Evidence from the Oman ophiolite for sudden stress changes during melt injection at oceanic spreading centres

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The system of dikes in the uppermost mantle below oceanic spreading centres bears witness to the processes involved in the supply of melt to the ridge. Such systems cannot be studied on currently active ridges, but can be seen in ophiolites; in particular, the Oman ophiolite allows us to examine segments of a fast-spreading ridge. Here we present a statistical analysis of the orientation of intrusions in the uppermost mantle section of the Oman ophiolite spreading centres, which points to the existence of two systems: dikes whose azimuth is parallel to the sheeted dikes (which we thus consider as related to the extensional lithospheric stress field) and sills, roughly parallel to the Moho. Branching contemporaneous dikes and sills are frequently observed. We suggest that these relations can be explained by repeated sudden changes of the dominant stress field from lithospheric to asthenospheric. Such changes could result from the episodic relaxation of lithospheric stress in response to tension fracturing of the lithospheric lid, related to sudden melt surges. This episodic behaviour is recorded in the sheeted dike complex, with each dike (each about one metre wide) representing one of these fractures.

Various types of dikes and veins may be distinguished and mapped separately in Oman. The density of dikes in mantle sections of this ophiolite is variable, but it is always high in diapiric areas. In those diapirs, it is still possible to observe the original dike organization, in contrast to other areas where mantle flow may have deformed and transposed the dikes parallel to the flat-lying foliation. We can separate the observed intrusions into two main groups. The first group comprises early 'indigenous' gabbro and pyroxenite dikes (equilibration temperature >1,200 °C) which intrude into melt-impregnated peridotites and are bounded by dunite walls (formed by wall-rock reaction of the circulating melt in the dike). Dunite veins belong to this group. Pyroxenite dikes are dominantly olivine-bearing websterites or clinopyroxenites; they may grade into impregnation clots or into chromite schlieren and pods. The second group of gabbro, pyroxenite and diabase dikes is called 'intrusive' (emplaced at temperatures below the peridotite solidus) because the dikes have sharp and straight walls without reaction with the surrounding peridotites. Overall, this group represents a continuum in composition, ranging from pegmatitic gabbros and pyroxenites displaying comb structures (induced by the crystallization of melt from the cooler walls toward the core of the dike) to diabase dikes with chilled margins, the latter corresponding to host-rock temperatures <450 °C (ref. 4). Thickness ranges from a few centimetres to 1 m in both groups.

Whatever the nature and the time of intrusion of the dikes, analysis of their orientations in diapiric areas shows that they tend to cluster in two groups as already shown in two massifs of southern Oman (Fig. 1). We present here new data from the Batin area (Fig. 1, Southern Wadi Tayin massif), where a zone of steeply plunging foliations and lineations has been identified in the mantle section, suggesting that it is also a diapiric structure. In this area, after rotation of all measurements into the palaeo-ridge reference frame (Moho rotated to the horizontal, ridge trend defined by diabase sheeted-dike trend), the intrusions group into two main orientations which, admittedly, are not always clear-cut (Fig. 2). One set of dikes is nearly vertical and parallel to the sheeted-dike trend in this region, the other forms sills and moderately inclined dikes which have a tendency to wrap round the presumed mantle diapir (Fig. 2). Another common observation is that cross-cutting dikes and sills may not display any evidence of relative chronology. The dikes can post-date the sills, or vice versa. We can also observe branching dikes and sills in which melt has been flowing from one into the other (Fig. 3). The partitioning in dikes and sills is generally stronger in the intrusive group than in the indigenous group, where dikes and sills often display more dispersed preferred orientations. On average, there are more sills in the indigenous group and more vertical dikes in the intrusive group.

It has been proposed previously that in peridotites, as in other formations, dike orientations are controlled by the ambient stress field, the dike being perpendicular to the σ1 principal stress axis. Here, the group of vertical dikes sub-parallel to the sheeted-dike average orientation (assumed to represent the ridge axis), would be thus related to lithospheric fracturing, that is a stress field with σ1 horizontal and perpendicular to the ridge. This implies that the lithospheric stresses are transmitted, at least partially, to the upper mantle beneath the ridge. On the other hand, the occurrence of sills and gently dipping dikes implies, at least locally, the existence of another stress field, with σ1 nearly vertical. The switch between the two inferred stress fields must be rapid, both in time and space, because of the mutual cross-cutting and branching figures mentioned above. We believe it is best explained by a sudden and episodic relaxation of the lithospheric tensile stress, as demonstrated in similar context at the divergent plate boundary in northeast Iceland.

Such an event may be related to the release of melt in the crust. It has been proposed that the hydrofracturing events responsible for melt rise are episodic and short-lived, being recorded best in the sheeted-dike complex. Each dike, 1 m wide on average, represents a single and rapid melt surge (a dike stays molten for at most a few weeks). Consequently, melt surge through hydrofractures brings to the accreting crust a quantity of melt large enough to produce, on average, 1 m of crust. We speculate that this rapid opening would relax the lithospheric stress and

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FIG. 1. Simplified structural map of the mantle section in the Batin area. The foliation trajectories fit measurements collected over 220 stations. Grey-filled contours of the lineation epoch locate the presumed diapiric centre. The location of the two previously studied massifs (Nakhi-Ruwait and Murqad) is shown in the inset map.
momentarily allow some other process to cause the switch of the principal stress axes. Such a switch could result from the dike intrusions themselves. As suggested earlier, providing the magma supply is large enough, dike intrusion can locally increase the least compressive $\sigma_3$ until it is no longer the least compressive stress. If the magma supply does not shut off at this point, then subsequent sheet intrusions should be orthogonal to the 'parent' dike, taking the form of either ridge-perpendicular dikes or sills. We observe both dikes and sills, but sills are predominant (Fig. 2). The presence of the Earth's surface acts to favour the development of sills, because they produce smaller stress changes than ridge-perpendicular dikes. But, we suggest that the abundance of sills may also be explained by the following model, which takes into account the fundamentally dynamic character of the sub-ridge asthenosphere, as inferred from the structural mapping of Oman peridotites. Two-dimensional models of asthenospheric flow below fast-spreading ridges show a narrow sub-ridge mantle upwelling, which implies the occurrence of a fast divergent non-coaxial flow away from the diapir axis, immediately below the Moho. Such a forced flow should produce an asthenospheric stress field such that the stress axis $\sigma_3$ (which is vertical above the diapir axis) rotates rapidly towards the horizontal position at the edges of the diapir and finally dips away from the ridge. Thus, at the top of the diapir structure, slightly off-axis and below the Moho, one must expect a stress field with a steep $\sigma_3$ and the $(\sigma_1, \sigma_2)$ plane flat-lying or moderately dipping away from the centre of the diapir. We suggest that the sill injection is controlled by this 'asthenospheric' stress field related to mantle diapirism (Fig. 4). This hypothesis is supported by the predominance of sills in the indigenous (high-temperature, asthenospheric) group and by the tendency of the sills to dip away from the diapiric area (Fig. 2d and e), although it is difficult to locate precisely the diapir axis because of the complex geometry. The two proposed explanations, however, are not incompatible and may operate together to allow the rapid switch between dike and sill intrusions.

One of the goals of sub-ridge asthenospheric models is to explain how melt is focused at the ridge. The sheet-intrusion model described here may be part of the explanation, with sills and ridge-perpendicular dikes capturing flow from ridge-parallel dikes, and moving it to the ridge axis. One could propose, to explain the observed system, a simple elastic model in which a local switch between the principal stresses would be related only to dike intrusion itself. We believe (on the basis of the field arguments) that it is better explained by including in the model the effect on the stress field of plastic flow in the upper mantle.

Such a 'breathing ridge' model implies that at the onset of the melt surge, even at Moho depth beneath the ridge axis, the regional lithospheric stress field can temporarily predominate over the more local asthenospheric stress field that is related to the diapir uprise. This model explains how, during a single magmatic event, lithospheric and asthenospheric control may be

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**FIG. 4** Schematic cross-sections of the 'breathing ridge' model perpendicular to the ridge axis. The permanent stress field related to the diverging asthenospheric flow (a) allows the sills and moderately inclined dikes to open when the lithospheric tensile stress field is relaxed. In (b), the lithospheric tensile stress becomes progressively dominant, allowing the vertical dikes to open, until the next intrusion-related stress relaxation.
exerted successively, allowing dikes and sills to be opened almost simultaneously.