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Genesis of corrugated fault surfaces by strain localization recorded at oceanic detachments

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ABSTRACT

Seafloor spreading at slow and ultraslow rates is often taken up by extension on large-offset faults called detachments, which exhume lower crustal and mantle rocks, and in some cases make up domed oceanic core complexes. The exposed footwall may reveal a characteristic pattern of spreading-parallel corrugations, the largest of which are clearly visible in multibeam bathymetric data, and whose nature and origin have been the subject of controversy. In order to tackle this debate, we use available near-bottom bathymetric surveys recently acquired with autonomous deep-sea vehicles over five corrugated detachments along the Mid-Atlantic Ridge. With a spatial resolution of 2 m, these data allow us to compare the geometry of corrugations on oceanic detachments that are characterized by differing fault zone lithologies, and accommodate varying amounts of slip. The fault surfaces host corrugations with wavelengths of 10–250 m, while individual corrugations are finite in length, typically 100–500 m. Power spectra of profiles calculated across the corrugated fault surfaces reveal a common level of roughness, and indicate that the fault surfaces are not fractal. Since systematic variation in roughness with fault offset is not evident, we propose that portions of the exposed footwalls analyzed here record constant brittle strain. We assess three competing hypotheses for corrugation formation and find that the continuous casting and varying depth to brittle–ductile transition models cannot explain the observed corrugation geometry nor available geological observations. We suggest a model involving brittle strain localization on a network of linked fractures within a zone of finite thickness is a better explanation for the observations. This model explains corrugations on oceanic detachment faults exposed at the seafloor and on normal faults in the continents, and is consistent with recently imaged corrugations on a subduction zone megathrust. Hence fracture linkage and coalescence may give rise to corrugated fault zones, regardless of earlier deformation history and tectonic setting.

1. Introduction

Large-offset normal faults, known as detachments, are now understood to play a significant role in accommodating plate separation at slow- and ultraslow-spreading mid-ocean ridges (e.g. Escartín and Canales, 2011). This style of crustal accretion accounts for seafloor formation in large parts of the Atlantic, Indian and Arctic Oceans; for example, up to 50% of lithosphere accreted along the Mid-Atlantic Ridge (MAR) between 12.5° and 35°N is thought to be formed in the presence of detachment faults (Escartín et al., 2008). Seafloor spreading under these conditions leads to the exhumation of lower crustal and mantle rocks on the seafloor forming domes that can be tens of kilometers in width called oceanic core complexes (OCCs; e.g. Karson and Dick, 1983). These domes are exposed detachment fault footwalls, which preserve a history of ductile and brittle deformation, in a setting where magmatism and slip play important roles (e.g. Karson et al., 2006; Schroeder and John, 2004). The upper surface of OCCS are often characterized by spreading-parallel corrugations, which have been compared to those found on terrestrial normal faults (e.g. Whitney

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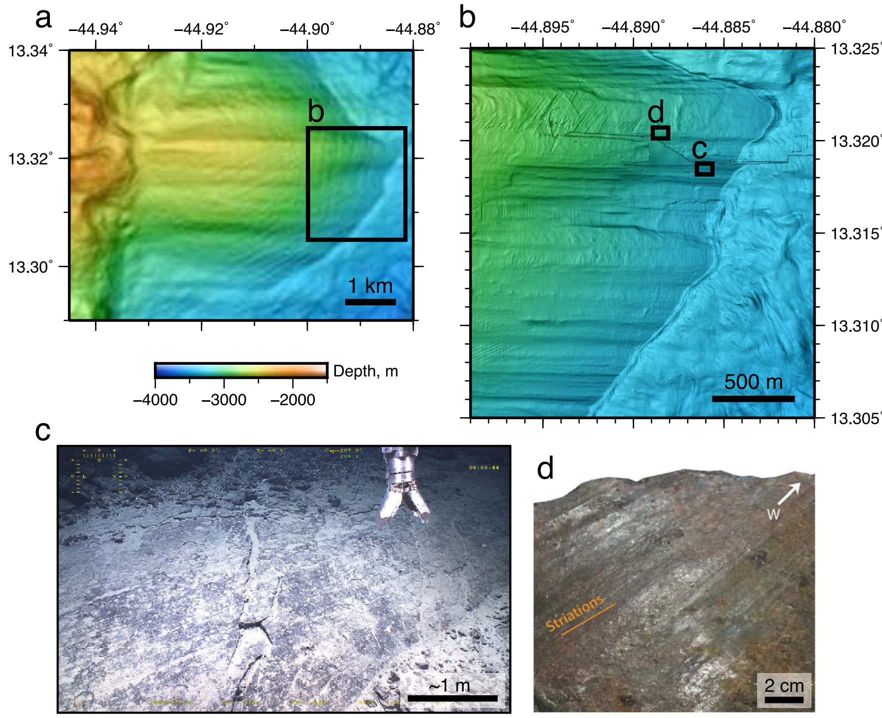

Fig. 1. Corrugated fault surface imaged at kilometer to centimeter scales, at 13°20′N on MAR. a) Shipboard bathymetric data, gridded at 40 m node spacing (Escartín et al., 2017). Note corrugations on hundreds of meters scale, on top of larger kilometer-scale domed fault surface. b) Bathymetric data acquired near-bottom by AUV (Escartín et al., 2017), location shown in (a). Note corrugations visible at wavelengths of tens of meters. c) Seafloor image of striated fault surface (Escartín et al., 2017), location shown in (b), on flank of a bathymetric corrugation. Note that fault striations are spaced <1 m apart, and are sub-horizontal, oriented parallel to displacement and to corrugations in (b). d) Macrophotograph of fault rock (sample ODM217), containing ultramafic clasts, showing cm- to mm-scale spreading-parallel striations (Bonnemains et al., 2017); sampling location shown in (b).

et al., 2013), and more recently, to those imaged on a subduction zone megathrust (Edwards et al., 2018).

Early seafloor mapping efforts revealed oceanic detachment corrugations with wavelengths of a few kilometers to hundreds of meters (Fig. 1a; e.g. Tucholke et al., 1998), however observations were limited by the ∼100 m spatial resolution of ship-mounted multibeam systems at the time. Images acquired using deep-towed sonars also revealed lineations at smaller spatial scales, superimposed on these larger-scale bathymetric corrugations (Cann et al., 1997; MacLeod et al., 2009; Searle et al., 2003). Recent developments in near-bottom mapping using autonomous underwater vehicles (AUVs) at ∼1–2 m resolution have revealed much smaller wavelength (∼10 m) oscillations in fault topography, in addition to previously known bathymetric corrugations (Fig. 1b). Recent submersible dives have revealed meter-scale corrugations and striations at outcrop scale (Fig. 1c; Escartín et al., 2017; Bonnemains et al., 2017), and spreading-parallel striations on the cm-scale in hand specimen (Fig. 1d; Bonnemains et al., 2017). While it is now well-established that corrugations occur on a wide range of scales, the mechanisms of corrugation development remain controversial, due to a lack of comparable quantitative observations across multiple sites.

The largest, kilometer-scale undulations have been compared to networks of cuspate fault scarps (John, 1987), and to shortening features seen on the footwalls of terrestrial detachments undergoing compression (Fletcher and Bartley, 1994; Tucholke et al., 1998). Karson (1999) suggested that undulations on the Kane massif on the MAR are ridge-perpendicular faulted blocks accommodating extension, although more recent observations at higher resolution have shown this to be unlikely (e.g. MacLeod et al., 2002). It has also been suggested that corrugations on the scale of hundreds of meters could arise due to depth variations in the brittle–ductile transition on which the fault roots (Tucholke et al., 2008). Alternatively, corrugations could arise due to the molding of a plastic or partially molten footwall in contact with a strong, brittle hanging wall, in a process termed continuous casting (Spencer, 1999). More recently, corrugations on detachment fault exposures at 13°N on the Mid-Atlantic Ridge have been explored by a combination of AUV surveys, remotely operated vehicle (ROV) observations and sampling (Escartín et al., 2017). These near-bottom observations have led to a suggestion that strain localization within an anastomosing three-dimensional network of fault segments results in corrugation formation (Escartín et al., 2017).

In order to evaluate these competing hypotheses for the origin of corrugations, we use near-bottom bathymetric data acquired in recent years by AUVs at five OCCs on the MAR to quantify the fine-scale structure and morphology of exposed fault planes. Our objective is to characterize the geometry of meter- to kilometer-scale corrugations, and compare these across detachments of differing age and lithology in order to test hypotheses regarding their origins. We then use these observations of corrugation geometry to constrain simple thermal and mechanical arguments for corrugation formation that are implied by the different hypotheses. Finally, we use spectral analyses of the fault surfaces to examine variations in fault roughness between the five study locations. Fault roughness plays a key role in fault and earthquake mechanics, and here we explore the possible implications for corrugation formation.

2. Study sites and data acquisition

We use near-bottom multibeam bathymetric data acquired using AUVs at five locations on the MAR to study fine-scale corrugations (Figs. 2 and 3): one at the Trans-Atlantic Geotraverse (TAG) segment; two at the 16.5°N segment (16°36′N and South Core Complex; SCC) and two at the 13°N segment (13°20′N and 13°30′N). Well-developed OCCs, with varying lengths of exposed fault surface (a proxy for displacement on the fault), are found at