of 0.8–0.9 and olivine with Fo% ranging from 72 to 77. The gabbro have plagioclase with composition $An_{65}Ab_{33}$ to $An_{78}Ab_{21}$ and pyroxene with low Mg# (Mg/Mg^{+} Fe^{2+}) within a range of 0.72–0.78.

The mineral chemical features of the ultramafic cumulates of the SCO (high Mg# in clinopyroxene and low Mg# in coexisting olivine) show that these rocks formed by crystal fractionation processes from a basaltic liquid at medium to high pressures (up to c. 10 kbar) (Salavati and Samadi Soofi, 2007). The main characteristics of low pressure (1 atm) phase relationships are that large amounts of olivine fractionation with or without plagioclase prior to pyroxene crystallization depletes the residual liquids in MgO, the Mg# of coexisting clinopyroxene, olivine is generally low (~82) and orthopyroxene has an even lower Mg# (~74) (Elthon *et al.* 1992 and Bağci *et al.* 2006) during the crystallization of oceanic basalts at low pressures.

Moreover, low-pressure crystallization of MORBs would yield dunites, troctolites and olivine gabbros (Elthon *et al.* 1992; Pearce *et al.* 1984 and Parlak *et al.* 2002). whereas the products of high pressure crystal fractionation in oceanic basalts would be dominated by dunite, wehrlite, clinopyroxenite, websterite and lherzolite with high Mg numbers for their mafic minerals (Elthon *et al.* 1982, 1992 and Parlak *et al.* 2002). The presence of dunite, wehrlite, olivine clinopyroxenite and clinopyroxenite within the ultramafic cumulates of the SCO would not be expected with the low-pressure crystalization of MORBs (Salavati and Samadi Soofi, 2007).

Mineral composition of clinopyroxene of ultramafic and basaltic rocks shows that Southern Caspian Sea ophiolite, were formed from the basaltic magma in an island arc/suprasubduction zone tectonic setting (Salavati, 2000 and Kananian *et al.* 2005).

The geochemical data for the volcanic, mafic–ultramafic cumulate rocks and their REE features (Nb, Ti and Zr negative anomalies (Salavati and Samadi Soofi, 2003), combined with the geological setting of the ophiolite, suggest that the SCO was generated in a subduction-related marginal basin, such as supra-subduction zone.

Discussion

Evidence for generation in a Slow-spreading center

It is now defined that the physical configuration of the crust–mantle sequence is related to differences in the spreading rate of an oceanic basin, which, to a certain extent, is related to the amount of magma extruded on the surface (Searle, 1992; Niu and Hekinian, 1997; Klingelhofer *et al.* 2000; Graciano and Yumul, 2003). Slow-spreading centers, which would include the Mid-Atlantic Ridge, Southwest Indian Ridge, and the West Philippine Sea, are characterized by a spreading rate of less than 5 cm/year and fluctuating magma supply with mechanical extension resulting primarily from faulting. Fast-spreading centers, with 10 cm/year full spreading rates, are characterized by robust magmatism with sheet flows dominating over pillow lavas. Sediments intercalated within volcanic rocks indicate gaps in volcanism and are indicative of generation along intermediate spreading-rate centers (Karson, 1998).

Slow-spreading centers contain tectonic features that are not readily apparent in intermediate- to fast-spreading centers (Tucholke *et al.* 1998; Fujioka *et al.* 1999; Allerton *et al.* 2000, Graciano and Yumul, 2003 and Khalatbari-Jafari *et al.*, 2004). Submersible dives and dredging data supported by geophysical information show that slow-spreading centers are characterized by (a) small volume of gabbros, (b) general absence of dike complex, (c) deep-water sediments or volcanic rocks directly overlying peridotites, (d) large-scale extensional faulting, (e) discontinuous axial magma chambers, (f) localized hydrothermal deposits, and (g) large-scale tilting of the crust (Cannat and Casey, 1995; Lagabrielle *et al.* 1998). As already mentioned, due to the paucity of magmatism and the low degree of partial melting, the crust has time to solidify and strengthen because the main cause of mechanical extension is faulting (Ishiwatari, 1985; Karson, 1998). Volcanism is also characterized by point source volcanism with the lava flows dominated by pillow structures (Searle, 1992). With the robust magmatism in fast-spreading centers, volcanism is fissure-type with the dominance of sheet flows with respect to pillow lavas. The typical magmatic activities of fast-spreading centers ensure the existence of long-lived magma chambers (MacDonald, 1998).

Comparing the SCO with the above geological attributes gives an idea of the responsibility of the kind of spreading center for the generation of this ancient sequence. The layered- and massive-gabbro suggest the presence of a local magma chamber (Figure 3). Slow-spreading centers have no well developed magma chamber and are dominated by gabbro pods within the peridotite indicating episodic intrusion or a low magma budget.

The SCO is intensely faulted - brought about by mechanical extension as is the case for slow-spreading centers. The presence of a sediment layer within the volcanic suite may indicate that a gap in volcanism was encountered. This supports the possibility of the SCO being formed in a slow-spreading center.

The paucity of well-developed layered-gabbro indicates that a magma chamber does not exist and supports the formation of the SCO in a slow-spreading center. Although the rate of spreading may change through time or even along the ridge axis (Lagabrielle and Lemoine, 1997), there is no compelling evidence to conclude that the SCO is formed in a fast-spreading environment.

The presence of widespread pillow lava with respect to sheet lavas in the studied area (ratio 90 to 10) indicates that the rate of the spreading center is slow. Based on the diagram of spreading rate versus pillow lava/sheet lava (Juteau and Maury, 1999), the rate calculated for this ophiolite is less than 5 cm/year.

In conclusion, based on the observed field characteristics of the SCO, it is believed that this ophiolite complex has characteristics of slow-spreading centers and was formed in a slow-spreading center.

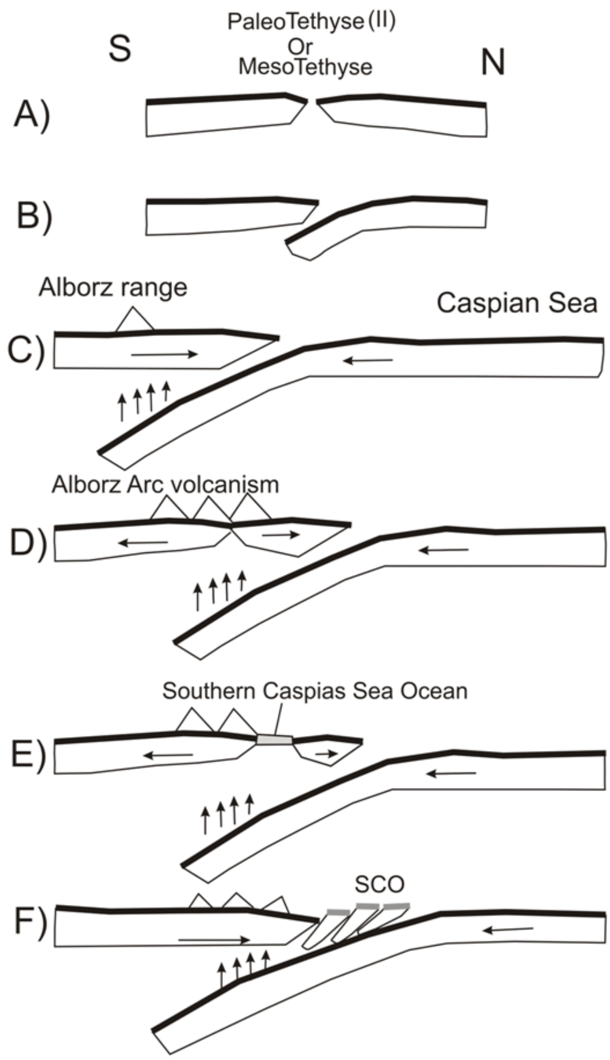
Harzburgite ophiolite type or lherzolite ophiolite type?

The crust–mantle sequences from slow-spreading centers correspond to the lherzolite ophiolite type (LOT) while those from fast-spreading centers are characterized by the harzburgite ophiolite type (HOT) (Nicolas and Al Azri, 1991). As presented in the works of Boudier and Nicolas (1986), the HOT is characterized by (a) a metamorphic sole made up of metamorphosed oceanic crust, (b) a thick cumulate gabbro layer, (c) an intrusive complex dominated by dikes, (d) volcanic rocks having tholeiitic characteristics and the mantle section composed of harzburgite and dunite, and (e) the presence of chromite pods. The LOT is defined as having (a) a metamorphosed continental or oceanic crust as the metamorphic sole, (b) thin to poorly developed mafic cumulate layer, (c) the preponderance of sills over dikes, (d) the presence of tholeiitic to alkaline volcanic rocks with the mantle section characterized by plagioclase lherzolite, and (e) rare to absent chromite pods. Considering at these varying parameters, it can be readily seen that the HOT has undergone greater degrees of cumulative partial melting in comparison with the LOT (Ishiwatari, 1991). This is because of the dissimilarity between fast- and slow-spreading centers. Fast-spreading centers, characterized by robust magmatism, have mantle source regions that have undergone more stages and greater degrees of partial melting resulting in the formation of harzburgite as the residual peridotite (Niu and Hekinian, 1997). On the other hand, slow-spreading centers are characterized by episodic magmatism, which is exposed to lower degrees of partial melting comparing with fast-spreading centers (Ishiwatari, 1985). As a result, clinopyroxene-bearing harzburgite or lherzolite, in general, characterizes the mantle peridotite section of slow-spreading centers.

Based on the field characteristics, the SCO contains pillow lavas and rare sheet flows with a rare associated hypabyssal dike complex and a small mafic cumulate sequence. Furthermore, no pods of chromite are present. It seems that the appropriate condition for the formation of chromite mineralization (e.g. high P_{H2O}; high fO_2; extensive mantle–melt interaction) was not achieved. Unfortunately, the mantle parts of SCO are not outcropped and we could not find any lherzolite or harzburgite sample in the whole study area. Although there is no occurrence of lherzolite because of dense rain forest, the absence of orthopyroxene in the samples of ultramafic sequences can be evidence for non-formation of harzburgite in this region. Now, based on the absence of harzburgite or lherzolite the important question that arises is, "is the SCO sequence a lherzolite ophiolite or a harzburgite ophiolite?"

After opening of the older ocean (Paleo-Tethys(II) (Eftekharnejad *et al.*, 1993) or Meso-Tethyse (Spakman, 1986 and Golonka, 2004)) in Northern Iran (Figure 5a), the Southern Caspian margin developed by seafloor spreading. Subduction began beneath the Central Iran Block, after the collision of this microcontinent with Eurasia (Figure 5b). This subduction produce Alborz arc volcanism during Cretaceous to Cenozoic (Figure 5c). The last oceanic lithosphere was produced during Upper Cretaceous in a closing oceanic basin and in a slow-spreading center (Figure 5d). Probably this oceanic lithosphere was formed above the arc volcanism zone and was possibly metasomatised by fluids coming from the subducted slab and may explain the observed island arc geochemical signature (Figure 5e). This oceanic lithosphere was never subducted and remained unmetamorphosed, creating the Upper Cretaceous ophiolite complex of the Southern Caspian Sea (Figure 5f).

Figure 5. Geodynamic evolution of the SCO.



Proposed scenario for the geodynamic evolution of the Southern Caspian Sea Ophiolite. See text for discussion.

Lastly (Lower Paleocene), due to a change in the stress field from a compressional to a local extensional regime due to a local or regional tectonic event, the Southern margin of the basin began to be thrust beneath the Upper Cretaceous oceanic lithosphere. Very local extension in this time produced the alkali rocks that intruded in all parts of SCO ophiolite. Just before collision, the ophiolite of Southern Caspian Sea was obducted over the older rocks.

Conclusions

The SCO is a complete ophiolite sequence that was disaggregated due to syn- and post-emplacement faulting. The absence of well-developed, layered gabbro, the presence of pyroxenite dikes such as Trinity ophiolite, the presence of small pockets of sepentenized dunites, the absence of well-developed dike complexes, the absence of chromite pods, well-developed and extensive point source volcanism onto pillow lavas, and the presence of gabbro pegmatoidic dikes in layered and isotropic gabbro (such as Trinity ophiolite) suggest that the SCO was formed in a slow-spreading center. The SCO is also classified as a LOT.

The available field and geochemical data show that the SCO was initially generated in a subduction-related marginal basin (or in a supra-subduction zone). A portion of the marginal basin was onramped above a subducting slab.

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