Reports

Mantle Uplifted Block in the Western Indian Ocean

Abstract. *An anomalous topographic high located close to the intersection of the Owen Fracture Zone with the Mid-Indian Ridge exposes exclusively ultramafic rocks for a thickness of more than 2 kilometers. The rocks, consisting of partly serpentinized spinel lherzolites, with minor harzburgites and dunites, display protogranular to porphyroclastic fabrics, but no cumulate textures. The chemistry of olivine, ortho- and clinopyroxene, and spinel crystals suggests that the rocks originated at a depth of at least 25 kilometers in the oceanic lithosphere and were partially reequilibrated and recrystallized during subsequent upwelling. Thus, field, textural, and mineral chemistry data indicate the presence of an uplifted block of upper mantle. The considerable vertical uplift can be explained by a two-stage process: mantle upwelling in the axial zone of plate accretion, followed by vertical tectonic uplift along the fracture zone. The rate of uplift in the fracture zone was of the order of 1 millimeter per year.*

The constitution of the upper mantle beneath the oceans cannot be determined directly because drilling through the entire crust is not yet feasible. Indirect information can be inferred from the velocity of seismic waves reflected or refracted from the mantle; the composition of basaltic magmas whose source region is in the upper mantle; and the constitution of ophiolite complexes thought to be uplifted fragments of former oceanic lithosphere. Ultramafic nodules of noncumulate origin, sampled from the mantle by upwelling magmas in oceanic islands, provide additional data. However, volcanic islands are thought to be located above thermally anomalous mantle (hot spots).

A potential source of additional information could be provided by the study of blocks of upper mantle uplifted to shallow levels in the oceanic crust and thus accessible to sampling. In this report we describe what appears to be a major tectonically uplifted block of upper mantle material which we have found along the Owen Fracture Zone (FZ) in the western Indian Ocean.

The Owen FZ, which offsets the axis of the Mid-Indian (Carlsberg) Ridge by about 300 km (*1*, *2*), is marked topographically by a series of ridges and depressions extending for more than 2500 km from the Somali Basin to the Pakistani continental shelf (Fig. 1). Seismic reflection and petrological data were obtained in several profiles across the Owen FZ during cruise V-33 of the R.V. *Vema* in 1976. One profile was taken close to the intersection of the Owen FZ with the northwest axial segment of the Mid-Indian Ridge (Fig. 1) which constitutes an active accretionary plate margin. This profile shows the sediments from the western Indian Ocean abyssal plain abutting against the upraised basement on the eastern side of the fracture valley (Wheatley Deep). The western side of the fracture constitutes the wall of a transverse ridge running parallel to the fracture zone. Similar transverse ridges are common along large oceanic fracture zones elsewhere (*3*).

Ultramafic rocks were the only material recovered by dredging at different levels on the wall of the transverse ridge (Fig. 1), suggesting that along this profile they outcrop from the base of the transverse ridge to its summit for a thickness of more than 2 km. Ultramafic rocks have been recovered at many sites on the ocean floor. In most cases it is not clear whether they represent tectonically uplifted fragments of upper mantle or cumulative products of differentiation which occurred in lower crustal magma chambers.

A lower crustal origin for such a large ultramafic body as that found at the Owen FZ is unlikely, because currently accepted models allow, at the most, for a very thin layer of cumulus ultramafic rocks at the base of the oceanic crust. These models are based on lower crustal seismic velocities obtained at sea (*4*) and on evidence from ophiolite complexes, which are generally regarded as uplifted fragments of ancient oceanic lithosphere (*5*). If we exclude a lower crustal source, we are left with an upper mantle origin for the ultramafic rocks from the Owen FZ. We consider next whether the textures and phase chemistry of the Owen FZ ultramafic rocks are consistent with an upper mantle origin.

Partly serpentinized spinel lherzolites comprise the dominant rock type at the three sites, but spinel-bearing harzburgite and dunite are present also. The coarse grain size (average, 2 to 10 mm) and variable mineral proportions of these rocks prohibit an accurate estimation of modes in thin sections, but in the lherzolites the approximate range is olivine (+ serpentine), 50 to 80 percent; orthopyroxene, 10 to 40 percent; clinopyroxene, 5 to 20 percent; and minor spinel, 0 to 3 percent; and in the harzburgites it is olivine (+ serpentine), 70 to 90 percent; orthopyroxene, 10 to 30 percent; clinopyroxene, 0 to 5 percent; and minor spinel, 0 to 3 percent. Two samples of dunite contain accessory spinel and no pyroxene. Texturally the rocks are similar to

Table 1. Composition of minerals in a representative spinel lherzolite (sample IN19C) from the Owen Fracture Zone. Values are percentages by weight.

Component	Olivine	Orthopyroxene			Clinopyroxene			Spinel
		Primary	Unmixed	Recrystallized	Primary	Unmixed	Recrystallized	
SiO_2	40.73	55.05	54.83	55.66	51.35	51.63	53.95	0.00
TiO_2	0.04	0.03	0.02	0.00	0.16	0.21	0.18	0.03
Al_2O_3	0.00	4.68	5.02	3.52	5.71	5.82	3.48	48.32
ΣFeO	10.18	5.31	5.75	6.81	3.05	2.92	2.52	13.57
MnO	0.15	0.04	0.03	0.05	0.04	0.02	0.05	0.05
MgO	48.29	32.48	32.36	32.31	17.73	17.63	17.00	17.50
CaO	0.09	1.78	1.42	1.30	21.20	22.13	23.10	0.00
Na_2O	0.02	0.01	0.02	0.01	0.16	0.16	0.13	0.00
K_2O	0.09	0.00	0.00	0.00	0.02	0.02	0.01	0.00
Cr_2O_3	0.02	0.52	0.52	0.39	0.88	0.86	0.37	19.08
NiO	0.45	0.04	0.05	0.03	0.05	0.06	0.09	0.20
Total	100.06	99.94	100.02	100.08	100.35	101.46	100.88	98.89*

*Includes 0.02 percent ZnO and 0.12 percent V_2O_3.

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alpine ultramafics (6) and ultramafic inclusions in kimberlites (7) and in basalts (8), displaying transitional protogranular to porphyroclastic fabrics. No cumulus textures, relict or otherwise, have been observed in any samples.

Both orthopyroxene and clinopyroxene form large (1 to 25 mm) rectangular to ovoid anhedra displaying mutual exsolution lamellae, various strain features, and recrystallized grain margins. The "primary" cores of orthopyroxene and clinopyroxene exhibit a very restricted compositional range (9) (Table 1) and show no correlation with variation in modal content (10). The fine-grained recrystallized margins are free of exsolution and compositionally distinct from the primary cores, having lower Al_2O_3 contents, and lower and higher CaO contents in orthopyroxene and clinopyroxene, respectively (Table 1). Zoning in the primary grains to compositions approaching recrystallized pyroxene is frequently developed in areas adjacent to the latter. Olivine, which forms the matrix to pyroxene in the lherzolites and harzburgites, is moderately serpentinized, unzoned, and compositionally indistinguishable (90.3 to 89.0 percent forsterite) in all three rock types. The spinel is anhedral, granular to distinctly intergranular, and unzoned in all but the more severely serpentinized samples, where it may contain mantles of secondary magnetite. Compositionally, the spinel ranges discontinuously from $(Mg_{0.75}Fe^{2+}_{0.25})(Cr_{0.30}Al_{1.65}Fe^{3+}_{0.05})O_4$ to $(Mg_{0.65}Fe^{2+}_{0.35})(Cr_{0.80}Al_{1.11}Fe^{3+}_{0.09})O_4$. The Cr-poor variety is common to lherzolites, harzburgites, and dunites, while Cr-rich spinel is found only in pyroxene-bearing samples and is correlated with higher Cr content in orthopyroxene. There is no apparent correlation between Cr/Al spinel ratios and orthopyroxene/clinopyroxene or pyroxene/olivine ratios, in contrast to the trend commonly observed in alpine ultramafics (11). The intimate association of much of the spinel with recrystallized Al-poor pyroxene (particularly orthopyroxene) suggests that it formed by the reaction Al-rich pyroxene + olivine $\rightarrow$ Al-poor pyroxene + spinel. However, no chemical differences are observed between this spinel and that spatially unrelated to recrystallized pyroxene.

The phase chemistry and textures of the lherzolites and harzburgites indicate a complex reequilibration history. Three stages of mineralogical evolution can be recognized: (i) crystallization of the primary pyroxene porphyroclasts, (ii) unmixing of Ca-rich and Ca-poor pyroxene from their respective host pyroxenes, and (iii) peripheral zoning and recrystallization of the primary pyroxene porphyroclasts. Application of the semiempirical, two-pyroxene geothermometer of Wells (12) to a representative sample of spinel lherzolite (Table 1) gives temperatures of 1110°, 1070°, and 990°C for primary, unmixed (13), and recrystallized pyroxene pairs, respectively. These values, together with the absence of exsolution lamellae within recrystallized pyroxene, substantiate the inferred chronological order of stages (ii) and (iii).

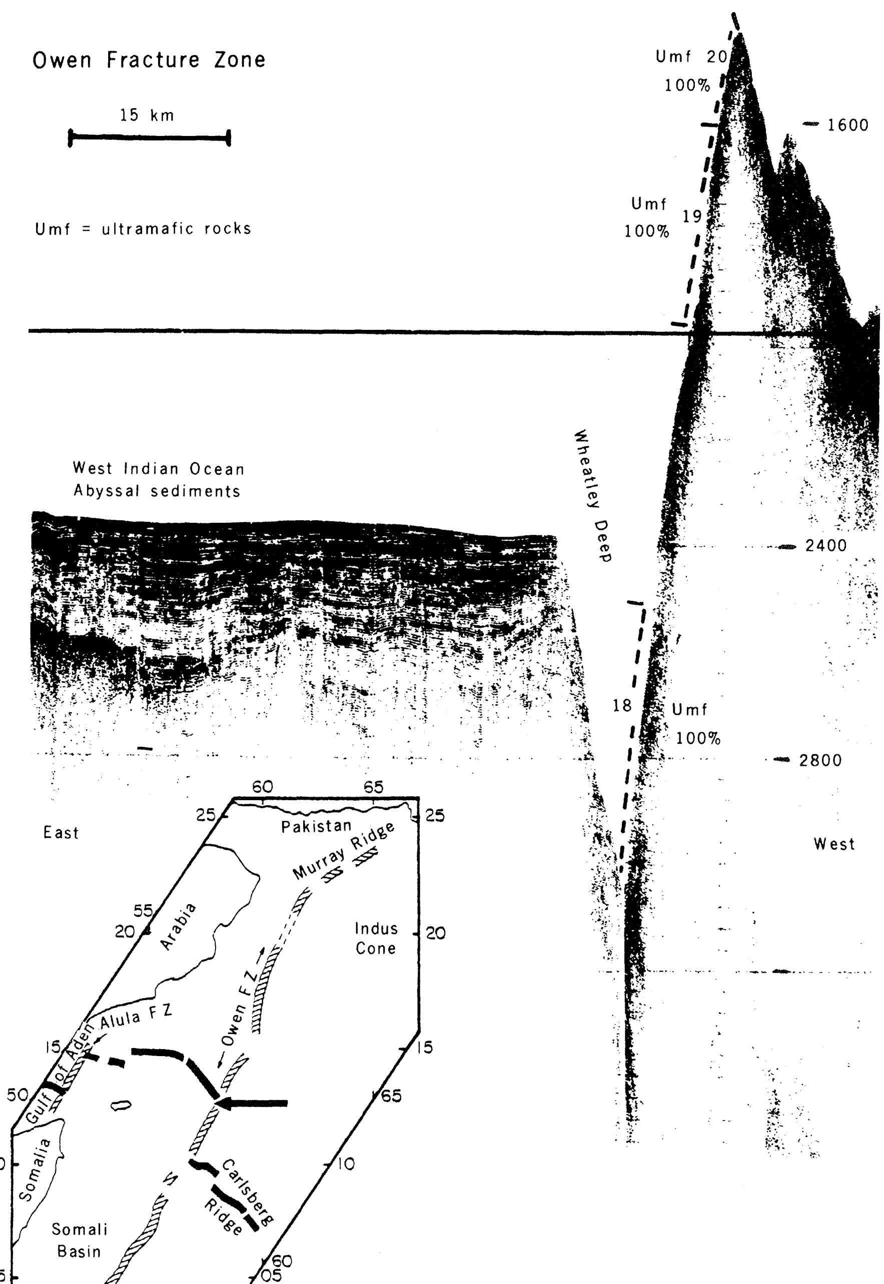

Fig. 1. Seismic reflection profile taken across the Owen Fracture Zone, near its intersection with the Mid-Indian (Sheba) Ridge. The location of the profile is indicated by the heavy arrow in the inset. The depth below sea level is indicated in uncorrected fathoms. The locations and depth ranges of three dredge hauls obtained from the flank of the transverse ridge of the western side of the fracture valley are shown with dashed lines. Station V33-18: 12°35'N to 58°11'E; depth range, 2500 to 3050 fathoms. Station V33-19: 12°36'N to 58°08'E; depth range, 1600 to 1950 fathoms. Station V33-20: 12°37'N to 58°17.5'E; depth range, 1450 to 1600 fathoms (1 fathom = 1.8 m). At each of the three stations more than 300 kg of material was recovered, consisting exclusively of ultramafic rocks.

The constancy in Mg/(Mg + Fe) ratios of coexisting olivine and pyroxenes, the Al-rich nature of the pyroxenes compared to those of cumulate origin, the absence of plagioclase, the lack of cumulate textures, the relative proportions of constituent phases, and the high Al/(Cr + Al) ratios and low Ti contents of spinel are all features consistent with currently accepted models of the constitution of the upper mantle. Thus, both field data and mineral chemistry support an upper mantle derivation for the Owen FZ ultramafic block. Considering that the summit of the ultramafic block is more than 1 km above the basement in adjacent "normal" crust, and that the crust-mantle boundary is normally at least 4 km below the basement, it follows that a vertical uplift of at least 5 km must be assumed for the Owen FZ mantle-derived block. In view of the current disagreement concerning the effect of pressure on alumina solubility in orthopyroxene (*14*), no reliable pressure estimate can be obtained for these spinel lherzolite assemblages. However, a minimum pressure of 8 kbar can be inferred based on the experimentally determined stability field of spinel lherzolite of about 8 to 24 kbar at 1000° to 1300°C (*15*). This indicates that the rocks in question originated at a depth of at least 25 km in the ocean lithosphere, calling for uplift greater than 25 km to their present crustal level. In order to explain these considerable vertical motions we envisage a combination of two distinct mechanisms: (i) upwelling of mantle material beneath the axial zone of crustal accretion, followed by (ii) vertical tectonic uplift along the fracture zone.

Mantle upwelling below axial zones of spreading is postulated by most thermal-structural-petrological models of accretionary plate margins, starting with that of Hess (*16*). Basalts emplaced along zones of spreading probably derive from partial melting of upper mantle material as a result of its upwelling. In the case of the Owen FZ ultramafic rocks, the initial stages of their ascent from depths > 25 km presumably occurred by upwelling beneath the Mid-Indian (Sheba) axial accretionary zone located about 40 km to the northeast (Fig. 1). Given presently accepted models of thermal gradients below zones of plate accretion (*17*), it is probable that the reequilibration observed in the lherzolites occurred during this upwelling.

Further vertical motions of the upper mantle material occurred by processes unique to fracture zones. The large oceanic fracture zones are the loci of intense vertical tectonic motions affecting upper mantle–crustal blocks and creating transverse ridges along the fracture zones (*18*). This vertical tectonism is determined by a number of factors, the most important probably being the creation along fracture zones of horizontal compressional and tensional stresses caused mainly by small changes in the direction of spreading of the plates adjacent to the fracture zones and by the shear motion within the transform zone (*19*). Such intense compressional and tensional stresses probably operated along the Owen FZ at different stages of its evolution, especially considering that the Owen FZ throughout much of the late Mesozoic and the Cenozoic marked the boundary between the north-moving Indian plate and the African or the Arabian plate, or both (*20*).

Lower and upper crustal material are frequently exposed on fracture zone transverse ridges; for example, sampling of the Owen FZ transverse ridge only about 50 km to the southwest of the section of Fig. 1 revealed lower crustal rocks (gabbros and metagabbros) prevalent in the lower and middle slopes of the ridge and basalt prevalent near its summit. However, other cases exist of thick sections consisting exclusively of ultramafic material of presumed mantle origin, in addition to the one discussed in this report, namely a 4-km-thick section at the Romanche FZ (*21*), the St. Peter-Paul rocks at the St. Paul FZ (*22*), both in the equatorial Atlantic, and a section at the Islas Orcadas FZ in the southern Atlantic (*23*). These large uplifted mantle blocks are probably mobilized initially as part of upper mantle–crustal sections by the aforementioned tectonic forces operating along fracture zones. The contrasting mechanical properties of ultramafic rocks (*24*) compared with those of lower crustal rocks (such as gabbros and amphibolites), combined with decreasing density due to progressive serpentinization during ascent, may lead in some cases to preferential uplift of ultramafic relative to crustal material (*18*). We believe such a mechanism may explain ultramafic protrusions of the type described here. Knowing the distance of the Owen mantle-derived block from the axis of spreading (about 40 km), assuming a spreading rate of 1 cm/year, and assuming that fracture zone tectonism uplifted the mantle block 3 to 5 km, we can estimate an average rate of uplift of the order of 1 mm/year. This rate of ascent is similar to that estimated for the vertical motion of some serpentinite bodies in the crust of the Atlantic (*25*).

Mantle-derived ultramafic vertical protrusions provide perhaps the best means of sampling the oceanic upper mantle. Judicious study of these uplifted mantle blocks, combined with data derived from oceanic basalts and with geophysical measurements at sea, will provide new information on the chemistry and mineralogy of the upper mantle beneath the oceans.

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