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Geological investigation of a lineated massif at the Kane Transform Fault: implications for oceanic core complexes

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Recently available new perspectives on the morphology of the sea-floor near the Mid-Atlantic Ridge reveal the widespread development of dome-like massifs with lineated upper surfaces. In form and dimensions, these features resemble continental metamorphic core complexes developed in regions of large-magnitude extension, and thus may be 'oceanic core complexes'. Excellent examples of these features occur south of the Kane Transform Fault where high-resolution geological data from side-looking sonar, deeply towed cameras, and manned submersibles are available. The geological data from two different massifs, representing somewhat different types of crustal structure, provide important constraints on the development of these oceanic core complexes. Inferences from these direct geological investigations of oceanic core complexes are a first step toward understanding the processes by which these features form in slow-spread crust.

Specific relationships in these massifs and nearby areas suggest that these structures have formed over significant lengths of ridge axis (tens of kilometres) and are not necessarily confined to any specific setting with respect to morphologic segmentation patterns. In some cases they are developed in thick gabbroic crust, but elsewhere have formed in crust composed of serpentinite riddled with gabbroic intrusions. Ductile stretching and thinning of these sections is recorded in extensive mylonites and shear zones. Syntectonic gabbroic intrusions are widespread and contradict the notion that the massifs develop during intervals of 'amagmatic spreading'. Cataclastic fault zones in gabbros and serpentinites developed during uplift, cooling and hydration of the stretched crust and may have been localized as major detachment faults. Sparse diabase dikes and basaltic lavas are the latest magmatic additions to these areas. Numerous joints and steeply dipping, small-offset faults are the youngest observed structures. Across part of the top surface of one massif, small-scale faults appear to bound elongated ridges of fractured basement rocks creating the lineated terrain. Thus, the extensive lineated surfaces nearby need not reflect prolonged displacement along a continuous detachment fault surface.

Geological relationships developed in the dome-like massifs along the Kane Transform Fault hint at a complex array of processes involved in the evolution of these features and raise new questions regarding their origin and analogies with continental core complexes.

Keywords: extension; stretching; detachment; sea-floor spreading; footwall deformation; weak faults

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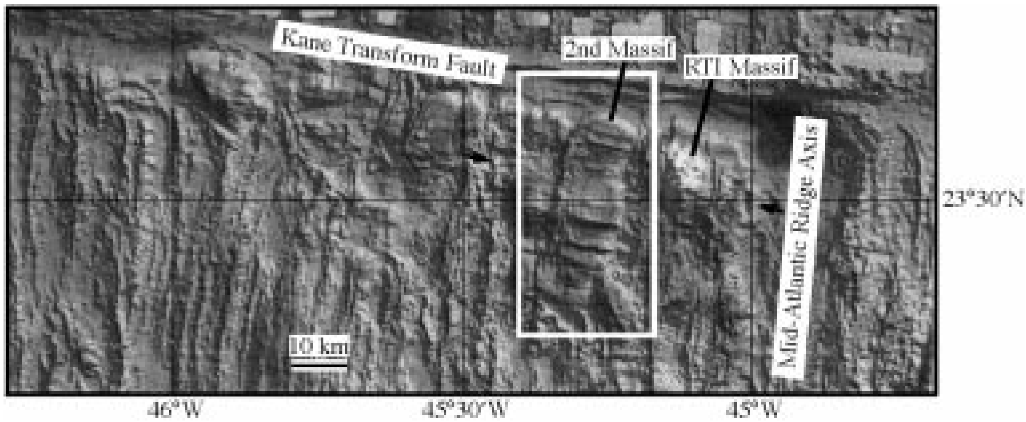

Figure 1. Regional bathymetric patterns in the vicinity of the Kane Transform Fault and adjacent section of the MAR axial valley (from RIDGE Multibeam Synthesis: http://imager.ldeo.columbia.edu). Note lineated massifs in the westward tapering area south of the Kane Transform Fault. Box shows location of figure 2. Arrows show location of cross-section in figure 9.

1. Introduction

Continental 'metamorphic core complexes' are highly extended and uplifted masses of middle to lower crustal rocks that develop in response to large-magnitude horizontal stretching of the lithosphere (Wernicke 1981; Crittenden *et al*. 1980; Davis & Lister 1988; Lister & Davis 1989). Middle to lower crustal rocks, deformed in the ductile regime and variably retrograded, are commonly uplifted and displaced relative to pervasively faulted upper crustal rocks by a major, low-angle normal fault or 'detachment fault'. The detachment faults separate these contrasting units into footwall and (commonly allochthonous) hanging wall domains. Core complexes were first recognized in thick orogenic crust, but have subsequently been identified in a variety of other extensional tectonic settings (Lister *et al*. 1984; Hill *et al*. 1992; Talbot & Ghebreab 1997). Although many aspects concerning the origin of core complexes and detachment faults remain controversial, they are generally considered to have developed in response to extreme extension of the lithosphere with strongly localized crustal extension (e.g. Buck 1991). Steadily accumulating geological and geophysical data from sea-floor created along slow-spreading ridges also suggest that core complexes can develop along mid-ocean ridges.

Different perspectives on highly extended oceanic lithosphere of slow-spreading ridges come from geological investigations of 'tectonic windows' into the oceanic crust at major fault zones (Karson 1998, and references therein), surface morphology and gravity data (Cann *et al*. 1997; Tucholke *et al*. 1997, 1998; Ballu *et al*. 1998; Blackman *et al*. 1998) and marine multichannel seismic data (White *et al*. 1990; Mutter & Karson 1992). Collectively, these data hint at the origin of widely developed, dome-like massifs with lineated upper surfaces ('megamullions' of Tucholke *et al*. (1998)) that may represent 'oceanic core complexes'. At present, different types of data are available at different sites and there has been no comprehensive study of any single massif that might be an oceanic core complex. Although large-scale morphologic features have been outlined, critical geological observations that can constrain the processes by which oceanic core complexes may form are scarce even in the best developed massifs.

In this contribution, geological observations from one of the most clearly defined, lineated, dome-like massifs are summarized in the context of large-scale morphologic features. This massif lies along the southern wall of the Kane Transform Fault at 23°30′ N on the Mid-Atlantic Ridge (MAR). It was the subject of high-resolution, near-bottom observations and sampling before compilations of multibeam bathymetry and low-light angle projections revealed that this area was typical of the lineated, dome-like massifs that are widely developed in the sea-floor of this part of the Atlantic ocean (see RIDGE Multibeam Synthesis: http://imager.ldeo.columbia.edu). The internal structure and processes attending the origin of this massif are discussed within the context of extensive sea-floor investigations of a similar massif at the Kane Ridge–Transform Intersection (RTI) just to the east and additional widely spaced submersible observations along the Kane Transform Fault to the west. The nearby RTI (or 'Inside Corner') massif appears to be a somewhat younger massif, with a similar origin, but a somewhat different structure.

2. Regional setting and previous work

The sea-floor of the central North Atlantic just south of the Kane Transform Fault has a complex morphology that apparently reflects different modes of sea-floor spreading through time (figure 1). Although much of the sea-floor in this region is characterized by highly elongated isochron-parallel abyssal hills (Pockalny *et al*. 1988; Tucholke & Schouten 1988), a triangular area bounded on the north for *ca*. 100 km by the Kane Transform Fault and on the east for *ca*. 50 km by the MAR axial valley, is characterized by more or less equant dome-like massifs. Many of the massifs have upper surfaces with a large-scale lineated structure resembling features referred to as 'mullions' developed at various scales along fault surfaces. Lineated surfaces such as these have been interpreted as major detachment faults analogous to those of continental core complexes (Cann *et al*. 1997; Blackman *et al*. 1998; Tucholke *et al*. 1998). Across the MAR axis to the east, sea-floor that formed over the same time-interval has more typical lineated abyssal hills that terminate along the (non-transform part of the) Kane Fracture Zone in 'hook-shaped ridges' (Tucholke & Schouten 1988). Regardless of morphology, magnetic anomalies trend across the sea-floor in an orderly pattern indicating generally asymmetrical spreading (faster to the west than to the east) and several small, eastward Ridge jumps (Schulz *et al*. 1988; Tucholke & Schouten 1988). Investigations along the MAR document the internal structure and composition of the most recently formed dome-like massif at the RTI 'inside corner' and most recent hook-shaped ridge across the MAR at the 'outside corner'.

The RTI massif has been extensively studied with deeply towed cameras (Karson & Dick 1983), side-looking sonar (Gao 1997; Gao *et al*. 1998), submersible dives (Karson & Dick 1983; Mével *et al*. 1991; Auzende *et al*. 1994; Karson *et al*. unpublished data), and crustal drilling (Cannat *et al*. 1995*a*). Karson & Lawrence (1997*a*) provide a summary of these investigations. This massif reaches 1500 m below sea level (mbsl) and has at least 3.5 km of relief on its northern (Kane Transform Fault) and eastern (MAR) edges. Steep scarps along these edges expose extensive outcrops of gabbroic rocks, serpentinized peridotites, and lesser outcrops of basaltic rocks. Especially on the eastern flank, there are extensive gently to moderately dipping

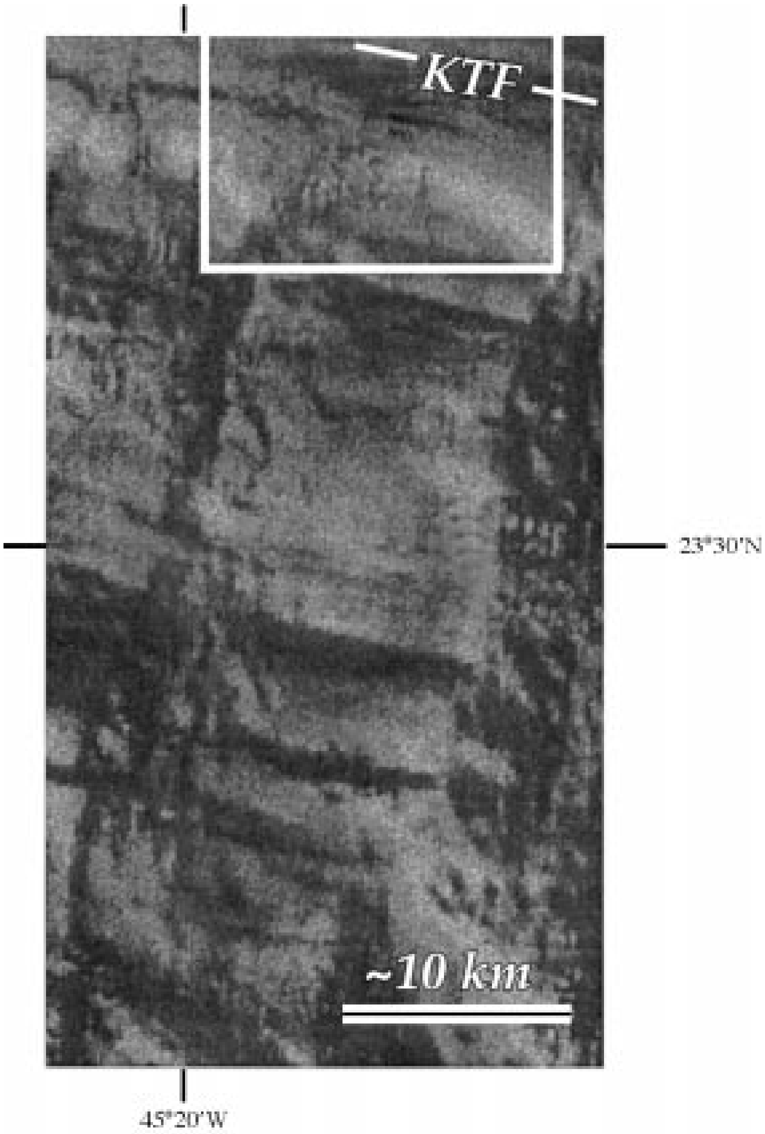

Figure 2. Detail of bathymetric patterns south of the Kane Transform Fault (KTF) including the second massif (about 2 Ma old) west of the KTF–MAR intersection. Lineated terrain persists for at least 60 km south of the transform fault. Box shows location of figure 3.

(*ca.* 30°) fault surfaces and shear zones that define relatively continuous (hundreds of metres) portions of the axial valley wall (Karson & Dick 1983; Mével *et al.* 1991). The slopes are interrupted by steep fault scarps parallel to the spreading centre, the transform fault, or oblique, intermediate orientations. In addition, the eastern slope has a well-developed series of down-slope trending ridges and salients with wavelengths of tens to hundreds of metres and amplitudes of tens of metres (Karson & Dick 1983; Karson 1990; Karson & Lawrence 1997*a*), comparable to the lineations imaged on the tops of massifs just to the west (figure 1; Tucholke *et al.* 1998).

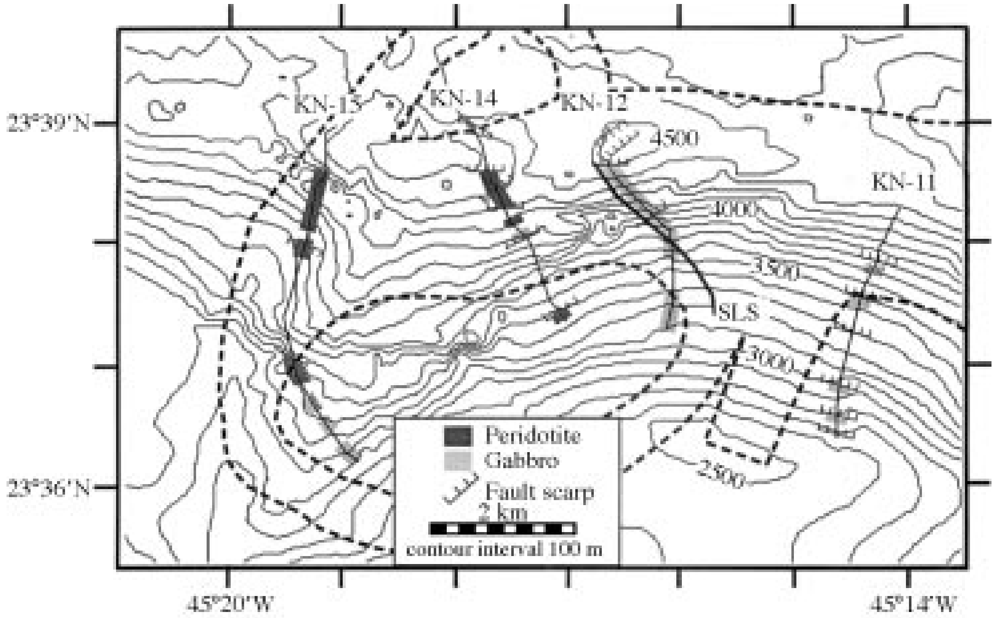

Figure 3. Bathymetric map (contour interval 100 m) of the second massif west of the KTF–MAR RTI. Track lines show *Nautile* dives with highly generalized geology (Auzende *et al*. 1994); bold dashed line shows extent of Deep-Tow side-looking sonar coverage. High-resolution, side-looking sonar and photographic transect (bold line; SLS) corresponds to figure 4*a*.

Drilling into the eastern flank of the massif resulted in several shallow (less than 100 m) penetration holes (Cannat *et al*. 1995*a*). Cores from these revealed a very complex assemblage of variably deformed and metamorphosed gabbroic rocks recording a history of deformation along normal-slip shear zones and periodic intrusion of gabbroic material. Extensive retrograde (greenschist facies and lower) metamorphism overprints igneous material as well as strongly deformed granulite to amphibolite facies metagabbros. The top of the massif is a gently undulating surface mostly covered by a smooth blanket of pelagic ooze and intermittent outcrops of shattered basalt. Magnetic anomalies (Schulz *et al*. 1988) and reversals captured in drill cores (Cannat *et al*. 1995*a*) suggest that the massif is about 0.5–1.0 Ma old (Karson & Lawrence 1997*a*).

The hook-shaped ridge at the outside corner of the RTI is relatively intact, block-faulted pillow basalts (Karson & Dick 1983). The relief of this feature is only about 1500 m and it reaches only 2500 mbsl.

Thus the MAR near the RTI is highly asymmetric with the broad, steep-sided, high-standing RTI massif on the inside corner and the narrower, gentler, lower hook-shaped ridge on the outside corner. The RTI massif is interpreted as the footwall domain of a major oceanic core complex whose corresponding hanging wall domain is the outside corner hook-shaped ridge (Dick *et al*. 1981; Karson & Dick 1983; Karson 1990; Karson *et al*. 1987).

Investigations along the southern wall of the Kane Transform Fault include side-looking sonar mapping (Gao 1997; Gao *et al*. 1998) and a series of submersible dives (Auzende *et al*. 1992, 1994). These show that the Transform valley wall, although commonly covered by pelagic sediment and rubble derived from basement rocks, has

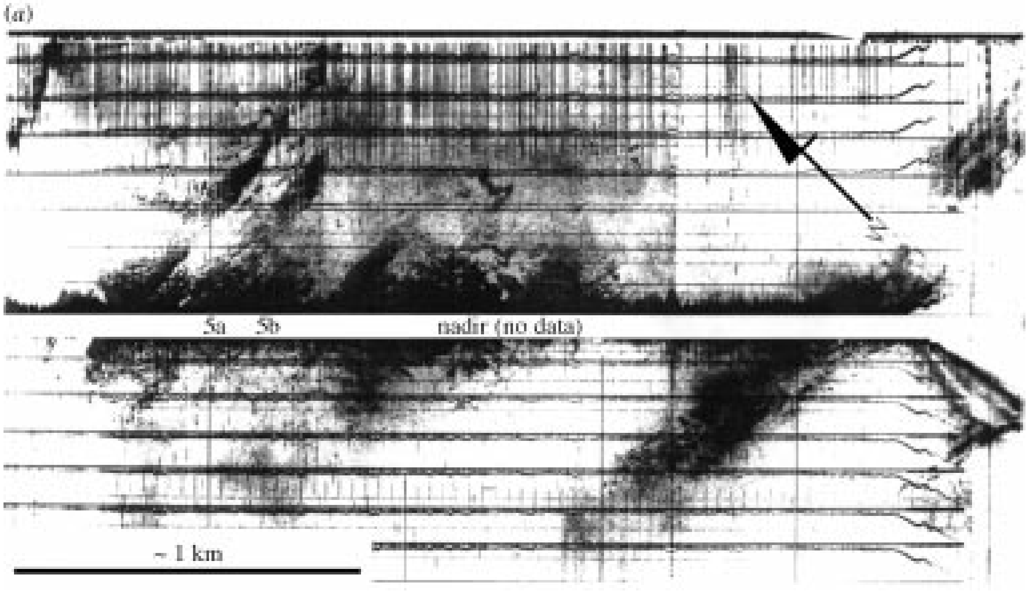

Figure 4. (*a*) Side-looking sonar image produced by towing SIO Deep-Tow vehicle less than 10 m above the sea-floor over the lineated upper surface of the massif. Note E–W-trending ridges of basement rock defined by areas of high backscatter intensity (corresponding to E–W lineaments in figures 1 and 2).

extensive bedrock exposures. Outcrops along the steep portions of the wall along the north edges of the dome-like massifs are mainly variably deformed and metamorphosed gabbroic rocks and serpentinized peridotites. Outcrops in the depressions between the massifs commonly include basaltic volcanic material and dikes (Auzende *et al*. 1992, 1994).

Just to the west of the RTI massif, a second massif, consisting of lithosphere about 2.5 Ma old, has very similar dimensions and shape (figures 1 and 2). It has a strongly and continuously lineated upper surface that is truncated by steep, north–south-trending fault scarps and depressions between the massifs to the east and west (Tucholke *et al*. 1998). The convex-north side of the massif borders the Kane Transform Fault valley and has steep slopes interpreted as fault scarps (Auzende *et al*. 1994; Gao *et al*. 1998). These scarps form a stair-step morphology with extensive outcrops from the upper surface at 2500 mbsl to the Transform valley floor. These scarps provide windows into the internal structure of this oceanic core complex, just to the north and presumably structurally below the well-developed lineated upper surface of the massif.

3. High-resolution side-looking sonar across a lineated surface

During the 'Tow the Mark' cruise in 1992, extensive Scripps Deep-Tow side-looking sonar (110 kHz) data were collected along the MAR RTI Area, and the southern wall of the Kane Transform Fault (Gao 1997; Gao *et al*. 1998). In contrast to most side-looking sonar studies, the Deep-Tow system was configured in an upslope- and downslope-looking geometry to optimize imaging of steep slopes. Part of the top and most of the north-facing wall of the massif were surveyed from an altitude of *ca*. 100 m

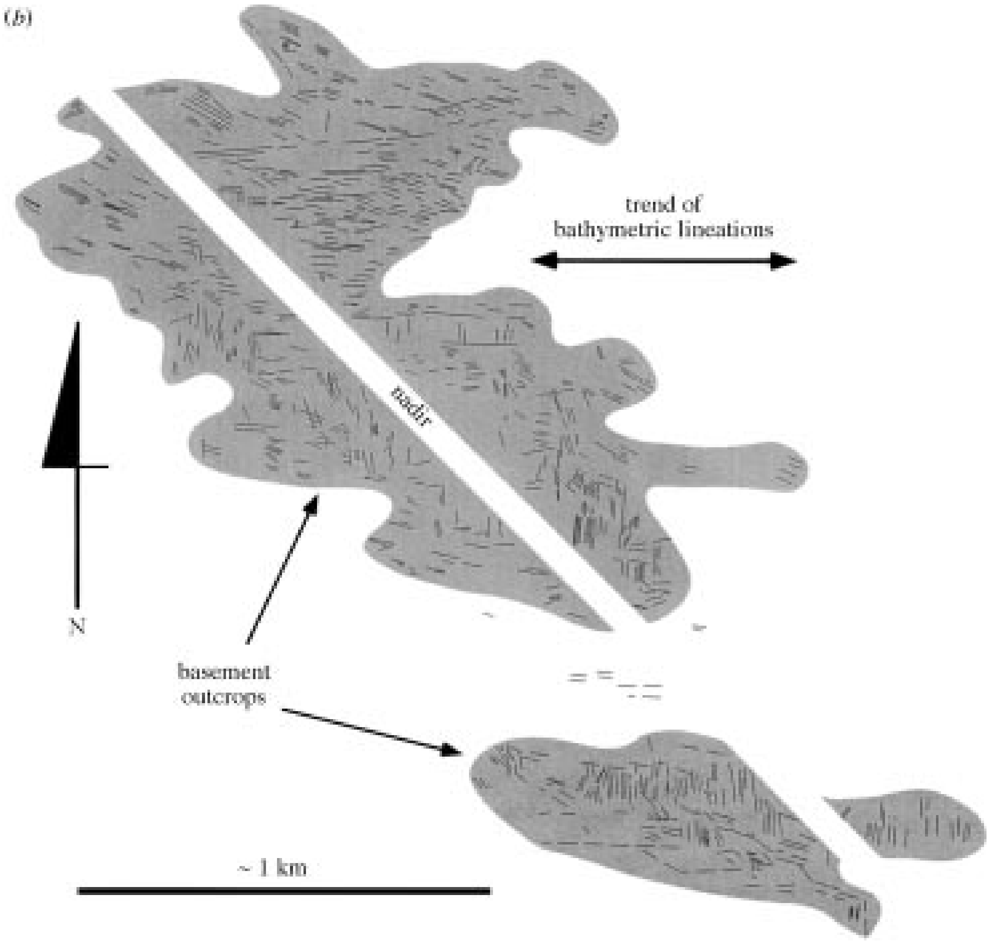

Figure 4. (*b*) Lineament map of backscatter patterns from area shown in (*a*). Note well-defined north–south and east–west lineaments within outcrop areas that are parallel and perpendicular to the larger-scale lineaments.

resulting in a swath width of *ca.* 1.5 km (figure 3). Backscatter patterns show mostly weak, patchy reflections on top of the massif and a series of steep, north-facing linear fault scarps and down-slope trending debris slides on the northern slope (Gao 1997).

During this study a single southeast–northwest transect of the top and northern edge of the massif was made at a height above bottom less than 10 m (figure 3). This resulted in both very high-resolution side-looking sonar data (figure 4) and bottom photographs (figure 5) across part of the lineated upper surface of the massif. The sonar data show a series of elongate ridges with high backscatter intensity interpreted as basement outcrops separated by continuous swaths of low backscatter intensity interpreted as sediment-covered areas (figure 4*a*). The elongate ridges imaged in this area are 100 m to more than 1 km long and 100–200 m across. They are below the resolution of available Sea Beam multibeam bathymetric data and therefore probably have relief of less than 10 m. Linear backscatter patterns within the ridges show rectilinear fracture sets with north–south and east–west orientations

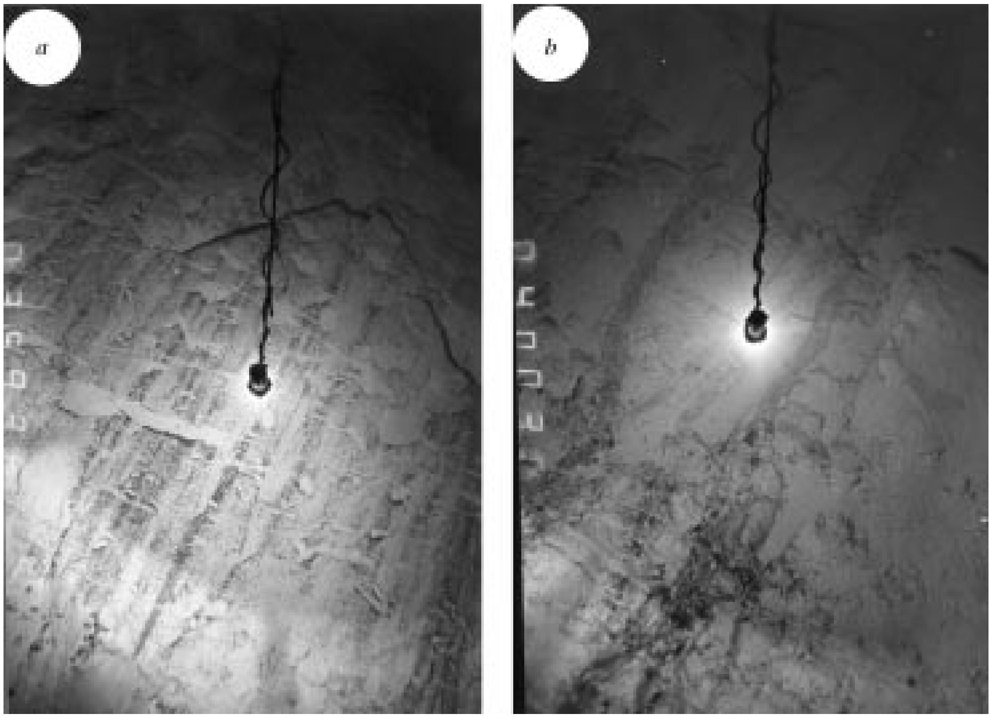

Figure 5. Deep-Tow photographs taken during same transect that acquired the data shown in figure 4*a*. Field of view for both photos is *ca.* 3 m across; top of photos to NW; locations on figure 4*a*. (*a*) Massive, jointed basement rock with down-slope-(north) trending rills in light-coloured pelagic ooze (lower left to upper right in photo). Note that these streaks do not correspond to internal geological structures. (*b*) Another outcrop of similar material, but with 'shingled' outcrop pattern suggesting very gently dipping foliation. Note several east–west scarps less than 1 m high (upper left to lower right in photo) that may correlate with fine-scale sonar lineaments.

(figure 4*b*). Outcrop photographs show systematic, planar, joints that mimic the patterns and orientations of the backscatter lineaments. No slickenlines, grooves, or striae typical of fault surfaces are visible, but such fine-scale surface textures could be obscured by ferromanganese hydroxide crusts and pelagic ooze. Many outcrops appear to be massive, jointed basement rock (figure 5*a*) similar in appearance to outcrops of gabbroic material in sea-floor outcrops elsewhere (e.g. Karson 1998). Some outcrops have a shingled structure interpreted as the expression of a gently dipping foliation (figure 5*b*) similar to that of mylonitic metagabbros found nearby (see below). The foliation shows no evidence of folding associated with shortening normal to the extension directions as seen in some continental core complexes (e.g. Fletcher *et al*. 1995).

The backscatter patterns are interpreted as ridges of basement rock bounded by master joints and minor normal faults that separate domains with parallel but more closely spaced joints. If these types of structures are representative of the lineament patterns that occur across the upper surface of the massif, they are relevant to current hypotheses for the origin of the lineated surfaces. Specifically, they do not support interpretations of the lineaments as the result of fine-scale folding ('corrugations'), or as striations formed by abrasional wear along a fault surface (Cann *et al*. 1997; Tucholke *et al*. 1998). Instead, it seems likely that the lineations in this area are the result of flow-line-parallel faults spaced at a few tens to hundreds of metres. North-facing scarps on the northern edge of the massif suggest that they are related to normal faults. Thus the lineations may be extensional features rather than compressional features as previously suggested (Tucholke *et al*. 1998). It follows that the flow-line dimensions of the ridges need not be related to displacement lengths (or durations) along major detachment faults.

4. Submersible observations of footwall rocks

Four dives were made on the northern edge of the massif with the French submersible *Nautile* (figures 3, 6 and 7). Initial descriptions of these and other dives along the southern wall of the Kane Transform Fault may be found in Auzende *et al*. (1992, 1994). All four dives began at depths of *ca.* 4500 mbsl on the floor of the Kane Transform Fault and continued upslope to slope-break where the sea-floor flattens at the top of the massif at *ca.* 3000 mbsl. Two of the dives crossed part of the lineated upper surface of the massif. One of the dives (KN-12; figure 7) followed the side-looking sonar track and provided detailed observations and samples that can be correlated with backscatter patterns. Although these dives are located on the northern slope of the massif, it is likely that east–west-trending basement outcrops protruding from swaths of smooth, pelagic sediments represent the same linear ridges that define the larger-scale lineations imaged just to the south, on the top of the massif (figures 2 and 4). The rock units and structures observed and sampled on the dives are considered to belong to the middle to lower crustal components of the footwall domain of the core complex. Below, the results of these dives are briefly summarized with emphasis on features that may be related to core complex evolution.

The floor of the Transform valley is hummocky and variably sedimented. Basement rocks rise from the Transform floor in a steep, continuous wall sloping 30–50°. Only minor debris slides and talus occur locally along the base of the wall suggesting that it is an active or very recent fault scarp. Overall the Transform wall has a stair-step morphology with steep basement scarps up to 200 m high separated by terraces covered with talus and pelagic ooze ranging from a few metres to a few hundred metres wide. The terraces become wider and more continuous as the scarps become smaller upslope giving the slope an overall convex northward form. Toward the top of the massif the slope decreases to subhorizontal and the sea-floor is covered with a nearly continuous blanket of pelagic ooze.

The steep scarps on the slope in almost all cases are clearly fault surfaces with grooved and slickensided faces. In most cases the slickenlines and striae have gentle plunges to the northwest and asymmetrical morphologies consistent with highly oblique normal-dextral slip (figures 7 and 8). These are interpreted as young faults related to the uplift of the massif during dextral transform displacement. In many places these fault scarps have light/dark downslope-streaked surfaces. Based on photographs, this was initially thought to be north–south trending vertical compositional banding (Karson *et al*. 1992). Submersible observations and sampling demonstrate that the streaks are only rills produced by the downslope movement of cobbles and gravel over very lightly sedimented surfaces. Variable mass wasting has produced three-dimensional outcrop exposures that reveal the orientations of igneous and

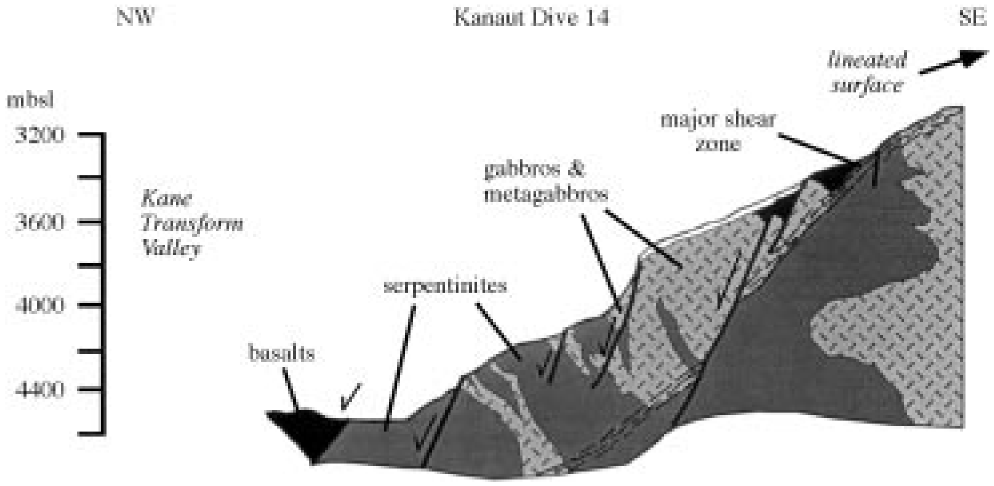

Figure 6. Generalized cross-section of *Nautile* Dive KN-14 (after Auzende *et al*. 1994). Major features include complex gabbroic intrusions in serpentinite, ductile shear zones that tend to parallel the slope, and later high-angle fault zones with oblique (normal–dextral) offsets. Small outcrops of basalt also occur locally. All subsurface features inferred.

deformation structures. The internal structure revealed in these outcrops is extremely complex and has important implications for the origin of the massif.

All four *Nautile* dives found similarly complex geological features in basement exposures on the north slope of the massif (figures 6 and 7). In general, approximately equal parts of mafic and ultramafic material are present. The ultramafic material is partly serpentinized in nearly all areas. Most of it is weakly foliated and lineated harzburgite to lherzolite with minor pyroxenite bands. Mesh-textured serpentine replaces olivine and orthopyroxene to a variable extent. These are typical of serpentinized peridotites sampled from the sea-floor in many other areas (e.g. Dick 1989). Locally amphibolite facies metaperidotites to metapyroxenites occur. These are very fine-grained and strongly foliated and lineated rocks that crop-out in platy exposures up to perhaps 100–200 m in vertical dimension. Outcrop measurements with the *Geocompass* (a sea-floor orientation device) and orientated samples show that the mylonitic foliation does not have a consistent orientation. In most areas it dips moderately (*ca.* 45°) to the north or south (figure 7). Locally vertical, north–south-trending orientations were also found. Kinematic indicators show mostly top-down, dip-slip (i.e. normal slip) shear sense. Schistose serpentinite shear zones cut the large outcrops of ultramafic rocks. These have highly variable orientations, but locally parallel the slope with a moderate northward dip. Schistose serpentinites and basaltic rubble are the most common rock types sampled near the top of the slope.

Gabbroic rocks have variable outcrop expressions. In some areas, intrusive gabbro bodies at least a few hundred metres across to irregular dikes and apophyses one to a few metres wide cut serpentinized peridotites. In some areas, gneissic to mylonitic amphibolite facies metagabbros occur (figure 8*b*). The largest volume gabbroic material crops-out just downslope from the mylonitic metaperidotites and deformation fabrics have similar orientations and kinematic indicators in both rock units. Massive gabbroic rocks that lack deformation fabrics are interpreted as parts of plutonic bodies that intrude highly deformed metagabbros that crop-out nearby. The massive

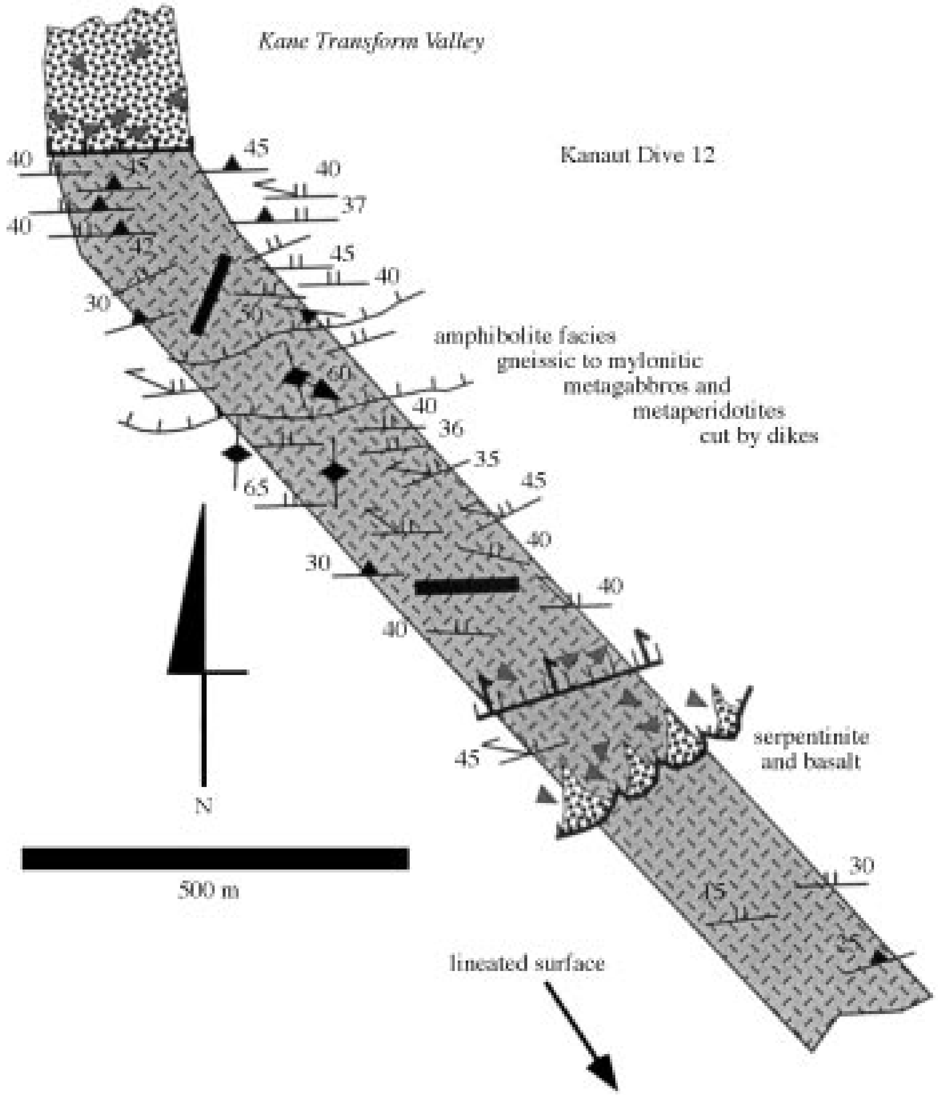

Figure 7. Geological strip map of part of *Nautile* Dive KN-12 (see figure 3 for location). Most of the area shown is gneissic to mylonitic, amphibolite facies metagabbro to metaperidotite (grey dashed pattern). Foliations (solid-triangle symbols; estimated and measured with the *Geocompass*) have a complex pattern in detail, but commonly dip parallel to the slope. Later retrograde shear zones in cataclastic metagabbros and serpentinites have steeper dips. Two undeformed, subvertical, diabase dikes (less than 0.5 m wide) with chilled margins (black) cut this assemblage. Very late fault surfaces (double-tick symbols) that parallel the slope and have low-pitch slickenlines (half arrows) overprint all of the other structures observed.

gabbroic rocks are typically bleached white and partly rodingitized, possibly as a result of interaction with fluids produced by serpentinization of nearby peridotites. Low-temperature, cataclastic fault zones and veins commonly cut the various types of gabbroic rocks.

Diabase dikes with chilled margins cut both the deformed ultramafic and gabbroic

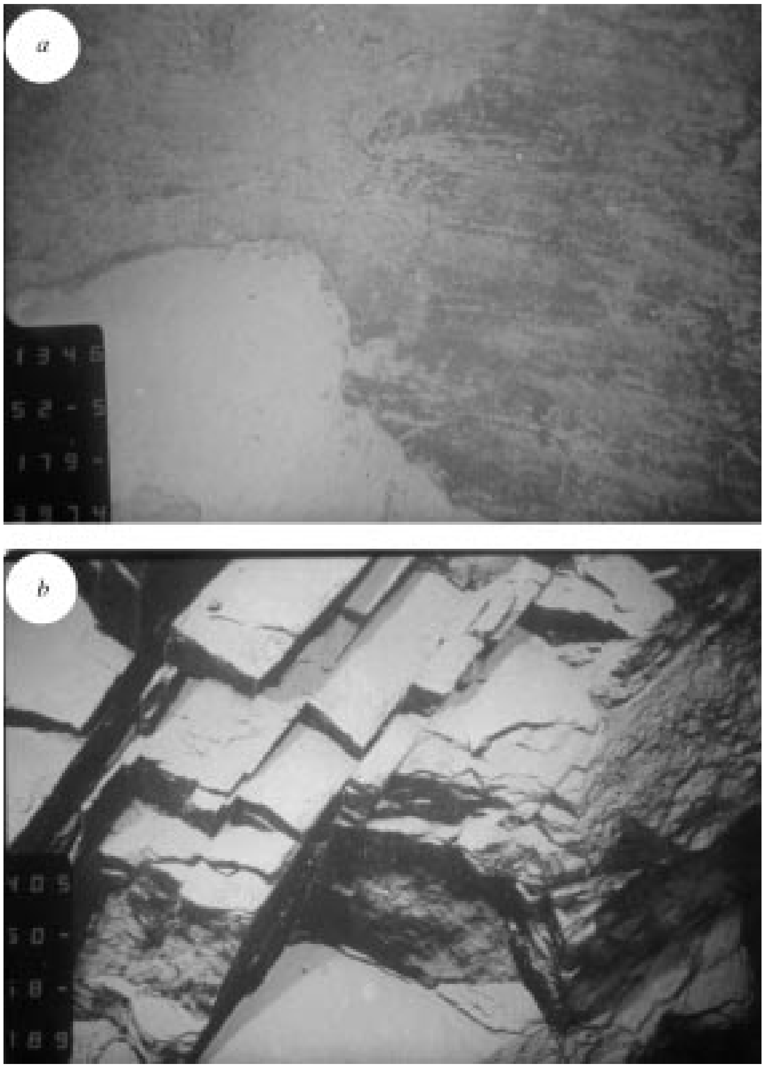

Figure 8. Outcrop photographs from *Nautile*. Field of view is *ca.* 2 m; view to south for both. (*a*) Typical late fault surface with near-horizontal slickenlines (highlighted by light-coloured pelagic ooze) in metagabbro. (*b*) Outcrop of gneissic to mylonitic metagabbro. Strong foliation dips to north (toward viewer). Two families of orthogonal, vertical joints are also present.

rocks (figure 7). Only a few of these dikes were found and apart from being near vertical they have no preferred orientation. They clearly post-date the high-temperature deformation and metamorphism of the other lithologies.

At the top of the scarp, highly fractured basaltic lavas were sampled. Similar material occurs near the tops of other massifs nearby. These appear to be part of a thin (less than 100 m) discontinuous cap of basaltic material. Contacts between the lavas and other units were not observed.

The middle to lower crustal rocks exposed on the northern edge of the second massif from the RTI appear to be continuous for *ca.* 20 km along the Kane Transform Fault. To the east, exposures of basaltic lavas and steeply dipping diabase dikes occur on the western slope of the RTI massif. The depression between the massifs is dominated by pelagic ooze and lesser rubble which obscure the nature of contacts between major rock units. The contact between the shallow crustal rock units of the RTI massif and material derived from deeper structural levels in the second massif has not been mapped, but it lies along a continuous north–south linear scarp that bounds these dome-like massifs (figure 2). These types of lineaments are typical of this terrain and are likely to be major ridge-parallel fault zones. They have been interpreted as 'breakaway zones' (original surface intersection of a detachment fault) and 'truncations' of detachment faults that define the flow-line dimensions of core complexes (Karson 1990; Cann *et al*. 1997; Tucholke *et al*. 1998).

5. Synthesis and interpretation

Geological observations from the second massif west of the Kane Transform Fault–MAR RTI permit a general geological history of the massif to be outlined. The oldest rocks are almost certainly the serpentinized harzburgites. These are interpreted as upper mantle rocks that have been depleted by partial melting and extraction of basaltic liquids beneath a spreading centre.

The peridotites were intruded by the masses of gabbros probably including small plutons (tens to a few hundred metres across), dikes, and veins. This assemblage was deformed by major shear zones that developed at amphibolite facies conditions (*ca.* 700–900 °C) resulting in crystal-plastic deformation and gneissic to mylonitic textures. The orientations of shear zones during this deformation are unknown, but foliation and lineation patterns and kinematic indicators suggest an anastomosing array of normal-slip ductile shear zones. More gabbroic bodies intruded this metamorphic assemblage. The metamorphic temperatures and igneous activity imply processes that were occurring beneath the floor of the axial valley.

Retrograde deformation at greenschist facies (*ca.* 350–500 °C) or lower temperature conditions was concentrated in serpentinite shear zones but also affected the peridotites across the entire massif. Cataclastic fabrics and low-temperature veins formed in the serpentinites and gabbroic rocks. The low-temperature materials are probably related to the uplift and exhumation of the entire assemblage as the footwall of an extending and thinning crustal section as it moved into the axial valley walls of the spreading centre.

The cooling crustal section was cut by chilled diabase dikes, probably while still near the axial valley floor. The dikes may have fed a thin cap of lavas that covered this complex mafic/ultramafic assemblage. Alternatively, the basaltic material may represent highly fractured allochthonous upper plate material that slipped relative to the footwall assemblage during or after formation of the serpentinite shear zones. Mass wasting may have helped redistribute and expose these materials.

Relatively fine-scale normal faulting related to minor north–south extension may have formed the lineated surface of the massif. Final uplift of the massif was accomplished by slip along north–south-trending, normal fault zones and steeply dipping, oblique-slip faults along its northern (Kane Transform Fault) edge. These include large-scale, widely spaced fault zones corresponding to major lineaments visible in the bathymetry (figure 1) as well as much more closely spaced, finer scale fractures imaged by side-looking sonar and seen in near-bottom photographs (figures 4 and 5).

6. Implications for oceanic core complexes

The observations summarized above provide direct geological constraints on the development of the widely developed lineated, dome-like massifs along the MAR. Previous interpretations of the origin of these features have been based mainly on morphological and geophysical considerations (Cann *et al*. 1997; Blackman *et al*. 1998; Tucholke *et al*. 1997, 1998). A number of the key issues concerning the development of the massifs along the Kane Transform Fault and their interpretation as oceanic core complexes are considered below.

In this discussion it is relevant to refer to the results of extensive studies of the dome-like massif at the Kane Transform Fault RTI just to the east and other observations along the south wall of the Kane Transform Fault (figure 1). The RTI massif has many of the same characteristics as the second massif and may represent a different type or earlier stage of development of an oceanic core complex. Figure 9 shows an interpretive cross-section along a sea-floor spreading flow-line parallel to the Kane Transform Fault that includes both of these massifs.

(*a*) *Is the top of the massif a fault surface?*

The lineated upper surfaces of the dome-like massifs near the MAR have been interpreted as major low-angle detachment faults (Cann *et al*. 1997; Blackman *et al*. 1998; Tucholke *et al*. 1998). The lineated fabric superficially resembles slickensides, grooves, striae, and ridges (mullions) that are common at various scales on fault zones where they are orientated parallel to the displacement direction. The implication is that these features have formed by abrasion along a major fault surface during frictional slip. In addition, they are commonly referred to as ‘corrugations’, implying a series of synforms and antiforms, prompting additional interpretations in terms of folding in response to ridge-parallel shortening.

The side-looking sonar data described above and photographs of rocks exposed in basement lineations do not support either of these interpretations. The lineaments surveyed are not smooth corrugations, but rather sharply bounded blocks of basement rocks. The apparent smoothly undulating antiforms and synforms may be artefacts resulting from smoothing of the available bathymetric and side-scan sonar data. In addition, images and photographs of the rock exposures do not show typical abrasional lineament patterns. The large-scale patterns (figure 1) lack many of the common details of lineations found on fault surfaces (e.g. Hancock & Barka 1987). On an outcrop scale, the most prominent features are north–south and east–west systematic, planar, vertical joint sets. These cut massive material (serpentinite and gabbroic rocks) with locally developed sub-horizontal foliation. Fine-scale slickensides were not observed; however, these could be difficult to see given the nature of the exposures.

It is noteworthy that large-scale, lineated basement ridges were previously described on the axial valley wall on the eastern side of the RTI massif (Karson & Dick 1983; Karson 1990). These are also visible on the RIDGE Multibeam Synthesis compilation (figure 1; http://imager.ldeo.columbia.edu). Similar features also occur on the steep fault surface of the eastern axial valley wall of the SMARK segment at 22°40′ N (J. Karson, unpublished data). In both cases, submersible observations show that these features correspond to basement ridges with extensive exposures of foliated and locally slickensided metagabbros or metadiabases with a more or less constant

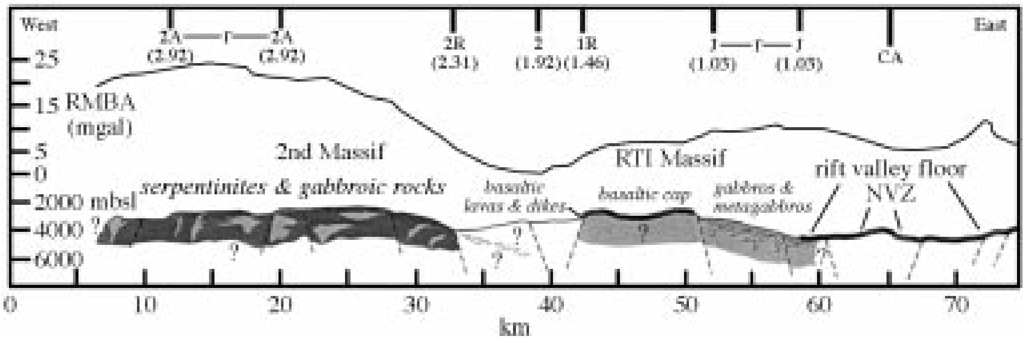

Figure 9. Geological cross-section from the MAR axis and neovolcanic zone (NVZ) across the RTI massif and second massif just south of the Kane Transform Fault (see figure 1 for location). Bathymetry, residual Bouguer mantle anomaly profile (RBMA), isochrons and ages (in parentheses) from Tucholke *et al*. (1998). Repeated magnetic anomalies suggest ridge jumps in intervals labelled 'r'. Note different types of crustal structures cropping-out beneath a discontinuous cap of basaltic material. Basaltic outcrops between massifs suggest either intermittent volcanic construction or locations of 'breakaway' zones separating different core complexes.

fabric orientation that is not visibly warped or folded. Swales between the ridges are filled with sediment and rubble. The ridges and depressions have similar dimensions to the lineations on the second massif to the west and appear to be the same types of features. Collectively, the available observations suggest that the lineaments are elongated blocks bounded by small faults or master joints. They may be accentuated by mass wasting on axial valley walls or partly buried by rock debris that tends to fill in the depressions. This interpretation would not prohibit the use of these lineaments to help identify core complexes, as they would mark major faults and shear zones. However, if they are not the products of abrasional wear on frictional fault zones, they need not mark enigmatic low-angle detachment faults.

(*b*) *How much horizontal displacement?*

The along-strike (flow-line-parallel) continuity of lineations has been used to estimate the horizontal displacement across the lineated surfaces (Cann *et al*. 1997; Tucholke *et al*. 1998). In addition, truncations by isochron-parallel lineations interpreted as 'breakaway zones' or other normal fault scarps are used to place limits on fault slip. Identifying these features is critical to placing constraints on horizontal displacements.

Lineated ridges on the MAR axial valley wall can be traced to the top of the RTI massif where they are at least partly covered by a highly fractured cap of basaltic material that may bury the lineations on the top of the massif. It seems very likely that intermittent volcanism could also bury the lineament patterns and create false terminations. Coherent basalts and dikes crop-out on the west side of the RTI massif and are subhorizontal and subvertical respectively. They may mark the breakaway zone for the detachment that extends across the top of the massif and dips beneath the axial valley floor. This type of geological information is essential to correctly identify breakaway zones and to reconstruct fault geometries (figure 9). The large displacements implied by the continuity of surface lineations suggests that slip was maintained on a single detachment fault for a long period (1–2 Ma) of time in preference to other plate separation mechanisms (Karson 1990; Karson & Lawrence 1997*a*; Cann *et al*. 1997; Tucholke *et al*. 1998). If the lineated surfaces are not individual fault surfaces and the lengths of lineaments do not mark slip intervals, then different types of strain accommodation must be considered.

(*c*) *Why are detachment faults weak?*

The low-angle orientation of the lineated surfaces, interpreted as detachment faults, implies that they are mechanically very weak. Sampling is very incomplete at present and until there is much more detailed information on strain partitioning and kinematics, few definite statements can be made regarding if and how slip on low-angle oceanic fault surfaces occurs. It has been suggested that diffusion creep in very fine-grained mylonites (Jaroslow *et al*. 1996) and slip focused in frictionally weak serpentinites (Escartín *et al*. 1997) may account for this behaviour (Tucholke *et al*. 1998).

At the Kane Transform Fault, the RTI massif is dominated by gabbroic rocks, and mylonites with very fine grain sizes are much less common than gneissic metagabbros (dominated by dislocation creep) and cataclasites (indicative of frictional behaviour). Serpentinites occur locally near the Transform Fault wall and in more continuous exposures along the axial valley wall tens of kilometres to the south of the RTI massif. In the second massif, serpentinites and gabbros appear to occur in about equal proportions, and it appears that serpentinites are concentrated near the top of the northern slope. The outcrop distribution of rock types in these two massifs is, therefore, very heterogeneous and suggests that no single mechanism is likely to account for the inferred weakness of the detachment faults or associated shear zones.

Although material properties mentioned above could account for slip on weak faults or shear zones, there are other potentially important mechanisms suggested by the geological relationships. One mechanism that is likely in these settings is slip promoted by elevated pore pressures that decrease normal stresses and thereby weaken the Fault zones (Axen 1992). Hydrothermal breccias (Delaney *et al*. 1985; Kelley & Delaney 1987; Rona *et al*. 1987), in some cases known to be concentrated along low-angle shear zones, may mark areas where this has occurred. Areas of elevated pore pressure in the footwall of the Fault zone could promote slip, if only in limited slip-patches along the Fault zone. Serpentinites or other hydrothermally altered rocks could provide the necessary hydraulic seals. The role of elevated pore pressures in these settings is a potentially important area for future investigations.

(*d*) *Have the lineated surfaces been rotated?*

The orientation of faults and shear zones where slip actually occurred is important because the lower the dip on these surfaces, the less footwall deformation is required to produce the dome-like final form of the lineated surfaces. The slope of the axial valley wall of the RTI massif and other major axial valley wall fault zones is 35–45°. This is a result of degradation of extensive low-angle shear zones and faults with dips as low as 20–30° that are offset by steeply dipping normal faults. Thus, the slope of the axial valley wall is steeper than the low-angle shear zones and faults (Karson 1990). Similar relations occur in axial valley walls dominated by metadiabase, metagabbro, and serpentinite elsewhere in the MARK Area. Palaeomagnetic studies of rocks cut by low-angle fault zones in three different parts of the MARK

Area spread over more than 100 km along the MAR show that the foliations have not been rotated from the orientations in which they formed (Hurst *et al*. 1997; Lawrence 1998; Lawrence *et al*. 1998). These results are in accord with observations of steeply dipping dikes and subhorizontal lava units found nearby. Collectively, these observations raise important questions concerning the lineated massifs. Are the lineated surfaces found on axial valley walls the same as those imaged on the upper surfaces of the massifs? Can axial valley wall faults rotate into the subhorizontal orientations corresponding to the tops of the dome-like massifs as they move off axis?

Following studies of continental core complexes (e.g. Lister & Davis 1989), the lineated surfaces, interpreted as detachment faults, are believed to have flattened as they moved away from the spreading centre to develop an overall dome-like form (Karson 1990; Tucholke & Lin 1994; Cann *et al*. 1997; Tucholke *et al*. 1998). This could be accomplished by a number of mechanisms (Spencer 1984; Buck 1988; Wernicke & Axen 1988; Reynolds & Lister 1990; Yin 1991). The overall surface could be flattened by slip on planar, steeply dipping faults that do not rotate structures in the blocks between them (Westaway & Kusznir 1993); therefore, outcrop structures in fault-bounded blocks need not be rotated, and structures formed near the Ridge axis would retain their original orientations at the outcrop scale.

In oceanic settings, slip on steep faults is probably the most likely mechanism for changing the slope of the lineated surfaces, but only a few widely spaced scarps are imaged (Tucholke *et al*. 1998). It is possible that arching of the surface takes place by slip on very small faults that have not been imaged by current regional-scale surveys. Numerous MAR-parallel faults have been mapped on the axial valley wall during submersible studies (Karson & Dick 1983; Karson *et al*. 1987; Mével *et al*. 1991), but these are not apparent in the Sea Beam data and are probably below the resolution of the available bathymetry. The north–south lineaments imaged in the Deep-Tow side-looking sonar data (figure 4) could represent these types of structures. Steeply dipping dikes in the footwall domain beneath the lineated surface of the second massif suggest no local rotations, but palaeomagnetic studies are needed in these types of areas to assess the rotation history.

(*e*) *Amagmatic extension?*

The large-magnitude extension inferred from geological relations in the lineated massifs south of the Kane Transform Fault and other parts of the MAR have been interpreted as developing during periods of very low or zero magma production. The occurrence of lineated massifs near RTIs where the magma supply is thought to be low has been taken as corroborating evidence, despite indications of robust volcanism at some RTIs (Auzende *et al*. 1989; Karson *et al*. 1987; Cannat *et al*. 1997*b*). The distribution of lineated massifs south of the Kane Transform Fault calls into question the notion that this terrain marks areas of low magma supply and that they may develop as a consequence of ‘amagmatic spreading’ (Karson *et al*. 1987; Karson 1990; Brown & Karson 1988; Tucholke & Lin 1994; Tucholke *et al*. 1997, 1998).

In fact, geological relations in the massifs south of the Kane Transform Fault and in hanging wall remnants on the opposite side of the MAR axis do not support this view. It would be more accurate to say that during the intervals in which large-magnitude extension occurs, little or no *volcanic* material is added to the footwall domains preserved in the massifs. Substantial volcanic material and probably associated deeper crustal magmatic material could be produced at the same time, if it is preferentially carried away on the opposing side of the plate boundary. Magnetic anomaly lineations, developed roughly symmetrically across the MARK Area, show that the lineated massifs formed in the same time-intervals as corresponding hook-shaped ridges. Although the total magmatic production may be insufficient to build a continuous igneous crust, it appears that it is the *distribution and style of magmatism* during oceanic core complex formation that produces such strongly contrasting crustal structures.

Geological relations suggest that magmatic activity took place in the footwall domain during extension where it could have accommodated footwall strain, but also produced a number of potentially important mechanical effects. Detailed studies of cores drilled into the upper hundred metres of the axial valley wall of the RTI massif provide evidence of syntectonic magmatism (Cannat *et al*. 1997*a*; Karson & Lawrence 1997*a*). Cores from several holes all within 2 km of one another show masses of variably deformed and metamorphosed gabbroic rocks that cannot be correlated laterally (Cannat *et al*. 1995*a*). The crustal sections sampled appear to represent a collage of gabbroic bodies that were intruded at various stages of deformation resulting in a range of magmatic to crystal-plastic to cataclastic textures. Results from ODP Site 735B in a dome-like massif along the Atlantis II Transform Fault along the Southwest Indian Ocean Ridge provide additional evidence of syntectonic magmatism in metagabbro shear zones in a similar setting (Dick *et al*. 1991). Thus, some oceanic core complexes appear to have developed in thick gabbroic crust produced by robust magmatism (Karson 1998).

Magmatic intrusion during footwall extension in these settings is likely to have two important types of mechanical effects. (1) Magmatic material would alter the rheology of the footwall by heating and adding magmatic fluids during deformation. (2) Elevated pore pressures could develop as a result of thermal expansion of fluids in hydrothermally altered rocks, especially along faults and fractures. This could be especially dramatic in serpentinites undergoing dehydration reactions (Raleigh & Paterson 1965).

Considering the geological data available, it is unlikely that the lineated massifs develop during amagmatic spreading. It would be more accurate to say that they appear to develop during intervals characterized by asymmetrical faulting and asymmetrical magmatic accretion across the spreading axis. In some continental core complexes, magmatic events are thought to play a key role in localizing and triggering crustal extension (Lister & Baldwin 1993). Given these considerations, it is possible, and even likely that magmatism is *required* to create oceanic core complexes even within a region of relatively low magma budget.

(*f*) *How much vertical thinning of crustal units has occurred?*

Previous accounts of the dome-like lineated massifs emphasize the external morphology and analogues with continental detachment faults. However, the most dramatic crustal thinning in core complexes is accomplished by ductile stretching represented by mylonitic rocks. Mylonitic fabrics are locally parallel, but more generally discordant with later detachment faults (Crittenden *et al*. 1980; Lister & Davis 1989; Reynolds & Lister 1990). Seismic and gravity studies show that despite extreme horizontal extension, the geophysically defined crust is not thinned proportionally beneath core complexes (Gans 1987). Thus, it appears that relatively low-density crustal material must be added beneath the highly stretched crustal areas. Lateral inflow of weak, quartz-rich, 'fluidal' mid-crustal material from surrounding regions (Gans 1987; Kruse *et al*. 1991) and underplating by mantle-derived magmatic material (Gans 1987; McCarthy & Thompson 1988; Gans *et al*. 1989) are possible mechanisms proposed to counteract mechanical thinning in continental terrains. Similar processes may affect oceanic core complexes.

Horizontal stretching of rock units in continental core complexes is estimated by detailed reconstructions of both hanging wall and footwall domains (Crittenden *et al*. 1980, and references therein; Wernicke 1981; Miller *et al*. 1983). Stretching factors can then be used to predict corresponding vertical thinning of the crust. This is not yet possible in oceanic core complexes, and would be very difficult because of the general lack of stratigraphic markers in the oceanic crust. A growing number of studies show that the internal structure of oceanic crust produced at slow-spreading ridges is much too complicated and heterogeneous to permit the use of geological contacts or crustal structures inferred from geophysical data to estimate the magnitude of crustal thinning (Brown & Karson 1988; Karson 1990; Cannat 1993; Cannat *et al*. 1995*b*, 1997*b*; Karson 1998). However, factors such as unroofing of plutonic rocks, tectonic rotations, gravity data and seismic data suggest a complex interplay of effects that could modify the geophysically defined crustal thickness.

Uplift of rocks that formed in the middle to lower crust provide important clues to the magnitude of thinning of crustal rock units. The widespread exposure of middle to lower crustal gabbroic rocks, or peridotites with high-temperature fabrics, alone demands substantial (kilometres) crustal thinning and unroofing (Karson 1990). Microanalysis of high-temperature fluid inclusions in these rocks demonstrates that as much as 2 km of crustal material has been removed at least locally (Kelley & Delaney 1987). If the lineated surfaces interpreted as detachment faults have been rotated by tens of degrees (Karson 1990; Tucholke & Lin 1994; Tucholke *et al*. 1998; Blackman *et al*. 1998), then additional thinning would occur. As pointed out for the massifs south of the Kane Transform Fault and other lineated massifs near the MAR, they tend to be associated with positive residual Bouguer mantle gravity anomalies consistent with 1–3 km of crustal thinning (Tucholke & Lin 1994; Tucholke *et al*. 1997, 1998). This value, however, is likely to be the net result of mechanical thinning and other processes (e.g. serpentinization) that tend to thicken the crust as defined geophysically.

In oceanic core complexes, at least three mechanisms might come into play. (1) One could be the inflow of weak, 'fluidal,' wet, plagioclase-rich (?) crustal material. Current understanding of rock rheology suggests that even wet, plagioclase-dominated material in the oceanic crust would be much less likely to flow than wet, quartz-dominated materials thought to occur in the continental crust (e.g. Hirth *et al*. 1998). Very large strains in gabbroic and ultramafic mylonites in the massifs suggest that this kind of fluidal behaviour may have occurred. (2) A second mechanism would be magmatic intrusion and underplating. Geological observations from the massifs clearly show that syntectonic magmatism has been important, at least locally. (3) In areas of large-magnitude stretching in oceanic crust, horizontal displacements on moderately dipping faults may exceed the vertical crustal thickness, resulting in the uplift and exposure of upper-mantle material (e.g. Karson 1990). The progressive hydration of upper mantle peridotites as they are cooled and hydrated during uplift beneath areas of extreme crustal stretching, could result in 'serpentinite underplating' of the crust. Serpentinization of upper-mantle-derived rocks could also contribute to the formation of relatively low-density crustal volumes in crust composed of mixed mafic and ultramafic material (e.g. Cannat 1993). Sorting out the relative contributions of these types of mechanisms in the context of geophysical data will be a major challenge in learning how oceanic core complexes develop.

(*g*) *Where do oceanic core complexes form?*

Several previous papers state that lineated massifs and areas of large-magnitude crustal extension and exposures of plutonic rocks occur preferentially at RTIs or other axial discontinuities (Severinghaus & Macdonald 1988; Tucholke & Lin 1994; Cannat *et al*. 1995*a*; Escartín & Lin 1995; Durand *et al*. 1996; Tucholke *et al*. 1997, 1998). The widespread development of lineated domes along isochrons far from transforms (figures 1 and 2) and the distribution of gabbroic rocks and serpentinites along the rift valley walls of the MAR (Karson *et al*. 1987; Juteau *et al*. 1988; Cannat *et al*. 1997*b*; Karson & Lawrence 1997*b*) shows that this is an overstatement. Lineated massifs and outcrops of plutonic rocks with low-angle fabrics occur for at least 60 km south of the Kane Transform Fault in the MARK Area (figures 1 and 2). At present, outcrops of plutonic rocks with nearby lineated massifs occur along the entire length of this spreading segment. The length of the MAR along which this type of crustal structure and morphology has been generated appears to have been lengthening southward for about 8 Ma, creating a triangle of sea-floor with lineated domes (figure 1). These relations indicate that outcrops of plutonic rocks or dome-like morphology are not always reliable indicators of segment boundaries along spreading centres. In the MARK Area, the formation of lineated massifs appears to be related to spreading processes that occur on a segment scale (i.e. tens of kilometres along-axis). The mechanical decoupling expected at transform faults and segment boundaries does not appear to be necessary for extreme extension to occur, though some of the most obvious dome-like uplifts do appear to be preferentially located near such discontinuities.

7. Conclusions

Available geological information from dome-like massifs with lineated upper surfaces that are widely developed in the slow-spread crust of the MAR supports the interpretation that they are oceanic core complexes, that is, regions of extreme crustal stretching and thinning. Massifs south of the Kane Transform Fault show evidence of large-magnitude ductile stretching and thinning in both mafic and ultramafic rocks. Ductile strain was accompanied by the intrusion of numerous gabbroic bodies, typically only a few hundreds to a few metres across—not by 'amagmatic spreading'. Cataclastic deformation and low-temperature hydrothermal metamorphism including widespread serpentinization of peridotites overprint the ductile structures and intrusions. The latest igneous activity includes the intrusion of sparse diabase dikes, possibly related to local outcrops of basaltic lavas that occur upslope. The dikes (and lavas?) appear to post-date all but the latest faulting and to require that these complex assemblages developed very near to a spreading axis. The lineated upper surfaces of the massifs do not necessarily correspond to major detachment faults. Near the northern slope of the massif, lineations are identified with the same form and dimensions as those imaged on the top. They appear to be fault-bounded blocks of basement rock produced by small-scale faulting. The broad, lineated surfaces develop initially beneath the axial valley floor and may flatten progressively as they move off axis by mechanisms that are not yet defined.

The formation of oceanic core complexes appears to be a fundamental response to plate separation at slow-spreading mid-ocean ridges. They appear to have many similar aspects to continental analogues, but also some characteristics that may be unique to large-magnitude extension in oceanic lithosphere, for example serpentinite underplating. Quantifying the processes by which these major structures form will be a major challenge to the next generation of mid-ocean ridge studies.

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Discussion

N. White (*Bullard Laboratories, University of Cambridge, UK*). How can Professor Karson discriminate between the low-angle features he observes and large-scale landsliding, which would not actually stretch the crust itself, along the lines of what was originally proposed in the Basin and Range Province by people like Misch and others?

J. A. Karson. Recognizing that there is probably a sort of continuum between those two phenomena, I think that one of the important features is the fault rocks themselves. These include mafic to ultramafic rocks with magmatic to crystal-plastic deformation features. Granulite to amphibolite facies mylonites are fairly common, though in most cases overprinted by lower grade cataclastic fabrics. These types of fault rocks imply temperatures from more than 1200 °C to 500 °C and therefore must have been exhumed from one to a few kilometres depth. This magnitude of unroofing is corroborated by fluid inclusion studies of Kelley & Delaney (1987), which indicate about 2 km of unroofing. Our outcrop observations show that low-angle fault zones dipping toward the spreading axis commonly provide zones of weakness that are exploited by surficial mass wasting.

L. Curry (*Geological Survey of Canada, Canada*). I would like to take Professor Karson's analogy with core complexes one step further. Faulting within a core complex is generally initiated by a change in either boundary conditions or thermal conditions. What does he think caused the initiation of faulting in the case of his inferred core complex?

J. A. Karson. At this stage my best guess is that it begins during a magmatic event when the crust is thermally softened; however, I don't have any direct evidence to support this suggestion. Mapping out the internal structure of these massifs and documenting the relative timing and spatial relations of deformation and magmatic features will be an important first step in addressing this question.

L. Curry. Does he think the crust was previously over-thickened by a magmatic process?

J. A. Karson. That is another really good question and it recalls another point in the developing debate surrounding these structures. Some people suggest that oceanic detachment faults have developed only in areas with abundant serpentinites and that the low frictional coefficient of serpentinite is necessary in their development. Available sea-floor mapping shows that major detachment faults appear to have developed in massifs with very different rock assemblages. At the eastern intersection of the Mid-Atlantic Ridge and the Kane Transform Fault a detachment fault has formed in a 4 km thick section of gabbroic material. Elsewhere, for example in the massif just to the west, on the upper surface, which is interpreted as a detachment fault, serpentinites dominate. So, at present it appears that major detachments may have formed in thick gabbroic crust or in crust that is mainly serpentinite which has little magmatic material.

D. McKenzie (*Bullard Laboratories, University of Cambridge, UK*). What I've never understood about these highs on the inner corners of fracture zones is how they go away. As the material gets transported along the fracture zone, the high becomes smaller. This behaviour seems to me to be a powerful constraint on the mechanisms of their formation. It's no good underplating, because that won't go away, and it's no good serpentinizing because that won't go away either.

J. A. Karson. Along many oceanic fracture zones bathymetric highs appear to form initially at 'inside corners' and then to pass laterally into 'transverse ridges' that border the fracture zones. Several studies have shown that these ridges have along-strike profiles that mimic the subsidence patterns of 'normal' sea-floor. However, they generally remain higher than nearby sea-floor of the same age that was created farther from a ridge–transform fault intersection.

D. McKenzie. Well, they remain higher, but the highest bit, in all the ones I've seen, is actually on the inner corner high, just as you've found. The gravity ought to be diagnostic, because if the topography is supported by a passive process and the density isn't changing much, the gravity anomaly is easily calculated. What do the free air gravity anomalies do?

J. A. Karson. Investigations of inside corners and transverse ridges, where oceanic core complexes appear to be common, have concluded that they are dynamically supported as you suggest.

R. S. White (*Bullard Laboratories, University of Cambridge, UK*). Results from a seismic refraction survey we shot across the transverse ridge adjacent to the Vema Fracture Zone in the North Atlantic show that the crust beneath it is of normal oceanic thickness (Potts *et al*. 1986). This suggests that the crust is being supported dynamically rather than pushed up by, say, serpentinization of the underlying mantle.

J. A. Karson. I think there is general agreement that this relief is dynamically supported regardless of geological structure. Some crustal exposures along fracture zones are dominantly serpentinite, whereas others are dominantly gabbroic. Although their density and velocity structures may be similar, they have very different geologic histories, especially with respect to magmatic construction. The density and bathymetry relations do not tell us much about how the crust in these core complexes was constructed.

D. McKenzie. They tell you it is being held up.

J. A. Karson. That is true.

A. B. Watts (*University of Oxford, UK*). Planar reflectors in the lower crust remind me that sometimes, in the older parts of the Atlantic, you see reflectors dipping away from the mid-ocean ridge and not toward the ridge.

J. A. Karson. The large-scale detachment faults mapped near the Mid-Atlantic Ridge presently have very low dips, commonly less than 30°. Although it is a continuing area of investigation, it is possible that these have rotated to low angles from steeper original orientations. If such footwall rotations occur, any initially horizontal reflectors will also be tilted just in the sense you suggest, that is, so as to dip away from the spreading centre. What these reflectors are is still anybody's bet; there are any number of possibilities. I think deep drilling is the only way to correlate specific reflectors with geological features.

N. Kusznir (*University of Liverpool, UK*). Linking to what Jean-Pierre Brun was driving at, and relating to Tony Watts's question, are you absolutely sure, in the example that you're looking at, that these faults go deep into the subsurface to the east? Could it be that they go deep to the west, that they dip the other way?

J. A. Karson. In the case of the detachment fault that borders the rift valley in the northern MARK Area, there are kinematic indicators so we know that it is a normal-slip fault zone. It dips beneath the median valley, but how far it extends, or exactly what shape it has in the subsurface is unknown. In fact, I know of only one place where a seismically imaged median valley fault zone can be traced from the subsurface into the rift valley walls. That is in the southern MARK Area, where Toomey *et al*. (1988) used microearthquakes to define a 45° dipping fault zone that we later mapped at the surface. Almost no kinematic indicators, and no surface geology, are available for the other lineated massifs that appear to be so common in slow-spread crust, so they could possibly dip into the subsurface either toward or away from spreading centres.

K. E. Louden (*Dalhousie University, Halifax, Canada*). This may be an unfair question. Professor Karson has been involved both in these bottom studies from submersibles to map out areas and also in the Ocean Drilling Program and, given the mixed history of ocean drilling, we might have one or possibly two more chances to drill in these zones. Given the complexities that he has shown on the surface and the fact that the mantle underneath these zones may not be the same mantle as when it formed, what does he think we're going to get from drilling through the base, or trying to drill through the base, of these zones?

J. A. Karson. I think there are a couple of good reasons to drill into oceanic core complexes. We can get a certain amount of information from the surface with submersibles, but there is always a sampling bias. In addition, we never collect a continuous vertical section; we get blocks of rock that are a few centimetres across that are likely to be preferentially exposed along faults. I think by drilling into one of these massifs, we would at least begin to address some of the questions that I raised earlier: 'How thick is the region that is actually deformed, or that has undergone crystal-plastic deformation and what is the spacing of major fault zones in that interval?' Are there duplexed detachment systems throughout the crust? Have they been rotated during or after slip? Drilling will provide the kind of sampling necessary to answer these questions. Of course, a single drill hole provides only vertical information and drilling multiple deep holes is probably unrealistic at this point. So, I do not think that we will learn everything we need to understand about the formation of oceanic core complexes from either drilling or submersible studies alone. We will need the kind of information that both of these approaches can provide. This became very clear to us in our coordinated drilling and submersible studies in the MARK Area.

N. Kusznir. Ten years ago Professor Buck presented a very nice model that could explain the exhumation of metamorphic core complexes. More recently, with Alexei Poliakov, he developed models that do not. Would he like to comment?

R. Buck (*Columbia University, Palisades, NY, USA*). We are just beginning to learn how fault systems can be modelled numerically and what parameters control the pattern of faulting. I showed that there was a magnitude and rate of cohesion loss which could lead to a very large offset normal fault that rotated to a low dip angle at the surface. This mechanically consistent model gives results that are similar to those from the semi-kinematic model for core complex faults that I published 10 years ago. For a higher rate of cohesion loss with strain, we find that faults are offset a relatively small amount (compared to the brittle layer thickness) before new faults formed. For stretching lithosphere with a fixed thermal structure, these parameters give topographic patterns that look similar to axial valleys and abyssal hills. I am not sure that we yet know which parameters of strain weakening are appropriate for normal faulting. My working hypothesis is that the parameters that give large offset normal faults for extension of a brittle layer may be closer to being correct than those that give small offset faults. To explain the small offset of typical abyssal hill bounding faults, we have to invoke the effect of magmatic accretion. Sections of slow-spreading ridges that don't have large offset fault structures may have a greater supply of magma per unit thickness of lithosphere. Essentially there's a greater proportion of the lithospheric extension that is accommodated by magmatic injection, so you might say that there is less stretching. That is one possible way to get differences in the style of extension. What magma does during extension is a gigantic question and it's harder than I used to think. One view is that magma is injected as a dyke that may or may not reach the surface. If it doesn't reach the surface, you get small faults going off from the top of the dyke. Maybe it is much more complex and there are things like Jeff Karson is talking about—magma intruding along faults and perhaps weakening them.

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