

Geology

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Geology 2003;31:e14

doi: 10.1130/0091-7613-31.1.e14

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Notes

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COMMENT

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MacLeod et al. (2002) made a strong case that subhorizontal corrugated surfaces adjacent to the slowly spreading Mid-Atlantic Ridge near 15°45'N are exhumed fault surfaces that have been uncovered by normal faulting associated with oceanic-lithosphere divergence (see also Cann et al., 1997; Tucholke et al., 1998; Blackman et al., 1998). They identified submarine "rock outcrops in the form of elevated ridges tens of meters wide, hundreds of meters long, and <10 m in relief elongated parallel to the spreading direction" with smooth surfaces "covered with centimeter-scale striations, also parallel to spreading direction" (MacLeod et al., 2002, p. 880). Dredge and drill core samples included mylonitic fault rocks "formed primarily of talc, chlorite, and tremolite-actinolite, and minor serpentine" "with strong foliations dipping subparallel to the striated surfaces." (p. 880). At deeper structural levels, "most serpentinized peridotites" contain "relict undeformed olivine" (p. 880–881) and other features indicating lack of high-temperature crystal-plastic deformation. Fault zone thickness was estimated to be ≤ 100 m.

Because they did not identify evidence of penetrative crystal-plastic deformation of nonhydrous minerals in these rocks, the authors infer that the detachment fault is a brittle, shallow structural feature unrelated to a deeper and hotter "brittle-ductile transition." They "propose that the detachment soled out along an alteration front horizon at relatively shallow depth within the brittle lithosphere, a rheological boundary distinct from the brittle-ductile transition" and suggest that the fault was localized along "a profound rheological contrast between a serpentine-free, stronger, lower lithosphere and a weaker, slightly serpentinized upper lithosphere" (MacLeod et al., 2002, p. 882).

This concept of a strength contrast with stronger below and weaker above is inconsistent with the great continuity of footwall grooves. A weak hanging wall could not mold, shape, or cut a strong footwall into grooves as it was tectonically exhumed. However, a strong hanging wall could mold a weak footwall. A molding process whereby the cool and strong side of an irregular slip surface molds the hot and weak side as it cools and acquires a grooved form has long been proposed for extrusion of grooved lavas with remarkably continuous, straight, and parallel grooves (e.g., Nichols, 1938; Marocco, 1980; Chadwick et al., 1999). Such grooves are much smaller but otherwise resemble multibeam images of deep-ocean corrugations (e.g., images in Feininger, 1978). This molding process is used by industrial metal fabricators to shape products with a continuous linear form, and is known as "continuous casting" (e.g., Tselikov, 1984). Continuous casting at tectonic rates and scales has been proposed for corrugation genesis at mid-ocean ridges and continental metamorphic core complexes (Spencer, 1999), and for an enormous grooved surface on Venus (Spencer, 2001).

In tectonic continuous casting, irregularities in the initial shape of a normal fault (e.g., Ferrill et al., 1999) are inferred to be responsible for the grooved footwall form, with such a weak footwall and a strong hanging wall that the groove-forming protrusions on the underside of the hanging wall are not worn away. Such a strength contrast would

affect mid-ocean ridge settings where footwall rocks are weak, serpentinized ultramafic rocks, and hanging-wall rocks are olivine-poor gabbro or diabase not greatly weakened by fracturing. Recent experimental evidence that 10% to 15% serpentinization of peridotite can cause strength reduction to that of pure serpentine (Escartín et al., 2001) shows that such a strength contrast could develop fairly readily where water has access to warm peridotite. Serpentinized ultramafic rocks can be so weak, in fact, that they form dike-like intrusions and subaerial extrusions (e.g., Dickinson, 1966).

MacLeod et al. (2002) recognized serpentine in their sampled footwall rocks, but did not give an indication of whether serpentine was so sparse as to be consistent with their proposal that the footwall was the strong side of the fault. Furthermore, they did not identify any samples of the supposedly weaker and strongly serpentinized hanging wall. It seems possible, given their data, that irregularities on the underside of strong, gabbroic or diabasic hanging-wall rocks deformed weak, serpentinized footwall rocks as they were exhumed from beneath a mid-ocean-ridge normal fault, leaving grooves in the footwall. This is the reverse of the strength contrast across the fault surface envisioned by MacLeod et al. (2002) and highlights the importance of footwall serpentinization in the genesis of grooved fault surfaces in magma-poor oceanic rift environments. MacLeod et al. (2002) envision a different groove-forming process, but it is not clear from their article what that process is. It is also unclear why they are so confident in the applicability of this process that they completely ignore continuous casting, a widely used industrial process that has been proposed as the causative process for groove genesis in diverse geologic settings with a variety of materials, scales, and deformation rates.

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We thank Spencer for his comment and welcome the opportunity to debate the results of our study and its implications. We are glad that he supports our principal finding: subhorizontal corrugated surfaces adjacent to the Mid-Atlantic Ridge at 15°45'N are exhumed oceanic detachment faults (MacLeod et al., 2002). That the (low-temperature) fault rocks we recovered from the surfaces imply deformation mechanisms very different from those predicted in previous models (e.g., Spencer, 1999; Tucholke et al., 2001) is indeed intriguing but demonstrates the importance of testing models by direct observation.

Spencer argues that the spreading-parallel corrugations that occur on the surface of the 15°45'N structure (and other core complexes) could not form by the model we propose because it implies the hanging wall is weaker than the footwall, and he asserts that grooves could not form under such circumstances. Instead he proposes the reverse: the hanging wall must be strong and the footwall weak in order for the former to cast grooves into the latter. However, because high-temperature plastic deformation is absent in proximity to the detachment, we can rule out models in which a strong brittle hanging wall casts a weak ductile footwall (Spencer, 1999), at least for the 15°45'N structure (but see below). Spencer makes the additional suggestion that strong gabbro or diabase hanging-wall rocks could cast grooves into a weak serpentized footwall. We believe this model is also unlikely. Oceanic crust at slow-spreading ridges is now known to be far more heterogeneous than previously recognized: a regular magmatic crustal layer is not always developed, and serpentized peridotite may form a significant proportion of the geophysically defined "crust" (Cannat, 1993). The Mid-Atlantic Ridge between 14°30' and ~16°N is the best-known example of magma-starved ocean floor: extensive areas of serpentized peridotite are capped by thin, discontinuous lava flows (Cannat et al., 1997), indicating efficient serpentization of the upper lithosphere at the ridge axis. Gabbro and diabase are volumetrically minor. It is therefore highly unlikely that the hanging wall of the 15°45'N detachment was a continuous, strong layer with gabbro/diabase or un-serpentized peridotite rheology; the mechanical behavior of both footwall and hanging wall was probably controlled by the rheology of peridotite and its alteration products. Indeed, where we did map gabbro it was in the form of an isolated pluton intruding serpentized peridotite in the footwall of the detachment, not the hanging wall. The margins of this strong intrusion do not coincide directly with the highs on the corrugated surface, suggesting that strength contrasts between hanging wall and footwall are not the direct, or at least not the only, cause of groove formation. For grooves to be cast in a weak footwall by a strong hanging wall, as Spencer proposes, serpentization can only have occurred in the former and not the latter. This is implausible. That our peridotite samples from the footwall are indeed partially or completely serpentized has no relevance to the question of whether the detachment nucleated at a serpentization front or not, because serpentization of the footwall would have started as soon as movement and uplift on the fault commenced. We emphasize that the fault zone material (talc, chlorite ± tremolite schists; Escartín et al., 2003) appears to have been much weaker than either the footwall or hanging wall; this is necessary for strain to have remained localized on a single structure for ~1 m.y. and is demonstrated by undeformed mesh-textured serpentized peridotites in the footwall very close to the corrugated fault surface (e.g., MacLeod et al., 2002, their Fig. 3C).

From the limited observations we have to date it is clear that oceanic core complexes do not all have to form in the same way. We have also carried out a rock drill survey of the Atlantis Bank core complex (SW Indian Ridge), and find that the surface of this massif is formed predominantly of gabbros deformed under high-temperature plastic- or melt-present conditions and with subhorizontal fabrics (MacLeod et al., 1999). Ocean Drilling Program drilling has shown that deformation diminishes in intensity at deeper levels (e.g., Dick et al., 1991), suggesting not only that a detachment was active in the presence of magmatism, but that it must have rooted into a ductile magmatic lower crust. Such hot detachments must form in response to fundamentally different mechanisms of strain accommodation and localization from cold detachments such as the 15°45'N structure.

In conclusion, although Spencer's continuous-casting model may provide an explanation for the formation of grooves on continental and maybe some hot oceanic core complexes, it is not the only mechanism, and it does not explain how they formed at the cold 15°45'N detachment. Linkage of precursory faults, as we suggested, could generate corrugations, as could differing depths to the serpentization front resulting from spatial variations in the permeability structure of the upper crust. There are clearly many ways to form irregularities on a fault surface, but only those parallel to the transport direction are stable and have the potential to amplify and be preserved.

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