Art. N° 296
Contribution COB N° 443

Réimpression du JOURNAL CANADIEN DES SCIENCES DE LA TERRE
Volume 13, Number 9, 1976 - Pages 1223-1235

Oceanic fracture zones do not provide deep sections in the crust[1]

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Received 16 December 1975
Revision accepted for publication 13 May 1976

Data from rock-dredging have often been used to infer that oceanic fracture zones provide a 'window' into layers of the oceanic crust lying at a depth below the surface that is approximately equivalent to the vertical offset of the fracture zone, and thus permit the reconstruction of a crustal stratigraphy for the whole of acoustic layer 2 (commonly considered to have an average thickness of ~2 km) and, in some interpretations, for the upper part of layer 3. Alternatively, it has been suggested that fracture zones are preferential sites of serpentinite mega-dykes differing in composition from layer 3 but containing inclusions of the third layer. The published data indicate that basalts and basaltic rubble are abundant in fracture zones and, on analysis, do not justify the assumptions that have been made. The structure of fracture zones limits the possible extent of crustal sections exposed on their walls. Moreover, it is suggested that rocks of different layers of the lithosphere can be emplaced in the transform domain due to the dynamic of the transform fault system, itself.

Des données provenant de roches prélevées par dragage ont souvent été utilisées pour inférer que les zones de fractures océaniques fourniraient des 'fenêtres' montrant les couches de la croûte océanique à une profondeur sous la surface à peu près équivalente au rejet vertical de la zone de fracture et ainsi permettraient le rétablissement de la stratigraphie de la croûte pour toute la couche acoustique 2 (qu'on considère habituellement comme ayant une épaisseur moyenne de ~2 km) et, dans certaines interprétations, pour la partie supérieure de la couche 3. D'autre part, on a suggéré que les zones de fracture étaient des sites de choix pour des méga-dykes de serpentine de composition différente de la couche 3 mais contenant des inclusions de cette dernière couche. Les données publiées à date indiquent que les basaltes et les débris basaltiques sont abondants dans les zones fracturées et, après analyse, ces données ne justifient pas les hypothèses de départ. La structure des zones de fracture limite la dimension des sections de la croûte à ce qui est exposé le long de leurs parois. De plus il semble que les roches de différentes couches de la lithosphère ont leur origine dans le domaine transformant à cause de la dynamique du système de failles transformantes lui-même.

[Traduit par le journal]

Can. J. Earth Sci. 13, 1223-1235 (1976)

Previous Geological Models of Oceanic Fracture Zones

Early seismic refraction studies led to the division of the upper part of the oceanic crust into layer 2 and the thicker layer 3. The geometry (particularly of layer 2) and the range of compressional velocities are variable, even within a single province of the ocean floor (Raitt 1963); and there is insufficient field evidence to demonstrate whether the acoustic layers of the Mid-Oceanic Ridge, where sediment cover is thin, correspond to crustal units having a characteristic structure and overall composition. However, it is reasonable to suppose that there is a vertical zonation of rocks within the upper few

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kilometres of oceanic crust, and for the purpose of this paper we follow the convenient and common custom of referring to layers 2 and 3 as if they were distinctive crustal units (Christensen and Salisbury 1975).

Hess (1962), to explain the occurrence of the serpentinized peridotites from the Mid-Atlantic Ridge described by Shand (1949), expressed the idea that the "displacement on fault scarps in the oceans may have been sufficient to expose layer 3". The opinion of Hess has become, for many, a preferred working hypothesis, thus leading to a systematic search in fracture zones for exposed sections of deep oceanic crust. According, for example, to Engel and Engel (1970), "the most deeply exposed rocks of fault scarps represent upper parts of the basal oceanic layer". Following Hess (1962), Bonatti *et al.* (1971) state that "direct sampling of the crust beneath the ocean can be made in tectonic fracture zones where thick crustal sections are exposed". Melson and Thompson (1971) "favour the view that fracture zones provide windows into the deeper zones of the oceanic crust". In brief, a prevalent concept is that fracture zones expose sections of the crust more or less equivalent to their total vertical offset, which means that large fracture zones such as Vema or Romanche should cut right through layer 2, which has a maximum thickness of more than 2 km, and provide 'windows' into the upper part of layer 3. Data from the study of rock dredges have been repeatedly interpreted to fit this supposition.

Miyashiro *et al.* (1969*a*) considered the 'window' model of Hess (1962) to be only one of several possible structural interpretations. They suggested that fracture zones may be instead the sites of intrusion of serpentinized peridotites and some investigators; for example, Melson and Thompson (1971) adopted the latter idea as a second choice. The hypothesis that fracture zones are loci of huge linear plugs or megadykes differs in a fundamental way from the 'window' concept as introduced by Hess. It can dissociate layer 3 from the ultramafic rocks sampled in the deeper parts of fracture zones and adds a third, major unit to the simple two-layer model of the oceanic crust. Principal specific geological models of fracture zones that have been illustrated differ with respect to the identity and distribution of the various rock units and have different structural implications (Fig. 1).

In Miyashiro *et al.*'s (1969*a*) version of the 'window hypothesis' (Fig. 1, A1) and in the 1972 variant of Thompson and Melson (Fig. 1, B1), a thin cover of basaltic volcanics (layer 2) overlies a thick layer (layer 3) made up of ultramafic rocks with some associated metabasites or basalts and gabbros. The 'window' into layer 3 is essentially horizontal; that is, there is little or no exposure of layer 3 on the inner walls of the fracture zone. Conforming more closely from a structural point of view to the original Hess (1962) proposal as adopted, for example, by Bonatti *et al.* (1971), is the model schematically illustrated by Fox *et al.* (1973), in which there is substantial exposure of layer 3 on the inner walls of the fracture zone (Fig. 1, C). The 'window' is thus both horizontal and vertical with respect to layer 3. An *a priori* implication is that there have been large vertical displacements of crust, or there has been massive erosion (see Conditions for Exposing Deep Crustal Sections, this paper). However, layer 3 in this case is equated with gabbroic rocks, as originally suggested by Cann (1968); the model incorporates the idea of a 'fracture zone' mélange in the floor, and as a skin on the lower escarpment of the walls.

In the second model of Miyashiro *et al.* (1969*a*; see Fig. 1, A2), the serpentinite unit constituting the floor of the fracture zone can occur also on the inner walls and contains inclusions of layer 3, which is composed, in this case, of metabasalts and, presumably, of inclusions of layer 2. Melson and Thompson's (1971) two variants of this model (Fig. 1, B2 and B3) associate layer 3 with metabasalt and gabbro, permit incidental exposure of layer 3 near the bases of the fracture zone walls, and do not permit a contact between layer 2 and the rocks of the fracture zone plug. In one of the variants (Fig. 1, B3), gigantic dykes of the same material as the fracture zone plug cut right through both layers 3 and 2, and a diapiric structure similar to the fracture zone plug is portrayed under the Rift Valley walls adjacent to the fracture zone. The dykes are shown to parallel the fracture zone or have only a moderate angle to it.

The geological models of fracture zones that have just been briefly described were designed mainly to put some order in petrological data obtained from rock-dredging or coring. The models incorporated little structural analysis of the sampled rocks in their tectonic setting. We

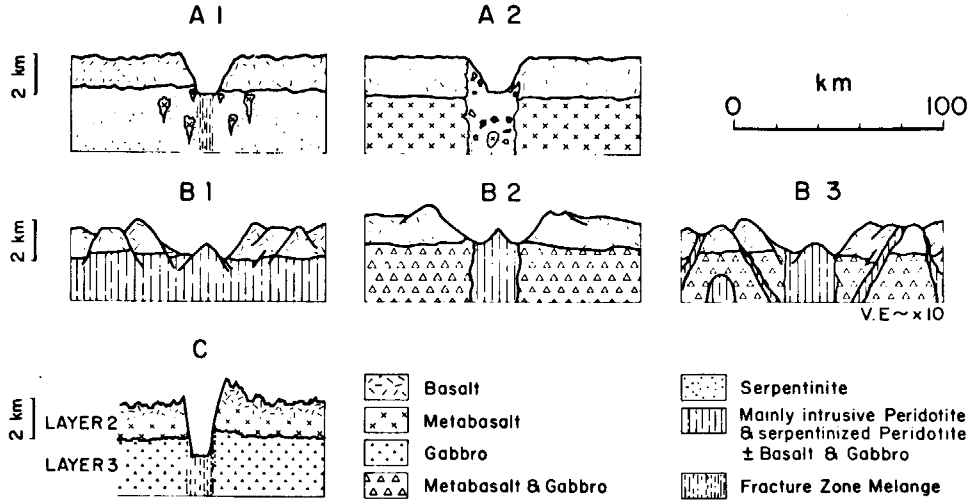

FIG. 1. Six simplified schematic cross-sections illustrating different notions of surface and subsurface geology of an oceanic fracture zone. A1, A2: Miyashiro *et al.* (1969*a*); B1: Thompson and Melson (1972); B2, B3: Melson and Thompson (1971); C: Fox *et al.* (1973).

feel that it is possible and timely to go to another scale of study and discuss more precisely the structural setting of oceanic fracture zone rocks. It is not our purpose to argue for or against the particular identities, sequences, or lateral distributions of lithologies making up the oceanic crust, nor do we exclude the possibility that layer 3 may, under certain circumstances, be exposed in fracture zones. The purpose of this paper is to discuss more fully the exposure of the oceanic crustal sequence in fracture valleys. First, we show that the published data on the morphology, structural pattern, and distributions of different rocks in the fracture zones of the North Atlantic do not, as claimed, demonstrate that circumstances of exposure of the crustal sequence exist, nor do they particularly support the idea of the presence of a single pipe-like body under fracture zones that differs in composition from layer 3. Second, incorporating arguments from a recent submersible study (Arcyana 1975), we stress the view that the structural style of fracture zones may be such that it typically places severe limits on the vertical extent of exposure of crustal sections. Finally, we go on to present a sketch that we think represents a more realistic view of fracture zones than is suggested by models in current favour.

Analysis of Published Data on Rock Dredges in North Atlantic Fracture Zones

For purposes of compiling information from the literature, we have approximated fracture zone valleys in the Atlantic Ocean by a single cleft separating two regions with typically different regional depths. The vertical relief shown as OO′ on Fig. 2, between the regional depth on one side of the fracture valley and the deepest part of the valley, is the valley height. The fracture valley is commonly bordered by a linear ridge called a "transverse ridge" by Bonatti (1973); and when such a ridge exists, the valley height is taken to be the depth difference between the summit of the ridge and the trough of the valley. The position of each dredge haul is fixed with respect to the maximum valley height of the sampled limb of the fracture valley. All the summits of the fracture valley, whether they are represented by a linear ridge parallel to the valley or by the regional depth along a line perpendicular to the valley, have been brought to a common depth datum (Figs. 2, 3).

The fracture zones have been arranged by increasing magnitude of valley heights, ranging from less than 2 km for Gibbs and Kane to more than 4 km for Vema and Romanche (Fig. 3). Within fracture zones, the dredge hauls have been arranged by increasing level of the valley height sampled. In each dredge haul, we have classified the rocks into basaltic (triangles), gabbroic (circles), and ultramafic (squares). Thus, basaltic rocks also include metabasalts and no distinction has been made in Fig. 3 between peridotites and serpentinites, since most perido-

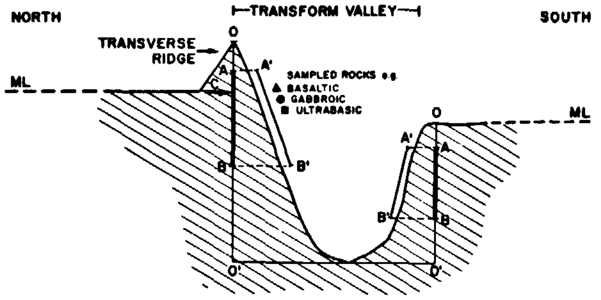

FIG. 2. Generalized cross-section of an oceanic fracture zone illustrating method and nomenclature used in this paper to analyse published data on rock dredge-hauls from oceanic fracture zones (Fig. 3). ML: Mean topographic level (regional depth) of top of either flank of fracture zone. O: Depth on top of either flank of fracture zone; corresponds with ML if no 'transverse ridge' exists; represents regional depth on top of 'transverse ridge' where present. O′: Depth along axis of maximum depth of fracture zone. O–O′: Flank height used to determine depth range of section sampled by dredging or coring. A′–B′: Sampled section. A–B: Normal projection of A′–B′ on O–O′.

tites dredged in fracture zones show various degrees of serpentinization. Ultramafic rocks include harzburgites, dunites, lherzolites, and pyroxenites, whereas gabbroic rocks include norites, troctolites, *etc.*

The adopted presentation is well suited to testing the validity of drawing the inference that dredge data show the layered structure of fracture zone walls. Models in which layer 3 is well exposed not only on the floor but also on the lower walls of a fracture zone (*e.g.* Fig. 1, C) imply that a clear lithologic zonation should appear when sampling increasingly deeper sections of an inner fracture zone wall. The model would require, for example, that below about 2 km (the average thickness of layer 2) only layer 3 would be sampled, whether it be gabbroic as suggested by Cann (1968) or ultramafic (serpentinized peridotite) as suggested by Hess (1955). The only way out of this would be to appeal to unlikely arguments (see Conditions for Exposing Deep Crustal Sections, this paper).

In models in which the 'window' into layer 3 is essentially horizontal (*e.g.* Fig. 1, A1 and B1), layer 3 rocks should be confined to the deepest part of fracture zone valleys. Models associating fracture zone floors with plugs of material different from layer 3, but containing inclusions from it, are more difficult to test. In one case (*e.g.* Fig. 1, A2), rocks of all types are allowed to occupy all levels; in another (*e.g.* Fig. 1, B2), it would clearly be difficult, without knowing the composition of layer 3, to be sure whether rocks sampled from the deep part of the fracture zone should be ascribed to layer 3 itself or to a fracture zone plug.

We comment on the distribution of the three principal rock-types (basalts, ultramafics, and gabbro) and make additional comments on the Vema and Romanche fracture zones because it is inherent in the concept of fracture zone crustal sections and deep exposures that only the largest fracture zones meet the conditions required to yield enough petrological and topographic information for constructing models (Bonatti *et al.* 1971; Melson and Thompson 1971; Honnorez and Kirst 1975).

Basalts

Basaltic rocks were dredged from the deepest sampled depth in Romanche (dredges BKS 7 to 10), Atlantis (dredge A 150-RD 20), Oceanographer (dredge FLH-1), Kane (dredges K9-D7 and V-25-D6, D8, D12, D13), and Gibbs (dredge D7). Only in Vema (dredge AII 20-9) and St Paul (dredge P6707-41) did the deepest dredge contain only serpentinized ultramafic rocks. In Vema, however, the upper, nearly 3 km deep section contains basaltic rocks; and in St Paul, basaltic rocks are also found in the upper 2.3 km of the Valley. Indeed, basaltic rocks are found at all levels except in two dredge hauls of Romanche (P6707 B-13 and -32), the deepest dredge hauls of Vema (AII 20-9) and St Paul (P 6707 B-41), one additional intermediate dredge haul of St Paul (P 6707 B-40), the Chain dredge haul (P 6707-5), one dredge haul of Kane (V 25-D 9), two dredge hauls of Gibbs (201 and 203), and in the single Chain dredge-haul (P 6707-5) that contained gabbroic and ultramafic rocks. Thus, it is considered significant that only nine dredge hauls out of the forty-two presented in Fig. 3 contained no basaltic rocks. The widespread abundance of basaltic rocks in fracture zones is a fact of observation that has not received proper recognition in the literature.

Ultramafic Rocks

The ultramafic rocks are distributed over the same vertical spread as the basaltic and gabbroic rocks. Ultramafic rocks for example occur in the upper portions of Gibbs (CH 4-DR 2, 203), Kane (V 25-D 9), Atlantis (A 150-RD 6), St Paul (P 6707 B-35, and of course near St Paul's

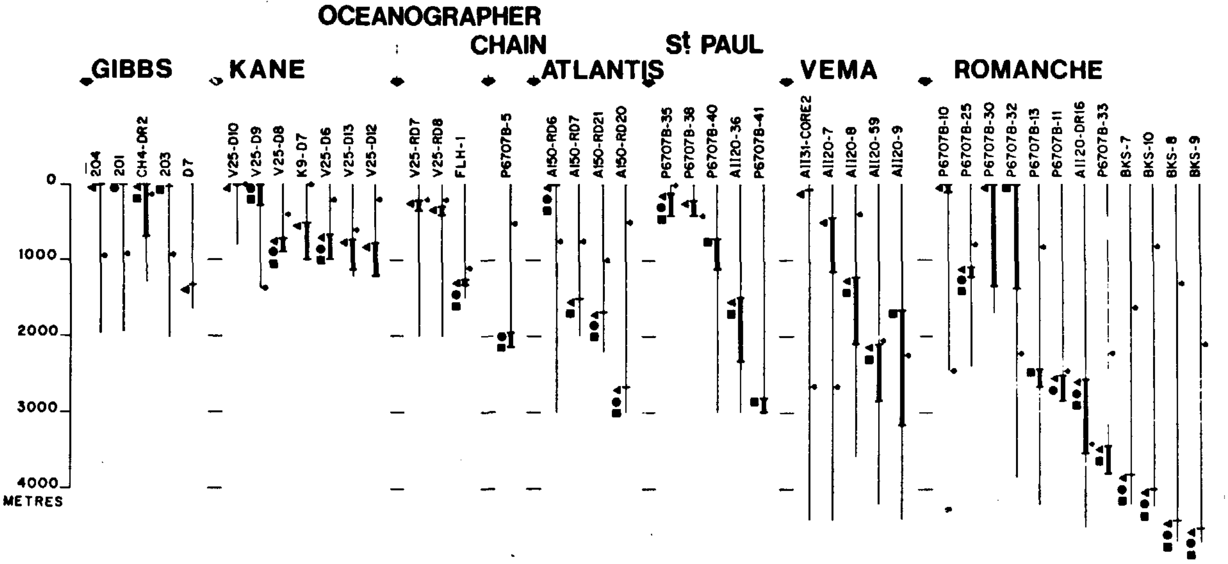

FIG. 3. Compilation of published data on dredged and cored rocks from oceanic fracture zones, showing distribution of major rock types with respect to the geometry of the fracture zones as determined from bathymetric information available in the literature. Gibbs: Fleming *et al.* 1970; Campsie *et al.* 1973; Hekinian and Aumento 1973; Olivet *et al.* 1974. Oceanographer: Fox *et al.* 1969; Shibata and Fox 1975. Atlantis: Shand 1949; Muir *et al.* 1966; Opdyke and Hekinian 1967; Miyashiro *et al.* 1969*a*,*b*, 1970, 1971; Kay *et al.* 1970. Kane: Miyashiro *et al.* 1971; Uchupi 1971; Fox *et al.* 1973; Fox and Opdyke 1973. Chain: Heezen *et al.* 1964*a*; Bonatti 1968; Bonatti *et al.* 1971. St Paul: Bonatti 1968; Bonatti *et al.* 1971; Uchupi 1971; Christensen 1972; Melson and Thomson 1973. Vema: Heezen *et al.* 1964*b*; Melson and Thomson 1971; Van Andel *et al.* 1971. Romanche: Heezen *et al.* 1964*b*; Bogdanov *et al.* 1967; Bogdanov and Plosko 1967; Melson and Thomson 1970; Bonatti *et al.* 1971. FLH-1: Dredge 1 in Fox *et al.* 1969. BKS-7 to -10: Dredges 7 to 10 in Bogdanov *et al.* 1967. Solid triangles: basalts and basaltic rocks in general; solid circles: gabbros and gabbroic rocks; solid squares: ultramafic rocks (peridotites, serpentinites, etc.). Light continuous lines represent sampled flank height (O′–O′, Fig. 2). Dark lines indicate sampled section projected on O–O′ (Fig. 2). Horizontal arrows mark mean topographic level (ML, Fig. 2). Flank heights adjusted to same datum; fracture zones arranged, from left to right, in increasing order of total vertical relief.

rocks), and Romanche (P 6707 B-32). In the case of Gibbs, Kane, Atlantis, and Romanche, these ultramafic rocks which are all serpentinized were dredged from the linear 'transverse ridges', which are stated by Bonatti (1973) to be predominantly composed of ultramafic rocks. We question this inference because the ultramafic rocks were accompanied by basaltic and/or gabbroic rocks in all dredge hauls mentioned above except core 203 of Gibbs. Ultramafic rocks represent the sole rock-type of a dredge in just 6 out of 42 dredge-hauls, and only in St Paul is it found in the deepest haul (Fig. 3).

Gabbros

The presence of gabbros is noted in 17 out of the 42 reported dredge-hauls (Fig. 3). With the possible exceptions of Oceanographer, Vema, and St Paul, they appear to have no preferential association at all with the deeper parts of the fracture zones.

Vema Fracture Zone

Melson and Thompson (1971) proposed that the ultramafic rocks are a major component of the lower part of the oceanic crust in the Vema fracture zone. This does not appear in our compilation of their data, especially if we note that it is not possible to sample the deepest levels because of the considerable sediment fill. It is unfortunate that only 5 out of the 23 dredge hauls made in Vema (Honnorez and Kirst 1975) could be incorporated in Fig. 3 because lack of precise information on dredges conducted during Miami's R/V PILLSBURY cruise 7003. Honnorez and Kirst (1975) mention that, from a total of 23 dredge-hauls, ultramafic rocks were recovered in 8 dredge hauls from the northern wall of Vema fracture zone, whereas they occurred in 5 dredge hauls from the southern wall, the Vema 'transverse ridge' of Bonatti (1971, 1973), leading Bonatti (1971, 1973) to state that "extensive dredgings have established that the Vema transverse ridge is essentially an ultramafic body". The Vema Transverse Ridge has a width of 30 km, a length of 350–400 km, a height above the mean topographic level of about 2000 m, and is bounded by scarps with slopes of about 15° (Van Andel *et al.* 1971). The size of the alleged ultramafic body is thus enormous even when compared with, for example, the 160 km-long, 10 km-wide Nahalin peridotite body of British Columbia (Ringwood 1969).

However, one notes from Fig. 2 of Bonatti *et al.* (1971), where dredge results of P 7003 are displayed, that in only two dredge hauls (AII 20-9 and probably P 7003-5, see Bonatti 1971 and Bonatti *et al.* 1971) were ultramafic rocks the only or 'main' rock-type (Melson and Thompson 1971).

Honnorez and Kirst (1975), who mention that ultramafic rocks were commonly dredged with gabbroic and basaltic rocks, have to suppose that the non-ultramafic rocks may be passively 'uplifted' on the backs of the ultramafic blocks. Thompson and Melson (1972) argue that the ultramafic 'intrusion' is capped by old, metamorphosed volcanics unrelated to the peridotite. For Melson and Thompson (1971), the Vema dredge results indicate that, in the fracture zone, in accordance with their model B1 of Fig. 1, the upper basaltic zone has been rifted apart by a change in spreading direction (Van Andel *et al.* 1969) and has exposed a predominantly serpentinized peridotite zone (layer 3?), capped in at least one region (dredges AII 20-59 and AII 31—core 2) by basaltic rocks. Melson and Thompson (1971) conclude that equatorial Atlantic transform fault zones appear to expose layer 3, which would be a complex in which peridotite predominates with subordinate gabbroic and metamorphosed basaltic rocks.

Van Andel *et al.* (1971) agree with Bonatti (1971) that the south wall or "transverse ridge", and possibly the north wall, did "uplift" slices of oceanic crust and suggest that the uplift of the south wall "may represent not only all of layer 2 but also the major part of layer 3". In support of this hypothesis, they refer to dredges AII 20-8 at the base of the wall north of the fracture zone valley and AII 20-9 at the base of the south wall, which contained serpentinized peridotite in contrast to three dredge hauls from the upper slope of the south wall (AII 31—core 2, AII 20-7 and AII 31—core 1?), which contained only basalt. In view of the recovery of basalt only in dredge AII 20-59 from the base of the south wall and the recovery of all three rock types in dredge P 7003-23 (Honnorez and Kirst 1975) from the eastern end of the south wall, the picture of a deeply exposed layer of ultramafics capped by basalt seems unjustified and invalidates the interpretation of Van Andel *et al.* (1971), that uplift of several kilometres expose ultramafics on the valley walls.

Bonatti *et al.* (1971) mention that during cruise P-7003, peridotites were dredged on the north wall of the Vema transform fault valley below a gabbro–basalt layer. This assertion has not been documented; but one should note that dredge hauls AII 20-8 and P 7003-17 (Honnorez and Kirst 1975) from approximately the same topographic levels recovered basaltic and ultramafic rocks, and gabbroic and ultramafics, respectively, so that the proposed layering is further cast into doubt.

Romanche Fracture Zone

A transverse ridge making up the northern wall of the Romanche fracture zone near the western end of its active portion is suggested by Bonatti *et al.* (1971) to consist essentially of ultramafic rocks. Their conclusion is based on the recovery of ultramafics from both the lower slope (dredge P 6707 B-33) and the summit (dredge P 6707 B-32) of the transverse ridge. However, the summital dredge yielded, in addition, 29% metamorphosed gabbroic rocks, and the basal dredge 43% basalts and metamorphosed gabbroic rocks (Honnorez and Kirst 1975). Thus, the transverse ridge cannot be an ultramafic body with a minimum exposed thickness of 3500 m (Bonatti 1968), especially if we note that a 2000 m high, intervening section of wall has not been dredged.

Bonatti *et al.* (1970) argue that they can establish an approximate stratigraphy for the crust of the Mid-Atlantic Ridge on the basis of dredges conducted across Romanche during cruise P 6707. They visualize essentially a pile of basalt about 1–2 km thick, grading downwards into gabbroic rocks and metabasalts–metagabbros, with the base of the exposed sections consisting of peridotites. Bonatti *et al.* (1970) give a composite section of the Romanche fracture valley at 17°–18° W with dredges P 6707 B-10, -11, and -13 plotted in increasing order of depth with respect to sea-level. This differs from the normalized presentation we use but equally fails to show any evidence of a definite petrographic level as suggested by Bonatti *et al.* (1970). The north wall at a depth of about 5000 m consists of metabasalt and gabbro near 17° W (P 6707 B 11); basalt, gabbro, and peridotite near 20° W (P 6707 B-25); basalt near 23° W (P 6707 B-30); and basalt and peridotite near 24° W (P 6707 B-33).

Discussion

The picture that emerges for fracture zones is one of lithologic heterogeneity with no clear evidence of any simple stratigraphy. We can state that, on the basis of the rocks so far recovered, fracture zones have not been demonstrated to provide deep sections in the oceanic crust. This also applies to the Vema and Romanche fracture zones. As well as the absence of any petrological zonation in any fracture zone demonstrated by Fig. 3, a second fact is considered very significant: the very frequent association of all three rock types or of basaltic and ultramafic rocks in many dredge hauls, even when the hauls are reasonably short. This is further evidence that no large-scale zonation of the crust is revealed in the walls of the fracture valleys. It is unfortunate that most petrological description of fracture zone rocks do not include the statistics of abundance of each rock type in the dredge bag. For reasons that will become clear later, however, presence or absence of any one type of rock is considered more important than percentage.

It is obviously possible to reconstitute a vertical stratigraphy if one argues that basaltic rocks found at deep levels have been transported from upper levels by gravity. This problem must be evaluated in the light of detailed information on the topography of the walls of fracture valleys, and it would have to be shown, in each case, that there are no steps on the walls that would act as traps for sediment and rock debris (Fig. 4). Furthermore, if the deep seismically active parts of fracture valleys were shown to be occupied by material transported from higher up, it would cast a doubt on the significance of all other rocks recovered from the valley floors. It can also be argued that basalts recovered in fracture valleys have been emplaced in this setting in a late phase of volcanism. If so, they may differ in composition from Rift Valley basalts.

The data on the distribution of rock types in fracture zones does not support the contention that fracture zones provide horizontal windows into the crust, as layer 3 material is not conspicuously associated with the deepest parts of the fracture valleys. The distribution of ultramafic rocks, which is pertinent, especially for those who view serpentinized peridotite as the major component of layer 3, is ultimately linked to the problem of the nature of the enigmatic 'transverse ridges', which do not appear, on the basis of rocks so far sampled, to be made predominantly of ultramafic rocks.

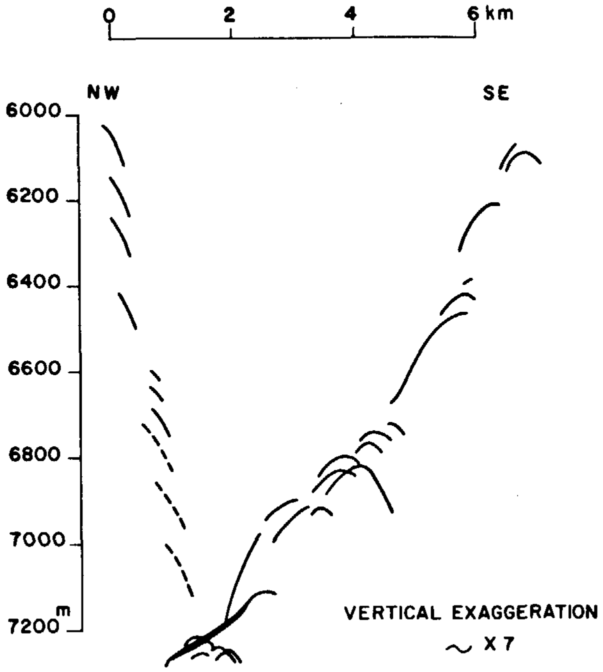

FIG. 4. Tracing of precision depth record across lower part of Romanche Trench (Heezen *et al.* 1964*a*). Vertical scale in metres derived from scale in fathoms (1/400 s) shown on original tracing. Vertical exaggeration 2 × 7. Mean slopes of walls are ~37 and 12 , respectively. Note presence of numerous steps.

As has been pointed out above, a model involving the presence of a fracture zone plug differing in composition from layer 3 and possibly covering the walls is difficult to test in the same way as other models, because it is to some extent free of field requirements.

Conditions for Exposing Deep Crustal Sections

Although the presently available rock information fails to support any one proposed model, it could be argued that this is because of poor sampling and lack of knowledge of field relationships. The problem could then be phrased in a different manner: is it likely that fracture valleys, if sampled extensively, would provide thick crustal sections or, alternatively, would provide horizontal windows into the crust? The problem, then, is to discuss the conditions that would be necessary for doing so. Recent results obtained from direct observations of the geology of an active fracture zone in the Atlantic Ocean (Arcyana 1975) provide key information on: (1) the significance of rock material recovered in the deeper parts of fracture zones, and (2) the nature and pattern of the deformation associated with the slip of lithospheric plates.

If fracture zone sampling is to be useful for establishing geological models of crustal stratigraphy, it is essential that the nature and position of the rocks recovered be considered representative of the proposed sequence. This is of course implicitly assumed by most authors who consider, in deriving fracture zone models from petrological data, that the rock samples are fragments of *in situ* material. This assumption may prove to be wrong. Thus, in fracture zone A of the Famous region, observations show that the deeper part of the transform valley is made up of important detrital material in the form of polygenic breccias, the formation of which is probably due to tectonic and seismic activity associated with the transform motion (Arcyana 1975). Observations also show that part of this material may have been transported for appreciable distances and that the material is continuously reworked by tectonic activity. It is therefore manifest that the breccia components are not representative of the nature of the underlying basement. This situation is probably not exceptional. Fracture zone B of the Famous region also shows abundant detrital material (R. D. Ballard, personal communication). The deeper part of Vema fracture zone showed the presence of a basaltic rubble zone at least 300 m thick during Deep Sea Drilling Project leg 39 (Perch-Nielsen *et al.* 1975).

Exposure of deeper portions of a horizontal lithologic series in fracture zones can theoretically be achieved through two main processes: an erosional process and a tectonic process.

Slumping induced by earthquake activity is a form of erosion that is quite likely in transform valleys. Erosion would, however, have to be massive to be significant and the large amount of erosion products would have to be present somewhere. This is not seen.

There are two main types of tectonic processes that may operate to expose deep layers: the first, without appreciable vertical movements, is extension of the bedded oceanic crust, producing megacracks on whose walls appears a stratigraphic section of the lithologic series. The extension could explain exposure of layer 3 in the floor of the valley, and even on the lower walls if the valley is deep enough (*e.g.* Fig. 1, A1, C). Two mechanisms that have been proposed for creating this extension are a change in the plate relative motion and resulting production of a leaky transform fault (Van Andel *et al.* 1971), and secondly, thermal contraction of the lithosphere (Turcotte 1974). The latter produces much too little extension to be significant and the former can obviously not be invoked as a general mechanism except in specific, well documented cases. Note further that rifting apart of the basaltic layer and resulting exposure of deep layers implies that leaky transform faults are not sites of magmatism, as this would conceal the deep layers. The second tectonic mode achieves exposure of the various deeper portions of the crust by way of vertical relative motions along transform fractures. For such a model to be possible, the vertical motions can not be distributed but on the contrary must be concentrated on two planes on either side of the deepest part of the transform valley (Fig. 5). The hypothesis that exposure is the result of concentrated vertical motions can be examined in the light of results obtained in fracture zone 'A' in the Famous area. It has been found (Arcyana 1975) that the transform motion and related vertical motions along the fracture zone faults are distributed on a large number of faults with a highly complex overall geometry. The step-like topography of transform fault A (Fig. 5) and the occurrence of numerous small vertical scarps on faults predominantly affected by shear (Fig. 6) show that exposure of deep layers of the crust is unlikely because vertical motions are small and are not associated with single fault planes.

Thus a 1-km offset apportioned between many faults can not yield exposure of deeper units, unlike an equivalent offset concentrated on a single fault (Fig. 5). This situation may be generalized and applied to other fracture zones which probably constitute masses within which the transform motion is widely distributed rather than slip zones with a simple geometry.

The above discussion leads us to question the validity of previous geological models of fracture

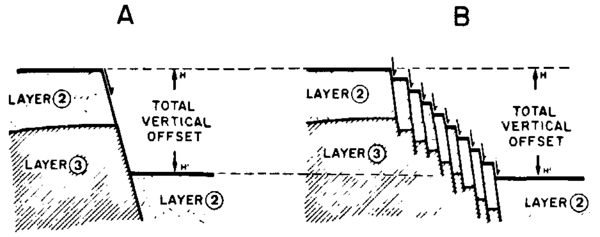

FIG. 5. Two hypothetical sketches illustrating consequences of different types of fault scarp distributions on possible exposures of underlying lithological units.

A: Total vertical offset H–H′ is achieved along single fault plane, and lithological unit 2 is exposed on lower part of wall.

B: Total vertical offset H–H′ is the same as in A, but is the product of 9 small offsets along individual fault planes. Maximum exposure of underlying crust is given by the maximum vertical offset along any one fault plane. No possibility with this geometry of exposing lithological unit 3.

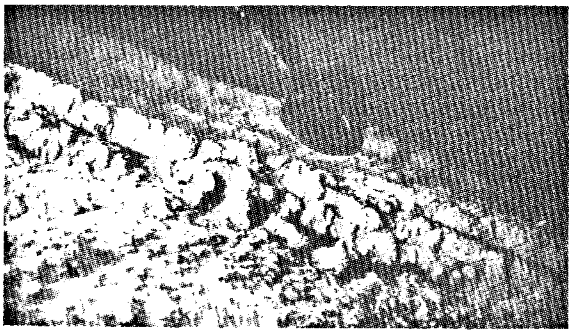

FIG. 6. Photograph of lower part of wall of fracture zone A near 37° in the Atlantic photograph from Cyana. Offsets on steps are < 1 m high and indicate the extent to which apparently small single scarps on fracture zone walls (such as illustrated in Fig. 5B) can be broken up into a fine-scale pattern of small offsets.

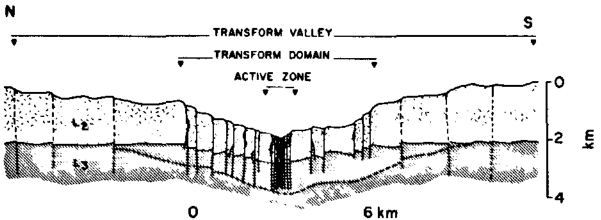

FIG. 7. Cross-section of fracture zone showing distribution of total vertical offset of fracture zone walls over a number of individual scarps with the result that underlying lithological unit will be exposed only in the case where thickness of overlying unit is less than the section exposed by largest of individual scarps. Unit 1 here is shown with diminishing thickness in fracture zone; solid line with unit 2 shows distribution of unit 1 if constant thickness is maintained.

zones. However, it has been noted that fracture zones contain a great abundance of plutonic and metamorphic rocks, so that we need to examine plausible mechanisms that would explain the presence in fracture zones of these possible constituents of layer 3 and the mantle.

Elements of a Working Hypothesis

We summarize arguments that we consider to represent key features for developing a working hypothesis for the geology of fracture valleys using a schematic hypothetical cross-section for illustration of the gross structures (Fig. 7). Note that these are shown without vertical exaggeration.

(1) The central, deepest part of the fracture valley is intensely fractured and the presence of hydrothermal deposits here suggests that the fractures are deep. Further, the deep part is occupied by abundant detrital material (basaltic rubble, breccia, . . .) and one notes that in long fracture zones, the time available for accumulating breccia is considerable (much greater, for example, than in transform fault A, Arcyana 1975), so that rubble zones may be very thick. It is interesting to note that deep drilling in Vema fracture zone showed the presence of a basaltic rubble zone at least 300 m thick (Perch-Nielsen *et al.* 1975).

(2) The presence in fracture valleys of material quite probably derived from layer 3 (gabbroic rocks with minor serpentinized peridotite), although not requiring that the rocks are *in situ* or in preserved stratigraphic relationship, may be explained if one considers that intrusive rocks can be found at quite upper levels of the oceanic crustal sequence, and if the thickness of layer 2, which is very variable anyway, can in some places be particularly small. It is not known whether layer 2 keeps the same thickness in fracture valleys compared to adjacent portions of crust. It could be argued that the basaltic layer 2 may be thinner in fracture valleys because it has been created in the region of the Rift Valley close to the intersection between Rift Valley and fracture zone, where—among other possible causes—the additional boundary condition imposed by the thicker, colder plate on one side of the intersection may make volcanic extrusion less abundant. A thinner layer 2 can explain gravity anomalies of Atlantic fracture zones (Cochran 1973). Christensen and Salisbury (1975) mention that refraction studies give the impression that

the oceanic crust is thinner under fracture zones, but it is not known if this is at the expense of layer 2. In fracture zone 'A', an intrusive unit of doleritic rocks has been found at high levels of the crust.

(3) The presence of ultramafic rocks can be explained in a number of ways. First, we must note that possible representatives of the mantle found in fracture zones are almost invariably altered and tectonized, and it is reasonable to suppose that serpentinization is contemporaneous with fracturing. Ultramafic rocks may represent samples of tectonic slivers or slabs, which are frequent and well known in the great continental shear zones.

In continental shear zones, the state of stress is highly variable: the geometry of the shear fractures is generally such that along the major shear regions in which there is compression can alternate with zones in which there is extension (Kingma 1958; Harland 1971; Wilcox *et al.* 1973; Harding 1973; Crowell 1974*a*,*b*). This situation can explain the origin of tectonic slivers, in which the rocks show intense deformation and easy transformation to serpentine if water is present. In the zones where there is compression, forceful drag of mantle material between two rigid blocks can explain intrusion in the crystalline state of dense material in the upper levels of the crust. In the extensional zones, it is conceivable that the low density of serpentinites (2.6 g/cm^3; *e.g.* Coleman 1971), coupled with high lateral pressures and with fault disruption of the overlying crust, could be sufficient to induce the rise and extension of the serpentinite masses as diapirs along deep vertical faults (Aumento and Loubat 1971). For example, the lherzolite massif of Lanzo (Western Alps), which is about 20 km long and 10 km wide, was emplaced in the solid state in a zone characterized by left lateral horizontal shear along a subvertical plane (Nicolas *et al.* 1972; Nicolas 1974). The Lanzo intrusion zone also shows evidence of horizontal shortening and the vertical component of motion corresponds to a minimum pitch of 15° (Nicolas 1974). If the pitch of the line of movement on the near-vertical shear plane is only 5–6° upwards, material that is 2 km below the crust can be brought to the surface after it has travelled horizontally 20 km. This mechanism is feasible for large fracture zones. If layer 2 has a reduced thickness under the fracture valley, either the pitch of motion or the extent of horizontal motion can be reduced. Nevertheless, because of the high density of shear faults in the active part of the fracture valley, it is likely that only narrow slivers will be brought up this way and there would probably be destruction of stratigraphic relationships by erosion contemporaneous with the shear. The dunite-mylonites of St Paul's rocks may also provide another example of dunitic material from the mantle that has been pushed up as a solid mass with concurrent mylonitization but absence of serpentinization because the ultramafic body was kept at too high a temperature (Bowen and Tuttle 1949).

In contrast, the Ronda harzburgite massif (Southern Spain) was, according to Loomis (1972), diapirically emplaced in an extensional zone above a hotter column of asthenosphere. Medaris and Dott (1970) speculate that "where serpentinization was thorough, the ultramafic masses appear to have risen as diapirs through more dense surrounding rocks". The highly fractured nature of the terrain makes deep penetration of sea-water and consequent serpentinization of peridotite rather likely in the case of oceanic fracture zones, and thus serpentinization may be more prevalent in fracture zones than, for example, in the Rift Valley. It is possible that diapirs ~~of~~ serpentinite operate like balloons to bring small blocks of unserpentinized peridotite to the surface. On land, ultramafic masses often consist of peridotite blocks and serpentinite (*e.g.* Medaris and Dott 1970); but in the ocean, the extent of unaltered peridotite bodies is not known.

In any case, even if gravity-induced emplacement (a form of diapirism) of serpentinized masses is uncertain, the serpentine has mechanical properties, due to its slickensided, slippery shear zones, that promote continued deformation and intrusion of the ultramafic mass (Bowen and Tuttle 1949). Serpentine intrusions behave "in much the same way that a watermelon seed moves when squeezed between one's fingers" (Hess 1955).

Conclusions

The proposed model (Fig. 7), like other fracture zone models, lacks several key tests, but it can account for the observations at the present time. It explains the abundant basaltic material found at all levels of fracture valleys (Fig. 3) and predicts that important predominantly basaltic rubble will be found by drilling in the axis of the fracture valleys. It also accounts for the emplacement of ultramafic masses by tectonic transport, either entirely by fault drag or partly by diapiric action of serpentinized material. The model does not incorporate the transverse ridges because their composition has not yet been defined. We feel it is important to compare the structural characteristics of oceanic fracture zones with those of fracture zones on land. In particular, the mantle slivers emplaced on continents in zones of intense deformation may be closely analogous to the oceanic transverse ridges. Careful kinematic studies of the deformations of material comprising the transverse ridges will be necessary to establish their mode of emplacement.

If crustal stratigraphy cannot be determined by sampling in fracture valley walls, then the nature of the seismic layers of the oceanic crust will have to be determined by first drilling deep in the crust away from fracture zones and second by investigating the physical properties (velocity, Poisson's elastic constant ratio, magnetization, density, and so on) of potential rock candidates for the layers. Even if they do not yield crustal stratigraphic sections, fracture valleys are clearly useful in that they provide samples of these candidate rocks. The comparison of true ophiolitic sequences with normal oceanic crust could then be done in a circular way after the oceanic crust layers are characterized through their inferred physical properties.

In summary, we do not wish to state that stratigraphic sections of the upper part of the oceanic crust cannot be found in fracture valleys, but we suggest that carefully controlled field exercises must be done before any credence whatsoever can be given to this possibility.

Some sites other than typical fracture zones have been mentioned as providing oceanic crustal sections: Gorringe bank (Allegre *et al.* 1973) and Palmer Ridge (Cann and Funnel 1967; Cann 1971). Their tectonic setting is different from that of fracture zones because they probably represent slices of oceanic crust associated with thrust-faulting. However, that an orderly crustal sequence is exposed in these two sites remains to be demonstrated.

A more likely exposure of a crustal section is probably to be found in the leading edge of a plate that is underthrusted at a trench. An ideal test would be to examine such an edge at the inception of underthrusting before an island arc appears, and before the crust becomes too different from a 'normal' oceanic crust. Perhaps one such opportunity exists in the Indian Ocean (Sykes 1970).

Note: After this paper was submitted, we received an unpublished manuscript by Fox *et al.* (1976) that presents three geologic models for the crust within oceanographer fracture zone. The refraction data and dredge hauls results reported in this manuscript add support to the discussion of fracture zone geology presented here.

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