It is not important whether these rocks end up being called members of the "sanukitoid suite." What is important is understanding why certain Archean "calc-alkaline" rocks tend to have higher Ni and Cr contents and are thus more primitive than most modern "calc-alkaline" rocks. We need to be able to distinguish the intermediate to siliceous rocks with high Ni, Cr, and LILE abundances and high Mg#'s from other "calc-alkaline" rocks, evaluate their abundance, and determine their origin, because they may be an important ingredient in the evolution of the continental crust. We recommend the use of the term "sanukitoid suite," because giving this suite of rocks an unambiguous name—whatever the name—helps us to distinguish, describe, and discuss them.

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

W. R. CHURCH

Department of Geology, The University of Western Ontario, London, Ont., Canada N6A 5B7

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The authors ascribe the grouping of ore bodies along the north flank of the Troodos ophiolite to the regular periodic (10^6 years) addition of magma to a single slow-spreading oceanic ridge. The model predicts that the addition of each magma batch would lead to voluminous sea-floor eruptions, and enhanced hydrothermal circulation and ore deposition within or marginal to "the location of arrival of major magma batches" (p. 1182). This contrasts with the "ridge jump" model of Varga and Moores (1985), according to which the periodicity of location of the ore bodies is related to a change in locus of the zone of crustal construction.

The simpler model of the authors approximates a quasi steady-state "conveyor belt" system involving lateral growth of oceanic crust of relatively constant compositional character—varying quantitatively only in the relative thickness of the Basal Group (BG), Lower Pillow Lava (LPL), and Upper Pillow Lava (UPL) crustal constructional components, and possibly in the frequency of sheet flows. The model also assumes that the vertical and lateral stratigraphic variation in the constructional components represented on most maps of the Cyprus ophiolite (e.g., Mukasa and Ludden 1987) reflects only the variation in magma input (total thickness = BG + LPL + UPL), frequency of dike occurrence (BG), or degree of alteration (UPL). In this context the compositional character of the lavas presumably varies only within the limits of fractionation and degree of mixing of fractionated residual liquids and new magma batches.

Given the proposed importance of this representation of the Troodos ophiolite to ore exploration strategies, I would like to draw attention to several aspects of the proposed model that require elaboration.

[1]Paper by J. M. Hall, C. C. Walls, and J-S. Yang. 1989. Canadian Journal of Earth Sciences, **26**: 1172–1184.

Compositional variation in the extrusive series

Data presented by Desmet (1977), Robinson *et al.* (1983), Cameron (1985), and Thy *et al.* (1985) indicate that the LPL and BG lavas of Troodos ophiolite include two distinct chemical series. One set (low-Ti series) exhibits a continuously varying range of TiO_2/MgO values on a TiO_2 vs. MgO diagram (Robinson *et al.* 1983) from ~0.26 (high-Ti source, high degree of fractionation) to ~0.026 (low-Ti source, low degree of fractionation). The low-Ti series includes all three magma types of Cameron (1985), as well as the UPL. The other set is relatively enriched in TiO_2 and is more fractionated, giving rise to a preponderance of rocks of andesite–rhyodacite composition. It was the presence of these siliceous rocks in the Troodos complex that led Miyashiro (1973) to question the oceanic origin of the ophiolite. At Akaki the low-Ti series overlies the high-Ti series. Nevertheless, high-Ti volcanics are described by both Desmet (1977) and Schmincke *et al.* (1983) as being interlayered with low-Ti volcanics in unit F of the Akaki River sequence, and by J. A. Pearce (personal communication to Robinson *et al.*, 1983) as being interlayered in the Yialias Canyon sequence. This implies that the low-TiO_2 and high-TiO_2 volcanic rocks of the BG and LPL were extruded penecontemporaneously, at least at Akaki and Yialias Canyon, or that the section is more structurally complicated than envisioned. The high-Ti rocks represented in the data set of Desmet (1977) are found only along the north flank of the ophiolite, and even here tend to be concentrated in the area between Akaki and Kannavia. In areas where the high-Ti lavas are seemingly not represented, the analytical data of Desmet (1977) indicate that (1) along the southwest flank of the ophiolite the TiO_2/MgO ratio of the low-Ti series decreases upwards from the BG to the UPL and (2) at the east end of the ophiolite the TiO_2/MgO ratio initially decreases and then increases upwards.

The chemistry of the clinopyroxenes of the stratiform unit of the Troodos plutonic series (Dion 1987; Thibault 1987; Thy 1987) indicates that the latter is entirely related to the low-Ti series, and is characterized by the crystallization sequence Ol–Cpx–Opx–Plag–Amph or Ol–Cpx–Plag–Opx–Amph (Dion 1987, p. 44; Thibault 1987, p. 28). Thy (1987), however, claims that the less fractionated part of the stratiform unit is younger than the more fractionated part—which it nevertheless underlies. In this respect the plutonic series likely correlates with either the older low-Ti series of the BG and LPL, or with the younger low-Ti series of the UPL. I am not aware that equivalents of the high-Ti series have been found in the plutonic sequence, since even the younger rocks of the Intrusive Sequence, characterized by the crystallization sequence Ol–Cpx–Plag–Opx–Amph, contain low-Ti clinopyroxenes (Dion 1987; Thibault 1987). The even more primitive plutonic (crystallization sequence Ol–Opx–Cpx–Plag) and effusive rocks occurring within the Arakapas fault zone are usually taken to have formed in an oceanic transform fault (Murton and Gass 1986).

While it is not possible to differentiate in terms of Ti between the low-Ti rocks of the BG–LPL and the UPL units, Desmet (1977, p. 54) stated that the UPL lavas differ from those of the LPL not only because they are less altered (low-temperature adularia in the UPL compared with albite in the LPL) but also because they are less fractionated, invariably containing olivine, augite, and magnetite, and characteristically containing high-MgO (>20 wt.% MgO) picritic lavas.

There are, therefore, good petrographic–chemical reasons to doubt that the Troodos hypabyssal–extrusive series represents the products of only a simple one-magma single-axis "conveyor belt" system. In this respect it should be noted that the authors claim (p. 1179) that a convincing correlation is only evident between spatial variations in the thickness of LPL and the total thickness, because variations in LPL essentially control variations in the total thickness. However, in the G1, G3, G4, and G5 stratigraphic sections the total thickness correlates at least as well with variations in the thickness of the UPL (authors' Fig. 3*a*), but with the BG unit best simulating the variation in the G4 section. Only in the case of the G2 section is the total thickness clearly controlled by the LPL—but this is the one group that the authors consider to be anomolous and without explanation. The G2 group of ores is located near the base of the LPL, whereas some of the G1, G3, G4, and G5 ores are found within the UPL. It is not inconceivable, therefore, that the latter ores, which must be younger than the UPL, as must also be the umbers, are genetically unrelated to the G2 ore group.

The off-axis model

In a paleomagnetic test of the "ridge jump" model of Varga and Moores (1985), Allerton and Vine (1987) concluded that the dike and associated pillow lava units of the Solea and other Troodos grabens have undergone extensive rotation relative to the Troodos magnetization vector (Clube *et al.* 1985), and that the crustal sections in the grabens have been extensively thinned. *If this is the case the present thickness of the constructional units in the grabens cannot be representative of their thickness at the time of crust formation.* Allerton and Vine (1987) furthered argued that the Solea Graben was formed by off-axis extension during lulls in the supply of magma to an intermediate- to fast-spreading axis, in which case the relationship between ores and magma supply becomes debatable. Furthermore, Varga and Moores (1985, p. 848) stated that in the Solea Graben the sediments overlying the Troodos ophiolite are little deformed and dip gently to the north. This implies that the Perapedhi Formation was deposited after graben formation and that the Troodos umbers were also deposited off-axis. Since the authors state that the umbers are contemporaneous with the last vulcanicity, it is further implied that at least the upper part, if not all, of the UPL was also laid down off-axis, and cannot therefore be directly related to the axis rocks of the LPL and BG units. This is corroborated by the statement of Varga and Moores (1985, p. 847) that in the Solea Graben the youngest dikes are the most steeply dipping and therefore the least likely rotated.

Comparison with in situ *oceanic crust*

The Troodos ophiolite and other low-Ti ophiolites, such as those of the Mediterranean region (such as Baer Bassit; Parrot 1977) and the Appalachians (Church and Coish 1976), have long been considered anomalous because, although they obviously represent sections of oceanic material formed at a spreading centre and are underlain by mantle peridotite and slivers of dynamothermal subduction zone metamorphic rocks, they petrographically and chemically resemble primitive island-arc rocks (Miyashiro 1973). For this reason low-Ti ophiolites are commonly considered to have formed in back-arc ocean basins. The similarity, particularly in rare-earth-element patterns, of the very low-Ti rocks in low-Ti ophiolites to arc boninites would, however, support the suggestion by Pearce *et al.* (1984) that such ophiolites were generated at pre-arc spreading centres located above embryonic subduction zones. As a variation on this theme it has also been suggested (Church 1987) that low-Ti ophiolites (e.g., Harnois and Morency 1988) may have formed in spreading centres originating as transpressive basins in the frontal parts of developing arcs during oblique subduction. In this context the Arakapas fault would represent a transpressive shear along which a locus of spreading had begun to develop involving the intrusion and extrusion of magmas typically showing the crystallization sequence olivine–orthopyroxene–clinopyroxene–plagioclase found in primitive spreading centre ophiolites of the Appalachians (Betts Cove – Thetford – Mount Orford). If the Troodos ophiolite did indeed form as a supra-subduction complex of this type, comparisons of Troodos with "classic" ocean crust as made by the authors may not be entirely appropriate.

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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

JAMES M. HALL, CHARLES C. WALLS, AND JING-SUI YANG
Department of Geology, Dalhousie University, Halifax, N.S., Canada B3H 3J5

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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

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