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Constructional features of the Troodos ophiolite and implications for the distribution of orebodies and the generation of oceanic crust:[1] Reply

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Received March 12,1990
Revision accepted April 3, 1990

Can. J. Earth Sci. **27**, 1139–1141 (1990)

We thank W. R. Church for his thoughtful comments on our analysis of the cyclicity of construction of the extrusive series of the Troodos ophiolite and relationships to the distribution of orebodies. His comments provide an opportunity to bring to the attention of a wider audience a number of questions that we believe are basic to the proper interpretation of ophiolites in general and the Troodos in particular. Our response to Church's comment are incorporated in the discussion of several questions.

The first question to consider is the relative value of geochemistry in determining whether an ophiolite sequence formed continuously in one area or by different processes in different areas. It is now well known that rather different low-Ti ("boninitic") and high-Ti (andesite rhyodacite) geochemical suites are represented in the extrusive series of Troodos, and that difficulty has been experienced in the past in envisioning the contiguous formation of the source magmas. However, workers in several fields now believe that there is no difficulty in formation in a single area, presumably at a spreading ridge crest. Thus, Mehegan (1988), extending studies of the distribution of extrusives of Desmet (1977) and Schmincke *et al.* (1983), described further examples of interlayering of the two main magma types, including within the continuously cored 700 m drill hole CY-1a. Recovery of 94.5% in this drill hole precludes "structural complication," mentioned by Church as a possible explanation for the interlayering. Such explanation is also precluded for surface sections: current rapid uplift of Troodos has led to the formation of a series of parallel continuous sections in deeply incised canyons through the extrusive series. In this way Troodos differs from other ophiolites mentioned by Church, the difference leading to substantially less ambiguity in the interpretation of the setting of Troodos. Furthermore, the authors of a number of recent geochemical studies of Troodos extrusives (e.g., Cameron 1985; Thy *et al.* 1985) find reason for relationships between the two magma series, while Duncan and Green (1980) and Rabinowicz *et al.* (1987) suggest mechanisms for their contiguous formation.

A second question worth examination is the evidence for the presence of the products of an "off-axis" event or events in the Troodos extrusive series. The concept of "off-axis" volcanism appears to have originated with Gass and Smewing (1973), who described a number of lines of evidence for a time break between the Upper Pillow Lava (UPL) and Lower Pillow Lava (LPL) field mapping divisions of the extrusives. They suggested that the UPL is "analogous to the numerous sea mounts and volcanic islands that embellish the present day ocean crust away from the ridge axis and are probably produced by thermal plumes rising from the thermally unstable lithosphere/asthenosphere interface" (Gass and Smewing 1973, p. 28). While a situation such as Gass and Smewing envisioned provides a convenient explanation for extrusives belonging to two different magma series, the reality is that many lines of evidence are clearly against such "off-axis" volcanism. Thus, the UPL has been now recognized as a cold sea-water alteration facies of the extrusives (Gillis and Robinson 1985; Hall *et al.* 1987*a*), and careful reexamination of the boundary between the

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[1] Discussion by W. R. Church. 1990. Canadian Journal of Earth Sciences, **27**, this issue.

UPL and LPL has shown no evidence of an erosional break. Again, the geochemical breaks between the two main magma series in the extrusives do not, in general, coincide with the UPL–LPL interface. A number of other lines of evidence suggest that the extrusives and underlying sheeted dikes form a single crustal constructional unit, with continuous variation with depth of properties such as hydrothermal alteration, dike density (Hall *et al.* 1987*b*; Yang and Hall 1990), and physical properties (Salisbury *et al.* 1989; Hall *et al.* 1990). A simple model relating these properties involves alteration resulting from both downwards penetration from the sea floor of cold sea water and rapid increase in greenschist facies hydrothermal alteration everywhere dike density reaches 50% of the section, presumably as a result of the combination of increased temperature and decreased porosity and permeability. The zone below which little cold sea water penetrated and above the onset of the greenschist facies shows an alteration minimum, being characterized by the widespread presence of fresh glass, double Curie points, and maximum remanent magnetization and Q ratios. A final line of evidence against "off-axis" volcanism comes from comparison of the UPL of Troodos with confirmed off-axis volcanism associated with present mid-ocean ridge crests. Examples of the latter are series of isolated seamounts, such as the Cobb–Eikelburg chain (Karsten and Delaney 1989) and others on the flanks of the East Pacific Rise between 9 and 21°N (Batiza and Vanko 1984; Graham *et al.* 1987). In contrast, the UPL forms almost continuous belts along the 80 km long northern and southern flanks of the Troodos emplacement anticline. In the absence of analogs of this form in the present ocean basins, it seems most unlikely that the UPL was formed in an off-axis environment.

This conclusion regarding off-axis volcanism leads naturally to the next question: What is the expected process of crustal construction on a spreading ridge environment, and can the features of Troodos crust be accounted for by this process? Quantitative models for the constructional process at spreading axes have been developed by Palmason (1980). These models describe the trajectory of crustal elements with time and allow a number of predictions that can be tested for Troodos crust. For example, the deeper part of the extrusive section accumulates rapidly at the ridge crest where the magma supply to the sea-floor is at a maximum. Little opportunity occurs for cold sea-water penetration of a flow before it is covered by a succeeding flow. In contrast, the uppermost part of the extrusive sequence is, as a result of continuous transport of the section away from the ridge crest, formed of the distal ends of only the most extensive flows, with ample delay between flows to allow the extensive penetration of cold sea water. Again, tectonic disturbance through, for example, synconstructional listric normal or growth faulting, is expected to increase with depth, with the consequent increased rotation of deeper components. In these circumstances it would be expected, rather than being exceptional, that the youngest dikes of the Solea Graben would be the least rotated (Varga and Moores 1985, as quoted by Church).

The final question arising from Church's discussion concerns the large-scale tectonic environment in which Troodos was formed. Following Pearce *et al.* (1984) Church suggests that Troodos may have been formed at a spreading centre located in a transgressive basin located in the frontal part of a developing arc during oblique subduction. The difficulty with this suggestion is that no known example of this type of basin occurs in the present oceans. A substantial number of basins containing some oceanic crust do occur in association with subduction zones and a better way to proceed, following Moores *et al.* (1984), is to seek an analog for Troodos among these basins. Following tentative identification, key features of the comparison can be tested, as Moores *et al.* have suggested for the Andaman Sea basin, their suggested analog.

The Alpine-Himalayan belt provides many examples of extension as a secondary result of ongoing continent–continent collision, some of which have proceeded as far as the formation of oceanic crust. It seems reasonable to seek analogs for Troodos among these basins. Thus, Cenozoic oceanic crust, associated with subduction zones, underlies all or part of the Alboran, Algero-Provencal, and Tyrrhenian seas. A favoured method of accounting for the formation of these basins follows a suggestion by Elsasser (1971) that involves the suction of fragments from a continental margin by a pinned subducting slab, that is, a slab that is only free to move vertically (e.g., Fig. 5.3 of Livermore and Smith 1985). A small ocean basin then forms behind the continental fragments as they migrate towards the pinned subduction zone. In this way, the Algero-Provencal basin, for example, is seen to have formed behind Corsica, Sardinia, and the Kabylian fragments of the Algerian littoral. Since the slab is now only sinking, little further arc volcanism is anticipated. While this process provides an attractive explanation for the origin of Troodos in terms of the scale of the basins formed, and the lack of evidence of arc volcanism in Troodos, there are points where the comparison does not appear to be apt. Thus, the Neogene oceanic basin of the Mediterranean is characterized by the lack of widespread linear magnetic anomaly patterns, suggesting that crustal construction is more three dimensional, or less organized, than at a major mid-ocean ridge. Such a lower level of organization is in fact evident in the Tyrrhenian Sea, where isolated areas of young mid-ocean ridge basalts lie between fragments of extended continental crust (e.g., Wang *et al.* 1989). Troodos, with its largely uniformly directed sheeted dikes, and uniformly directed magnetization, shows an apparently higher degree of organization during crustal construction. The absence of linear magnetic anomalies over the ophiolite is readily explained by its formation during the long Cretaceous period of normal geomagnetic polarity. Thus, Troodos appears to be more like normal ocean crust than extant subduction-related ocean basins.

Two final comments can be made. The first is that, notwithstanding 30 years of intense investigation, knowledge of normal oceanic crust is still relatively poor. Surface features are much better known than features at depth. The principal known surface features concern the morphology and chemistry of the uppermost extrusives, the surface manifestations of hydrothermal circulation, and something of the apparent cyclicity of crustal construction. The widely scattered Deep Sea Drilling Project – Offshore Drilling Project drill holes, and their generally limited penetration and poor recovery, restrict knowledge of the crust at depth. Only one hole, no. 504B, has penetrated into the transition from extrusives into dikes. Rather more is known of the geophysical character of normal oceanic crust, particularly its velocity structure. This poor knowledge of normal oceanic crust severely limits our ability to test Troodos as a model for normal crust.

The second point concerns how to proceed properly with the problem of the relationship between Troodos-type and normal oceanic crust. Our working hypothesis is that the geochemical differences have little bearing on the processes of construction and alteration, which, until contrary evidence is forthcoming, we assume are similar in the two types of oceanic crust. In support of this hypothesis we note that Salisbury *et al.* (1989), using material from 4.5 km of continuously cored drill holes, show similarities between Troodos and normal ocean crust in a wide range of physical properties. Again, Hall *et al.* (1990) find that the large-scale magnetic structure of the extrusives closely resembles that of normal ocean crust. An earlier report (Vine and Moores 1972) that remanence was higher in Troodos than in normal oceanic crust was probably the result of insufficiently representive sampling. The morphological features of Troodos extrusives, synconstructional faulting, and hydrothermal alteration, all appear to closely resemble these features in normal oceanic crust, as far as they are known. In particular, the Troodos massive sulfide deposits have been shown to be of the "black smoker" type of normal oceanic crust (Oudin *et al.* 1981; Oudin and Constantinou 1984). Cyclicity of construction on a scale of the order of 10 km, as now recognized in Troodos by us, has been demonstrated in both surface features (e.g., Crane and Ballard 1981; Macdonald 1982; Stakes *et al.* 1984) and, through seismic profiling, at depth in normal oceanic crust (McCarthy *et al.* 1988).

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