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Supra-subduction zone ophiolites: The search for modern analogues

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ABSTRACT

The development of ideas on modern analogues for ophiolite complexes can be divided into three parts. In the first (1963 to 1972), ophiolites were mainly viewed as on-land analogues of the crust and upper mantle formed at mid-ocean ridges. The second (from 1972 to 1984) is a period of paradigm shift to the view that the majority of ophiolites forms above subduction zones, and can be grouped as the class known as supra-subduction zone ophiolites. The third (from 1984 onward) is a period that has led to a much better understanding of what these supra-subduction zone settings represent. The realization that many ophiolites were linked to subduction resulted from a combination of advances in geochemical discrimination methods, exploration through dredging and drilling of arc-basin systems of the Western Pacific and South Atlantic, and further field studies in ophiolite terranes. The transition in ideas from a mid-ocean ridge to a subduction origin was prolonged and much-debated, primarily because many of the best-developed ophiolites had the geochemical characteristics of subduction environments, yet none of the geological characteristics (arc volcanics and overlying volcanogenic sediments) thought to characterize those environments. This in turn led to a need for a non-generic term, supra-subduction zone, to describe this ophiolite type. Since the supra-subduction zone concept became established, precise analogues continued to be debated. Subduction initiation and ridge-trench intersections are probably the most important settings, with back-arc rifting and spreading and oblique subduction also significant.

Keywords: ophiolites, geochemistry, mid-ocean ridges, subduction zones, marginal basins.

INTRODUCTION

Supra-subduction zone (SSZ) ophiolites have the structures or inferred structures of oceanic crust, yet a geochemical composition which indicates that they formed not at mid-ocean ridges but at spreading centers associated with subduction zones. Such ophiolites are common in the geological record; in fact, they are much more common than ophiolites from mid-oceanic ridges themselves.

The recognition of SSZ ophiolites in the geological record has not been a sudden (Kuhnian) jump in knowledge and understanding. From the time that ophiolites were first recognized as land-based analogues of oceanic lithosphere, some 10 years elapsed before the presentation of evidence that ophiolites may not all form at mid-ocean ridges. Another 10 years were occupied by controversy over whether they had a mid-ocean ridge or subduction-related origin. By the end of this time, accumulation of new data from land and the oceans provided sufficient evidence that both options were possible and led to the publication of a formal definition of supra-subduction zone ophiolite. The remaining period up to the time of this writing has seen the emergence of the significance and diversity of the SSZ ophiolite type.

My account begins in 1971, at which time ophiolites had been highlighted as on-land slices of oceanic lithosphere with the capacity to ground-truth marine geophysical models of oceanic crust and document the seafloor spreading process. The "jewel in the crown" was the Troodos Massif of Cyprus, mapped in detail by the Cyprus Geological Survey, and exhibiting the full ophiolite stratigraphy, including an extensive sheeted dike swarm, the key piece of evidence for a seafloor spreading origin (Gass, 1963; Moores and Vine, 1971). Ophiolites were about to be defined formally by the Penrose Conference Participants (Anonymous, 1972).

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In this paper, I document the increasing awareness of the diversity of ophiolites and the subduction signal that many exhibit. I report how exploration of marginal basins transformed our knowledge of ophiolite analogues, and describe the increasing part played by geochemical discriminant diagrams in fingerprinting the subduction signal. I explain how the increase in knowledge of ophiolites, modern analogues, and geochemistry led, by 1984, to the supra-subduction zone concept. I then trace the subsequent efforts to find more exact analogues for this class of ophiolites. Finally, I attempt an analysis of the evolution of ideas from Kuhnian and Bayesian perspectives.

I have also included two figures that present the conclusions reached in the text in graphical form. Figures 1A and B illustrate some of the key advances in our concept of modern analogues. Figure 2 illustrates some of the key advances in the fingerprinting of SSZ settings through geochemical analysis of the various rocks that make up the ophiolite sequence.

RECOGNITION OF OPHIOLITE DIVERSITY AND SUBDUCTION INFLUENCE

The Troodos Debate

The ophiolite definition published by the Penrose Conference participants in 1972 was the culmination of a decade of study of ophiolite complexes, reflecting the consensus that ophiolites are fragments of oceanic lithosphere formed at mid-ocean ridges by seafloor spreading (Anonymous, 1972). So strong was this consensus that, in our initial attempts at geochemical discrimination of tectonic setting, Joe Cann and I (Pearce and Cann, 1971, 1973) used lavas from known tectonic settings (arcs, ridges, and intra-plate) to define discriminant fields, and used lavas from ophiolites to test the method. We assumed that, if the method of discrimination were correct, the ophiolites would plot in the "ocean floor basalt" field. In the event, our first discriminant diagrams were based solely on the elements Ti, Zr, and Y. On these diagrams, the Troodos and Oman ophiolites, as well as greenstones from the "Steinmann trinity" in the Austrian Alps, did plot predominantly in the "ocean floor basalt" field. Only a subset of Greek ophiolite samples plotted in the island arc field, and we interpreted these as not part of a true ophiolite. Thus, we assumed that the method had worked successfully, the results having shown that "ophiolites [including the Troodos Massif] had ocean floor affinities."

Whereas we had worked primarily on dredged rocks from ocean ridges, Akiho Miyashiro had worked for much of his career on subduction-related rocks from Japan. He saw strong similarities in major element geochemistry between the Troodos lavas and the volcanic rocks of the Izu-Bonin arc south of Japan and concluded that the Troodos Massif formed in an island arc (Miyashiro, 1973). He developed this theme further in *Classification, characteristics, and origin of ophiolites* (Miyashiro, 1975a). Essentially, he argued that the Troodos lavas have a greater range of silica contents than do dredged rocks from ocean ridges, and a lesser degree of iron-enrichment that resembles the calc-alkaline rather than tholeiitic series. He was the first to propose a subduction-related origin for the Troodos Massif, and thus raise the question of whether all ophiolites really formed at mid-ocean ridges.

Miyashiro had never visited Cyprus, however, nor viewed the rocks in the field or in thin section. He abstracted published major element data and focused on the elements (Si, Mg, and Fe) that were successful in characterizing island arc lavas in the 1960s. Many of the principal ophiolite scientists of the time, most of whom had worked on Cyprus, queried his approach in a series of discussion papers in *Earth and Planetary Science Letters* by Hynes (1975); Moores (1975); Gass et al. (1975a), and Church and Coish (1976). Miyashiro attempted to deflect these criticisms in his replies to Hynes (Miyashiro, 1975b) and Moores (Miyashiro, 1975c). Some of the key elements of this scientific exchange are reported below.

> …about one-third of the analyzed rocks of the lower pillow lavas and sheeted complex in it follows a calc-alkalic trend. This strongly suggests that the massif was created as a basaltic volcano in an island arc with a relatively thin oceanic-type crust rather than a mid-ocean ridge. Miyashiro (1973, p. 218)

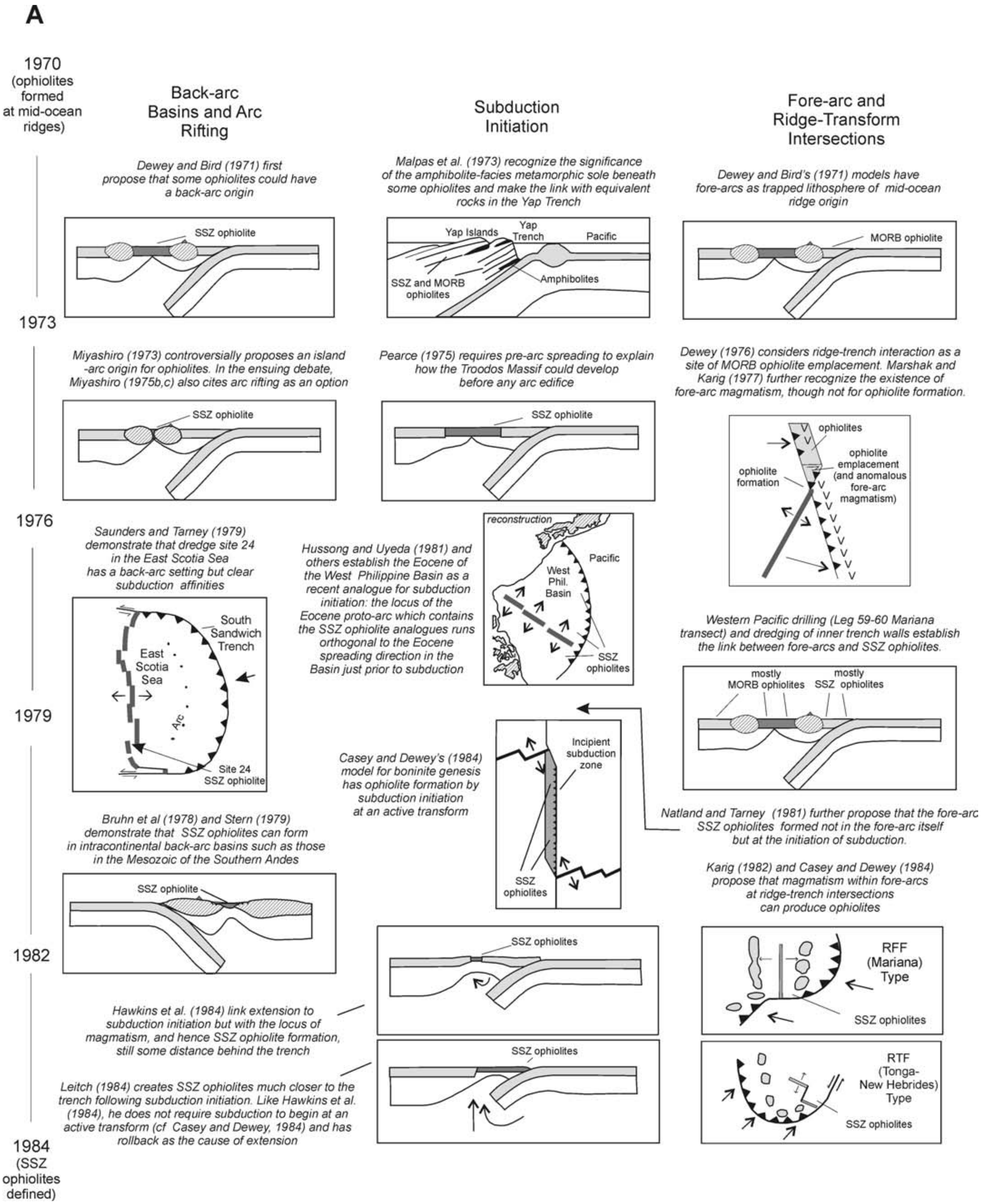
> In view of the alteration described it is not surprising that the data from Troodos produce a broad scatter on Miyashiro's diagrams. Clearly there is a strong possibility of chemical mobility. Any direct comparison of these chemical data with an island-arc igneous suite and with unaltered rocks from the ocean floors can have little validity. Hynes (1975, p. 213)

> In spite of his denial of its possibility, much of the bulk chemical variations cited as evidence for calc-alkaline origin by Miyashiro appears to be due in fact to metasomatic alteration. Moores (1975, p. 223)

> The Sheeted Intrusive Complex, measured across strike, is 120 km of nothing but near-vertical dykes. Miyashiro dismisses this as "overlapping vent volcanoes." Having, between us seen several hundred central vent volcanoes in various states of erosion and tectonic setting, we venture to suggest that if Professor Miyashiro were to visit Troodos he might change his opinion. Gass et al. (1975a, p. 237)

> It is not clear whether the sheeted complex in Troodos may be regarded as a result of creation of new crust by spreading or some spreading-like process. Even if we assume it to be, it is not consistent with the island arc setting of the Troodos Massif. Spreading or some spreading-like process may well occur along island arcs, as was suggested by many authors in order to explain the origin of marginal seas and inter-arc basins. Miyashiro (1975a, p. 221)

> [Miyashiro's] conclusion is, however, contradicted by the observation that the cumulate units of all such ophiolites directly overlie mantle peridotite rather than basaltic oceanic crust (gabbro, dikes, pillow lavas). Church and Coish (1976, p. 13)



Dewey and Bird (1971) first propose that some ophiolites could have a back-arc origin

Malpas et al. (1973) recognize the significance of the amphibolite-facies metamorphic sole beneath some ophiolites and make the link with equivalent rocks in the Yap Trench

Dewey and Bird's (1971) models have fore-arcs as trapped lithosphere of mid-ocean ridge origin

Miyashiro (1973) controversially proposes an island-arc origin for ophiolites. In the ensuing debate, Miyashiro (1975b,c) also cites arc rifting as an option

Pearce (1975) requires pre-arc spreading to explain how the Troodos Massif could develop before any arc edifice

Dewey (1976) considers ridge-trench interaction as a site of MORB ophiolite emplacement. Marshak and Karig (1977) further recognize the existence of fore-arc magmatism, though not for ophiolite formation.

Saunders and Tarney (1979) demonstrate that dredge site 24 in the East Scotia Sea has a back-arc setting but clear subduction affinities

Hussong and Uyeda (1981) and others establish the Eocene of the West Philippine Basin as a recent analogue for subduction initiation: the locus of the Eocene proto-arc which contains the SSZ ophiolite analogues runs orthogonal to the Eocene spreading direction in the Basin just prior to subduction

Western Pacific drilling (Leg 59-60 Mariana transect) and dredging of inner trench walls establish the link between fore-arcs and SSZ ophiolites.

Casey and Dewey's (1984) model for boninite genesis has ophiolite formation by subduction initiation at an active transform

Natland and Tarney (1981) further propose that the fore-arc SSZ ophiolites formed not in the fore-arc itself but at the initiation of subduction.

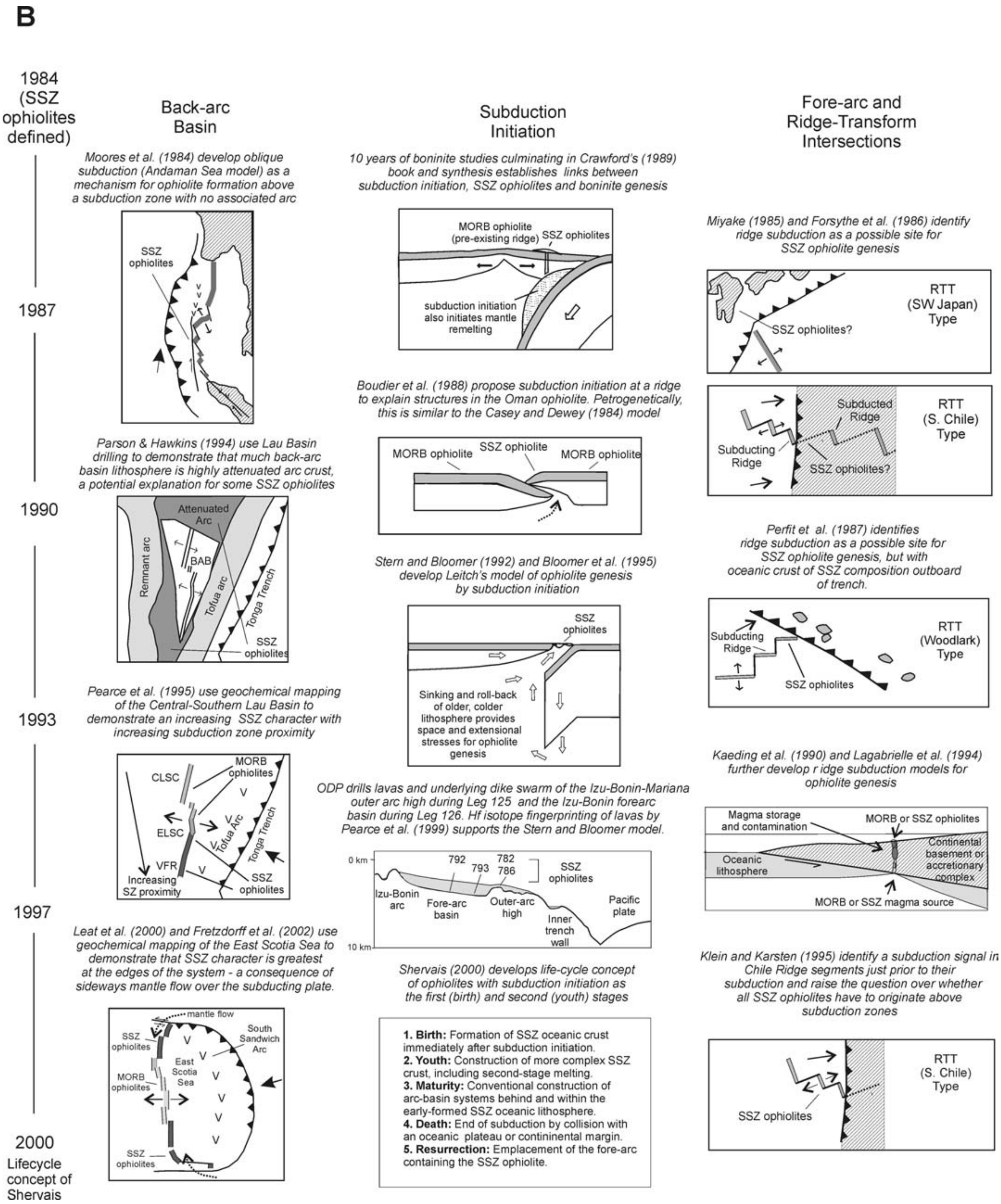
Bruhn et al (1978) and Stern (1979) demonstrate that SSZ ophiolites can form in intracontinental back-arc basins such as those in the Mesozoic of the Southern Andes

Karig (1982) and Casey and Dewey (1984) propose that magmatism within fore-arcs at ridge-trench intersections can produce ophiolites

Hawkins et al. (1984) link extension to subduction initiation but with the locus of magmatism, and hence SSZ ophiolite formation, still some distance behind the trench

Leitch (1984) creates SSZ ophiolites much closer to the trench following subduction initiation. Like Hawkins et al. (1984), he does not require subduction to begin at an active transform (cf Casey and Dewey, 1984) and has rollback as the cause of extension

Figure 1 (*on this and following page*). Evolution of ideas on modern analogues for supra-subduction zone (SSZ) ophiolite formation, 1970 to 1984 (A), and 1984 to 2000 (B). Illustration of some of the key advances in ideas on the tectonic setting of SSZ ophiolites. In the diagrams showing triple junctions, R is ridge, T is trench, and F is fracture zone. Note that the figures have been simplified. Refer to the original papers for full details.



Moores et al. (1984) develop oblique subduction (Andaman Sea model) as a mechanism for ophiolite formation above a subduction zone with no associated arc

Parson & Hawkins (1994) use Lau Basin drilling to demonstrate that much back-arc basin lithosphere is highly attenuated arc crust, a potential explanation for some SSZ ophiolites

Pearce et al. (1995) use geochemical mapping of the Central-Southern Lau Basin to demonstrate an increasing SSZ character with increasing subduction zone proximity

Leat et al. (2000) and Fretzdorff et al. (2002) use geochemical mapping of the East Scotia Sea to demonstrate that SSZ character is greatest at the edges of the system - a consequence of sideways mantle flow over the subducting plate.

10 years of boninite studies culminating in Crawford's (1989) book and synthesis establishes links between subduction initiation, SSZ ophiolites and boninite genesis

Boudier et al. (1988) propose subduction initiation at a ridge to explain structures in the Oman ophiolite. Petrogenetically, this is similar to the Casey and Dewey (1984) model

Stern and Bloomer (1992) and Bloomer et al. (1995) develop Leitch's model of ophiolite genesis by subduction initiation

ODP drills lavas and underlying dike swarm of the Izu-Bonin-Mariana outer arc high during Leg 125 and the Izu-Bonin forearc basin during Leg 126. Hf isotope fingerprinting of lavas by Pearce et al. (1999) supports the Stern and Bloomer model.

Shervais (2000) develops life-cycle concept of ophiolites with subduction initiation as the first (birth) and second (youth) stages

1. **Birth:** Formation of SSZ oceanic crust immediately after subduction initiation.
2. **Youth:** Construction of more complex SSZ crust, including second-stage melting.
3. **Maturity:** Conventional construction of arc-basin systems behind and within the early-formed SSZ oceanic lithosphere.
4. **Death:** End of subduction by collision with an oceanic plateau or conintinental margin.
5. **Resurrection:** Emplacement of the fore-arc containing the SSZ ophiolite.

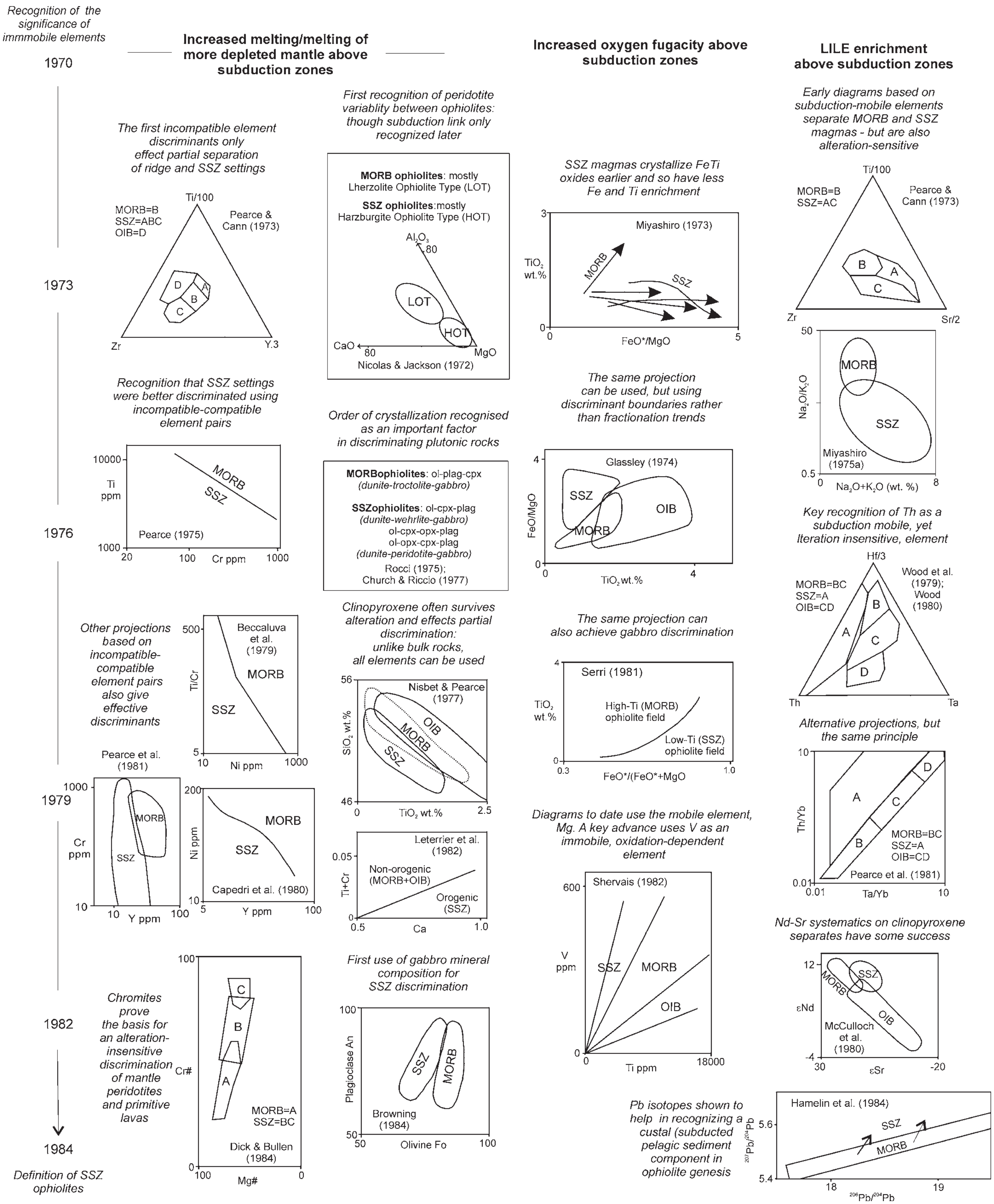
Miyake (1985) and Forsythe et al. (1986) identify ridge subduction as a possible site for SSZ ophiolite genesis

Perfit et al. (1987) identifies ridge subduction as a possible site for SSZ ophiolite genesis, but with oceanic crust of SSZ composition outboard of trench.

Kaeding et al. (1990) and Lagabrielle et al. (1994) further develop ridge subduction models for ophiolite genesis

Klein and Karsten (1995) identify a subduction signal in Chile Ridge segments just prior to their subduction and raise the question over whether all SSZ ophiolites have to originate above subduction zones

Figure 1 (*continued*).


Recognition of the significance of immmobile elements

1970

Increased melting/melting of more depleted mantle above subduction zones

Increased oxygen fugacity above subduction zones

LILE enrichment above subduction zones

The first incompatible element discriminants only effect partial separation of ridge and SSZ settings

First recognition of peridotite variablity between ophiolites: though subduction link only recognized later

SSZ magmas crystallize FeTi oxides earlier and so have less Fe and Ti enrichment

Early diagrams based on subduction-mobile elements separate MORB and SSZ magmas - but are also alteration-sensitive

1973

Recognition that SSZ settings were better discriminated using incompatible-compatible element pairs

Order of crystallization recognised as an important factor in discriminating plutonic rocks

The same projection can be used, but using discriminant boundaries rather than fractionation trends

Key recognition of Th as a subduction mobile, yet lteration insensitive, element

1976

Other projections based on incompatible-compatible element pairs also give effective discriminants

Clinopyroxene often survives alteration and effects partial discrimination: unlike bulk rocks, all elements can be used

The same projection can also achieve gabbro discrimination

Alternative projections, but the same principle

1979

Diagrams to date use the mobile element, Mg. A key advance uses V as an immobile, oxidation-dependent element

Nd-Sr systematics on clinopyroxene separates have some success

Chromites prove the basis for an alteration-insensitive discrimination of mantle peridotites and primitive lavas

First use of gabbro mineral composition for SSZ discrimination

Pb isotopes shown to help in recognizing a custal (subducted pelagic sediment component in ophiolite genesis

1982

1984

Definition of SSZ ophiolites

Figure 2. Fingerprinting of supra-subduction zone (SSZ) character in ophiolites—evolution of methodologies. Illustration of some of the key advances (up to 1984) in the geochemical identification of SSZ ophiolites and their discrimination from ophiolites of mid-ocean ridge basalt (MORB) and ocean island basalt (OIB) affinities. LILE—large ion lithophile elements.

Miyashiro's (1975b, 1975c) replies did address the effects of seafloor weathering, metamorphism, and vesicle infilling, and their impact on his methods of discrimination. In particular, he noted that weathered and metamorphosed basalts dredged from the ocean ridges were still not isochemical with the Troodos lavas. He also addressed the problem that the Troodos ophiolite sequence (pelagic sediments, thin crust, kilometers of sheeted dikes) was not that expected for discrete volcanoes, even overlapping volcanoes. He noted that radial dikes within volcanic centers may give rise to extension-parallel dikes between centers, and that extension parallel-dikes may develop during the transition from arc proper to back-arc basins. He pointed out that the Troodos dike orientations showed some variation, and argued that they could represent something more complex than a mid-ocean ridge environment.

It is an interesting exercise to review the Miyashiro interpretation in the light of present knowledge and databases. They demonstrate that the histograms published by Miyashiro were quite unrepresentative. Essentially, the published data he used were few and were designed to illustrate the range of rock types, not their distribution. Unlike the broad silica distribution shown by Miyashiro, the true plot (uncorrected for alteration) has a much lower standard deviation, more like ocean ridges, in fact. Nonetheless, the mean silica content is ~3% higher than for ocean ridges (basaltic andesite, rather than basalt), although the rocks are mostly very altered and silica certainly mobile. However, the remarkable discovery of fresh glass on the Troodos Massif (Robinson et al., 1983; Rautenschlein et al., 1985) does indicate that silica really is higher than in lavas from mid-ocean ridges. The "calc-alkaline" affinities identified by Miyashiro are somewhat misleading. By present arc terminology, the samples would be termed "island arc tholeiites" rather than "calc-alkaline" because of their low potassium content. Iron enrichment is essentially intermediate between ridges and arcs. As far as the structure is concerned, hindsight in the form of seismic evidence for arc crustal thickness (e.g., Suyehiro, 1996) shows that even the most primitive arcs are underlain by crust on the order of 15–30 km thick, many times the ~6 km crustal thickness of the Troodos Massif.

To be fair to Miyashiro, however, only three tectonic settings of oceanic magmatic activity were recognized at the time he wrote his paper: divergent plate boundaries (ridges), convergent plate boundaries (arcs), and intra-plate settings (continental rifts and oceanic islands). It was not unreasonable in that context to infer that, if the Troodos Massif had subduction characteristics, it must have formed in an arc.

Miyashiro himself "could not understand" the fuss his paper had created (Miyashiro, 1975, personal commun.). Despite the fact that few ever believed that the Troodos Massif formed in an island arc sensu stricto, he gets due credit for initiating the paradigm shift away from the view that all ophiolites formed at mid-ocean ridges. This was much easier to do from outside the ophiolite community, and emphasizes the need for any scientific consensus to be open to scrutiny. On the other hand, the ophiolite community might have received the paper better had Miyashiro based his work on systematic sampling and consideration of petrographic and field constraints! The scientific community also made its own judgment on the question of alteration: very few papers thereafter relied on the major elements to characterize ophiolites.

Miyashiro (1975b) had, however, correctly pointed out that Ti, Zr, and Y, although usefully immobile, were by themselves insufficient to assign the Troodos Massif uniquely to a mid-ocean ridge setting, as Pearce and Cann (1971, 1973) had inferred. The same argument applies to the rare-earth elements (REEs), as Smewing et al. (1975) and Kay and Senechal (1976) discovered. By this time, though, we had ourselves improved this aspect of the discrimination by extending the range of immobile elements to those with compatible behavior (see later). The resulting plot of Ti-Cr (Pearce, 1975) demonstrated to an extremely high level of probability that the Troodos Lavas had an arc, rather than an ocean ridge, affinity. Like the respondents to the Miyashiro paper, however, I could not envisage the Troodos Massif as an arc sensu stricto because its structure was quite different from that of overlapping shield volcanoes, as Gass et al. (1975a) had so graphically pointed out.

The obvious solution was that the Troodos Massif formed in a marginal basin. Dewey and Bird (1971) had stressed the potential of marginal basins for ophiolite genesis well before the Troodos debate. They had concluded (p. 3179):

> The ophiolite suite is probably generated by axial plate accretion at oceanic ridges and by diffuse slow spreading in marginal basins within and behind island arc complexes.

Bird et al. (1971) explained most of the Caledonian/Appalachian ophiolites in terms of marginal basins. For example (p. 31):

> In the western Pacific the marginal basins behind, and between, island arc complexes are fairly certainly the result of a sea-floor spreading process by which island arcs move slowly away from continental margins. We suggest that the Early Ordovician Appalachian/Caledonian ophiolites resulted from a similar process during the establishment of marginal basins within, and north-west of, the Early Ordovician metamorphic terrain."

Dewey and Bird (1971) had proposed that marginal basin ophiolites could be distinguished from mid-ocean ridge ophiolites by a number of features that included their apron of volcanogenic sediments (see later). The Troodos Massif differed from the Caledonian/Appalachian ophiolites described by Bird et al. (1971) because it had no contemporaneous, overlying volcanogenic sediments and no nearby arc. As a result, the Troodos Massif did not fit the Karig (1971) model of back-arc or intra-arc basin formation that formed the basis for Dewey and Bird's reconstructions. The marginal basin interpretations of Dewey and Bird (1971) and Bird et al. (1971) therefore avoided the subsequent controversy surrounding the Troodos Massif.

Essentially, then, the Troodos lithosphere had arc chemistry, yet ridge geology, something for which there was no analogue at that time. I speculated that the Troodos Massif formed in a marginal basin before, and at the inception of, arc volcanism (Pearce, 1975, p. 64):

> The Troodos Massif apparently contained rocks which have not been well sampled at the present time, the upper pillow lavas probably representing submarine island arc eruptions while the lower pillow lavas may have been produced by spreading in a marginal basin directly overlying a subduction zone.

Thus, according to my interpretation, the main Troodos Massif was a marginal basin formed by extension above the subducting plate, while the upper lavas represented the first constructional stages of an island arc edifice. My view was that collision with a continental margin had prevented the arc-basin system from evolving into a "proper" volcanic arc. As will be seen, the part of this hypothesis that required spreading to predate arc volcanism after the initiation of subduction successfully anticipated subsequent studies of marginal basins. However, the idea that the upper lavas are the first stages of arc activity was not supported by later studies. These are better viewed as off-axis eruptions (e.g., Smewing and Potts, 1976). Thus, it is likely that the Troodos Massif really did form by seafloor spreading, with no arc in evidence either before or after its formation.

The Troodos debate divided the ophiolite community into two groups. One group (mainly geochemists) was convinced of a marginal basin setting on the basis of the immobile element arguments. The other (mainly geologists) was convinced of a mid-ocean ridge setting on the basis of the crustal structure and the absence of any arc volcano or arc-derived sediments.

Ophiolite Diversity

The predictions of Dewey and Bird in 1971, coupled with the debate over the origin of the Troodos Massif that was initiated by Miyashiro in 1973, made it clear that a mid-ocean ridge origin for ophiolites could not be taken for granted. In parallel with the Troodos debate, therefore, geochemical fingerprinting of ophiolite complexes increased hugely as more X-ray fluorescence (XRF) instruments became installed worldwide, and as these machines became more automated. Major analytical and field programs were carried out on ophiolites, greenstones, and other lavas from orogenic belts, and there is no space to cite them all here. Notable among them were the Caledonides in Norway, the Newfoundland Appalachians, the Western Alps, Greece, and the Coast Ranges and Klamath Mountains in Western USA. By the mid-to-late 1970s, subduction chemistries outnumbered mid-ocean ridge basalt (MORB) chemistries by some margin, and it was becoming apparent that marginal basins may represent a better analogue for most ophiolites than mid-ocean ridges.

Meanwhile, even without immobile element geochemistry, scientists drew attention to the fact that ophiolites appeared to subdivide into distinct groups according to their geological and petrological characteristics. This was particularly evident in the Mediterranean region, where ophiolites of contrasting characteristics were closely associated in space and time. Mesorian (1973) divided Alpine ophiolites into three groups (a "Troodos-type," a "Pindos-type," and an "Antalya-type"), according to the distribution of dikes and consideration of whether the lavas had tholeiitic, calc-alkaline, or alkaline characteristics. Nicolas and Jackson (1972) and Menzies and Allen (1974) recognized that there was a bimodal distribution of peridotites in the Mediterranean region, one mode being a lherzolite-harzburgite subtype and the other a harzburgite subtype. Rocci et al. (1975) also recognized two groups, his "dualité" of ophiolite types:

- Type I: tectonized lherzolite, plagioclase peridotites, troctolites, gabbros, Fe-gabbros.
- Type II: tectonized harzburgite, dunite, chromitite, pyroxenites, norites, olivine gabbros.

Without immobile element geochemistry, however, it was not possible to resolve whether subduction or normal ridge crest variables such as spreading rate is responsible for the observed diversity. For example, Nicolas and Jackson (1972) and Menzies and Allen (1974) proposed that the lherzolites formed in small (Red Sea type) ocean basins and the harzburgites formed in major oceans—without discussing the subduction option. Rocci et al. (1975) additionally mentioned the possible role of marginal basins, but declared that "it was still impossible to distinguish between the various options." Thus, it was geochemistry, rather than petrology or geology that led to the subduction link.

By the middle to late 1970s, some scientists had moved to the opposite extreme from that represented by those still holding out for a mid-ocean ridge origin for all ophiolites.

> Most ophiolites so far studied in detail seem to represent allochthonous fragments of the crust of small oceans or marginal seas. No convincing representative from a major ocean has been identified. Gass et al. (1975b, p. 64)

> …although we do not rule out the possibility that ophiolites could originate in more than one tectonic setting, the structural, stratigraphic and trace element data we have summarised show that the most logical site for the origin of many ophiolites around the world was in the Western Pacific marginal seas bordered by island arcs on one side and continental margins on the other. Upadhyay and Neale (1979, p. 100).

Perhaps the most balanced view of the state-of-the-art at the time was presented by Coleman (1977) in his book, *Ophiolites.* On page 10, he states:

> Formation of oceanic lithosphere in other tectonic situations besides mid-ocean ridges should also be carefully considered when comparisons are being made between ophiolites and oceanic lithosphere. For instance, it is quite reasonable to expect some oceanic crust to form in marginal basins behind oceanic island arcs and presumably above subduction zones… Unfortunately, at this time, there are not enough detailed studies on marginal basins on which to formulate a model which can adequately explain the formation of oceanic crust in this situation.

So it was clear that many ophiolites had subduction zone affinities, but many of these still did not have a known analogue that had both ridge geology and subduction geochemistry. A geologist suspecting a tectonic setting but having no modern analogue was like a detective suspecting a murder but having no body. In both cases, direct evidence is all-important. Thus, the principal requirement was now a better coverage of rocks from the ocean basins, and the marginal basins in particular.

EMERGENCE OF POTENTIAL SSZ OPHIOLITE ANALOGUES

At the time of the controversy over the origin of the Troodos Massif, there were very few geochemical data from marginal basins. Those that were published were scarcely distinguishable from mid-ocean ridge chemistry (in fact, the Pearce and Cann (1973) MORB database included four samples from the Mariana Trough). Thus, it was not clear that mid-ocean ridges differed chemically from marginal basins. By 1975, the MORB database was fairly representative (though biased to slow-spreading ridges), as was the oceanic arc database (though biased to the SW Pacific). By contrast, construction of the marginal basin database had scarcely begun.

The key to understanding ophiolite geochemistry came from a series of cruises to the marginal basins of the western Pacific and South Atlantic. The first modern geochemical studies of back-arc basins were published by Hart et al. (1972), Gill (1976), and Hawkins (1976, 1977), and focused on the Lau and Mariana Basins. However, the vast majority of their published samples remained typical MORB, while the remainder was MORB with a small subduction component that scarcely influenced the discrimination. This subsequently led to the term back-arc basin basalt (BABB) to describe MORB with a small subduction zone modification. Gill (1976, p. 1394) describes such samples from the Lau Basin as follows:

> Basin extension is accompanied by intrusion of basalt generally similar to mid-ocean ridge tholeiite but having higher Sr^{87}, Ba, light REE and possibly alkali and H_2O contents, and lower Y, heavy REE, Zr, Hf and possibly Ti contents.

These still did not, however, resemble those of the Troodos Massif or the vast majority of the other ophiolites with distinctive subduction chemistry that were beginning to be identified. The first back-arc lavas to do so were the lavas from Site 24 from the East Scotia Sea back-arc basin, published by Saunders and Tarney (1979). Although not typical of the East Scotia Sea as a whole, they did finally demonstrate that lavas erupted at a marginal basin spreading axis could have a significant subduction component. Here, then, was the first back-arc site where the crustal structure could be "ophiolitic" while the composition of the lavas was arc-like.

At about the same time, Bruhn et al. (1978) and Stern (1979) demonstrated that mafic complexes with ophiolitic structures could also form in intracontinental back-arc basins. Their studies of the Tortuga and Sarmiento back-arc complexes of Early Cretaceous age in Southern Chile revealed selective enrichments in fluid-mobile elements, but lacked sufficient evidence to distinguish between a subduction-modified mantle source and a MORB mantle source in which the resulting MORB magma had undergone crustal contamination.

Back-arc basins proved, however, to be less important than fore-arcs in the search for analogues to ophiolites with subduction characteristics. There were good geological arguments for a link between ophiolites and fore-arcs because fore-arcs are among the first terranes to be emplaced during continent-arc collision (e.g., Dewey, 1976). Moreover, there are many structural and metamorphic similarities between fore-arc complexes and ophiolites (e.g., Malpas et al., 1973). However, their significance was not so apparent geochemically, as the first ophiolite-like sequences sampled and analyzed from fore-arcs, from the Yap islands south of the Marianas (e.g., Shiraki, 1971; Hawkins and Batiza, 1977), had Pacific Ocean provenance and MORB-like characteristics.

The major breakthrough in identifying fore-arc ophiolites with subduction characteristics came from two projects. The first was the Soviet-sponsored RV *Dimitry Mendeleev* cruise to the Western Pacific in 1976, organized scientifically by members of the International Geological Correlation Programme (IGCP) "Ophiolites" project led by Nikita Bogdanov (International Working Group of the IGCP Project "Ophiolites," 1977). The cruise carried out a series of dredges in the Philippine Sea, including the inner trench walls of the Yap and Mariana Trenches. Scientists obtained a range of rocks (peridotites, gabbros and basalts) that they recognized as part of a typical ophiolite suite. Importantly, they demonstrated that ocean basins in subduction settings could both have subduction characteristics and yield rocks similar to those recovered from ophiolites such as the Troodos Massif.

The results of this cruise first reached the international literature in the paper by Dietrich et al. (1978), and also resulted in a series of less "accessible" books and publications in Russian and conference proceedings (e.g., Sharaskin et al., 1980). Dietrich et al. (1978, p. 142) discussed the implications as follows:

> An interesting parallel may be drawn with the controversy about the origin of the "Troodos Complex." This ophiolite complex has been variously interpreted as representing oceanic crust or an island arc and contains many rocks similar to those dredged from the Mariana arc slope.

However, Dietrich et al. (1978) did not interpret the rocks as the product of spreading above a subduction zone. They assumed, as Dewey and Bird (1971) and Coleman (1971) had done, that the rocks represented slices of Pacific Ocean lithosphere that had become incorporated into the fore-arc and thus formed the basement to the subsequent island arc.

The *Dimitry Mendeleev* scientists also had the distinction of being the first to find and correctly identify boninites from the ocean floor, likening them to the (then) two reported localities from Bonin Island and Papua New Guinea. However, they did not immediately recognize their huge significance for identifying and interpreting subduction-related ophiolites. Dietrich et al. (1978), for example, assigned an ocean ridge origin to the boninites. In fact, at the time of the cruise, boninites were known in ophiolites but viewed as part of the komatiite lineage (e.g., Simonian and Gass, 1978). Sun and Nesbitt (1978) demonstrated that there are major geochemical differences between komatiites and “low-Ti ophiolitic basalts,” and made the key prediction that the latter were linked to subduction. They also made the first link between high-Mg lavas from ophiolites and from the Mariana Trench, though without mentioning “boninite” as a rock type.

> We suggest that these low-Ti basalts are not formed at mid-ocean ridges, but are products of a spreading center close to a subduction zone, for example, in an interarc basin or incipient island arc site. In this model, remelting of the refractory source is induced by the introduction of water from subducted oceanic crust. (Sun and Nesbitt, p. 689)

This led Cameron et al. (1979) to reclassify as boninites the “basaltic komatiites” from the “fossil transform fault” region of the Troodos Massif. A number of papers rapidly followed to describe boninites from ophiolites in other parts of the world, and so the link between boninites, ophiolites and fore-arcs was clear by the end of the 1970s. Importantly, the concept of boninite origin by remelting of a refractory source was clearly demonstrated. Boninites, therefore, appeared to require petrogenetic processes that were quite distinct from those of normal arc volcanism or of extensional processes well behind the trench.

The second breakthrough came from the Western Pacific program of the Deep Sea Drilling Project (DSDP). DSDP had drilled the Mariana Trough (the back-arc basin) during DSDP Leg 6 and the West Philippine Basin during DSDP Leg 31 but, like early dredging programs, had sampled only MORB and oceanic island basalts (OIB). The drilling program during Legs 59 and 60 drilled a transect across the arcs and marginal basins of the Izu-Bonin-Mariana system. The transect began in the West Philippine Basin in the west, crossing the Palau Kyushu Ridge remnant arc, the Shikoku and Parece Vela fossil back-arc basins, the West Mariana Ridge remnant arc, the active Mariana Trough back-arc basin and the Mariana arc. It finished in the Mariana fore-arc and inner trench wall. The drill sites yielded a bimodal distribution of samples: MORB in the active and fossil back-arc basins and arc-like in the active and remnant arcs (Wood et al., 1981). The only lavas that might resemble those of the Troodos Massif and many other ophiolites were the boninites and island arc tholeiites recovered from the fore-arc basin.

This fore-arc basin link even led Natland and Tarney (1981) to refer to the fore-arc terrane as the “Mariana Fore-arc Ophiolite” and to discuss the viability of fore-arcs as ophiolite analogues. They conclude (p. 895):

> We suggest that an appropriate equivalent of Troodos in an island arc setting is the Mariana fore-arc region and that at the earliest stages of arc volcanism, a type of sea-floor spreading may have occurred before volcanism focused along the line of the arc. …Whether or not true sea-floor spreading produced the Mariana fore-arc region remains to be seen in the light of more detailed geophysical experiments, careful dredging in the trench, and perhaps drilling. Regardless, the occurrence of boninites in certain ophiolites is good evidence that spreading has occurred in several ancient arc systems, probably early in their history.

Bloomer and Hawkins (1983) and Sharaskin et al. (1983) reached similar conclusions through renewed dredging of the Mariana and Tonga Trenches, respectively. The former concluded (p. 313):

> The trench slope assemblage in general is similar to that of an ophiolite. In particular it is similar to ophiolites containing low Ti, Si-saturated volcanic rocks and [orthopyroxene-rich] cumulate sections. It is suggested that these ophiolites represent oceanic crust formed in the early stages of island-arc volcanism.

Thus, for the first time, we had a convergence of interpretations from ophiolites and marginal basins that spreading could take place above a subduction zone before any arc had formed. This was not a full consensus, but it paved the way for the development of the supra-subduction zone ophiolite concept. The link between many ophiolites and subduction zones was made more rigorous through the development of discriminant diagrams that enabled the two groups of rock to be compared even when strongly altered.

EARLY DEVELOPMENT OF SUBDUCTION ZONE DISCRIMINANTS

Geological Discrimination

The first attempt to discriminate between a mid-ocean and marginal basin origin for ophiolite complexes was geological. Dewey and Bird (1971) identified a series of features that might distinguish a marginal basin origin. These included: overlying volcanogenic sediments; complex intrusive and extrusive relationships; irregular thicknesses of layers 2 and 3; and a large proportion of andesites mixed with the basalts.

These remain effective discriminants for oceanic lithosphere closely associated with active arc volcanism. As the Troodos controversy demonstrated, however, oceanic crust could have an arc signature even when there was no associated arc volcanism. Thus, geological criteria were not always sufficient and geochemical discriminants also had to be developed.

Immobile Element Fingerprinting of Lavas

Much of the conventional igneous geochemistry of the 1960s utilized major elements, particularly the highly mobile elements such as Na, K, and Mg. As the Troodos debate was to illustrate, however, this approach was ineffective (or, at best, difficult to apply rigorously) in interpreting and classifying the often highly altered rocks from ophiolite complexes. This led to the sudden surge in interest in elements that were not transported during deep-sea weathering and metamorphism. The key technological development was the XRF method of geochemical analysis, which opened a range of such elements to routine analysis. Cann (1970) provided the basis for this immobile element approach to ophiolite geochemistry. Making use of one of the first mass-produced XRF machines, he analyzed a large number of dredged basalts from mid-ocean ridges. He discovered that when he plotted pairs of immobile incompatible elements, such as Ti-Zr, the basalts formed highly significant linear correlations. If, on the other hand, he plotted a mobile element against an immobile element, such as K-Zr, the correlation became insignificant—more precisely, the fresh rocks still formed a good correlation but the weathered and metamorphosed rocks gave a large scatter. Thus, Cann (1970) was able to demonstrate that only immobile elements were likely to be effective in studying lavas and dikes from ophiolite complexes. This led to the immobile element (Ti-Zr-Y) fingerprinting of Pearce and Cann (1971, 1973)

As already pointed out, neither the Ti-Zr-Y combination nor REE patterns were very effective in discriminating between MORB and subduction-related basalts: the field of overlap was too large. The reason was that the fractional crystallization and partial melting variations were sub-parallel on these projections, so that crystallization masked the key variations in mantle melting that provided the basis for discriminating the ridge setting from the wetter subduction zone setting. The key was to take one of these three immobile incompatible elements and plot it against a compatible element. This meant that partial melting and fractional crystallization vectors were close to orthogonal and a much more effective discriminant resulted.

Glassley (1974) produced the first plot of this type for interpreting rocks from the Olympic Peninsula in Washington State. He used Ti as the immobile, incompatible element and FeO/MgO as the (inversely) compatible index. This approach differs from the equivalent plot used by Miyashiro in that the latter is based on fractionation trends, whereas the Glassley plot is based on compositional fields. Its use of the mobile element, Mg, presented potential problems in very altered rocks, however. As noted earlier, the Ti-Cr plot of Pearce (1975) used to interpret Troodos lavas, adopted the more immobile element, Cr, as the compatible index. Variations on a theme appeared, including Ti/Cr-Ni (Beccaluva et al., 1979), Ni-Y (Capedri et al., 1980), and my own Y-Cr projection (Pearce et al., 1981, Pearce, 1982). The point of the Y-based diagrams is that Y is a potential improvement on Ti because it is not affected by the crystallization of Ti-bearing oxides that is common in subduction-related magmas. In all these diagrams, displacement to lower incompatible element content (Ti, Y) at a given compatible element content (Cr, Ni, Mg) was a predictable consequence of subduction (fluid) influence, i.e. due to more melting or melting of more depleted mantle.

The second discriminant of this type to be used extensively by the ophiolite community was the Shervais (1982) plot of Ti-V. Subduction-related lavas have lower Ti than MORB at a given V content, whereas intra-plate lavas have higher Ti. As noted by Shervais, this diagram also had a strong petrogenetic base. Ti is more incompatible than V, so it is more depleted in magmas produced by increasing degrees of melting or more depleted sources. In this way, it resembles Ti-Cr, except that the discrimination due to degree of melting is less. The "bonus," however, is that V is highly sensitive to oxygen fugacity. For melting under hydrous (subduction) conditions, more vanadium is in the higher oxidation states 4+ and 5+ relative to the common 3+ state. This means that V is more incompatible during subduction zone melting, and so the lavas have higher V than under anhydrous (MORB) conditions. Thus, subduction-related lavas have both higher V and lower Ti, which improves discrimination.

Ti, Cr, Y, and V all had the advantage that they could be analyzed by the analytical technology of the moment, namely XRF, a simple and accessible technique. The disadvantage of XRF elements was that there was no analyzable element which was both mobile in subduction zones yet immobile during seafloor weathering and metamorphism. As studies of K, Ba, Rb, and Sr showed, a high mobility in subduction zone fluids provided an excellent basis for discrimination, but also meant a high mobility during the weathering and metamorphic events experienced by ophiolitic lavas and dikes. This mobility commonly masked the discrimination.

The breakthrough came with the development of routine (instrumental) neutron activation analysis (INAA). Although it required access to a nuclear reactor for irradiating samples, and so was less universally available, it opened up a range of "new" elements to routine analysis. The first applications of INAA to trace element discrimination began in the mid-1970s (e.g., Smewing et al., 1975; Kay and Senechal, 1976). As with most INAA-based geochemical studies, these focused on the rare-earth elements, which did not discriminate well between ocean ridges and island arcs. INAA did, however, permit analysis of the element Th at the low abundance levels found in basic, oceanic rocks. The significance of Th only became apparent several years later, when the Paris-based group of Treuil, Joron, and co-workers set up a semi-automated system that permitted accurate analysis of Th in large numbers of samples.

Th is a key element in subduction zone discrimination. As we now know, it is enriched in all arc lavas, and so is mobilized in subduction zones, but is immobile until temperatures close to melting temperatures are reached (Johnson and Plank, 1999). INAA is also effective at analyzing Hf (which behaves like Zr) and Ta (which behaves like Nb). From this emerged the Th-Ta-Hf discriminant devised by Wood and the Paris group (Wood et al., 1979, Wood, 1980). Subduction-related lavas have enriched Th relative to Ta and Hf. In addition, many intra-plate lavas have higher Th and Nb relative to Hf. Pearce et al. (1981) and Pearce (1983) used a variant of this theme for a projection of Th/Yb versus Ta/Yb, which is possibly easier to interpret petrogenetically, but has the same theoretical basis.

Geochemical Fingerprinting of Clinopyroxenes

Clinopyroxene discriminants provided an alternative approach. Glass and most minerals are easily altered in volcanic rocks, but clinopyroxene is commonly resistant to alteration because of the greater energy required to break the strong Si-O bonds in its Si_2O_6 chains. Nisbet and Pearce (1977) attempted the first set of clinopyroxene discriminants using discriminant analysis based on major and minor elements, a Ti-Si bivariate plot and a Ti-Mn-Na triangular plot. Leterrier et al. (1982) produced several projections, the most used being Ti+Cr versus Ca, which is 80% successful in discriminating "non-orogenic" from "orogenic" basalts. In all these methods, the key element is Ti, which (as bulk rock discriminants have shown) has lower abundances in subduction-related magmas at a given concentration of a compatible element such as Cr. In general, though, the clinopyroxene discriminants did not provide much new discriminant information. The advantage of using clinopyroxene was that major elements could be used for discrimination. This was counterbalanced by two disadvantages. First, ocean ridge basalts rarely contain clinopyroxene phenocrysts, so the chemically more variable groundmass clinopyroxene had to be used instead. Second, the constraints of stoichiometry, charge balance, crystallization rate, and temperature dependence tend to mask some of the most useful variations. In volcanic rocks, therefore, one might as well discriminate using bulk rock compositions. The most important use of clinopyroxene is thus likely to be in the interpretation of plutonic rocks, where crystal cumulation makes bulk compositions difficult to interpret, although this has yet to be exploited fully.

Isotopic Discrimination

Pb, Sr, and Nd isotope ratios had begun to be used to discriminate between tectonic settings by the late 1970s. Their major advantage is that, unlike trace elements, they can be used to fingerprint both volcanic and plutonic rocks. Sr and Pb, however, are mobile. Nd is much less mobile, but it is less useful without another isotope ratio for co-variation.

Richard and Allègre (1980) carried out the first systematic Nd isotope study of ophiolites, though with a maximum of two analyses from any one complex. They found that most of the ophiolites they studied had εNd values within the range of MORB, and that a few had lower values. They concluded that Nd isotopes were "not in contradiction" with a mid-ocean ridge origin. They plotted the data in Nd-Sr isotope space, and found that many exhibited an isotopic shift from within the diagonal MORB array toward higher Sr isotope ratios. However, it was not clear whether this shift was a consequence of subduction or of sub-seafloor alteration. McCulloch et al. (1980), Noiret et al. (1981) and McCulloch and Cameron (1983) applied Nd-Sr isotope systematics to more detailed studies of the Semail, Vourinos and Troodos ophiolites. Again, the method established that some samples (the Troodos boninites) had εNd values that were too low for MORB, but did not uniquely fingerprint the setting. McCulloch et al. (1980) and Pearce et al. (1981) demonstrated the importance of using clinopyroxene separates rather than bulk rocks to overcome the alteration problem and allow Nd-Sr isotope covariations to be used. However, the discriminating power of this projection is still limited by the fact that many lavas from subduction-related settings also plot along the MORB array.

Because seawater contains so little Pb, Pb isotopes are, in fact, surprisingly insensitive to alteration. The principal problem is that age-corrections are difficult to carry out because of the low abundances and high mobilities of Pb and U. Essentially, discrimination is based on observing whether the ophiolite complex plots within the MORB mantle array in Pb isotope space, or whether it plots toward pelagic sediments with their high $^{207}Pb/^{206}Pb$ ratios. Pb isotope ratios are not especially good at discriminating tectonic settings, however. This is partly because recycled subduction components (as found in "Indian" MORB, for example) can be difficult to separate isotopically from the effects of recent subduction. Moreover, subducted lead can derive from a number of sources—from subducted MORB crust and volcanogenic sediments derived from oceanic islands, as well as from the pelagic sediments upon which the discrimination is based.

The earliest Pb isotope data focused on the easy-to-analyze metalliferous sediments. Thus, Gale et al. (1981) analyzed samples from the Troodos, Syrian, and Oman ophiolites. They found that the first two of these formed a trend between MORB and pelagic sediments. However, they interpreted their results in terms of the mixing of basalt lead and seawater Pb during sub-seafloor fluid circulation, rather than in terms of subduction processes. Hamelin (1984) carried out a systematic study of the igneous rocks from a number of the world's best-known ophiolites, and demonstrated a large variability, some of it certainly linked to tectonic environment. Significantly, the lavas of the Troodos Massif and some other ophiolites plotted above the MORB array toward pelagic sediment compositions, whereas other ophiolites plotted within the MORB array, pointing to a potential contribution of subducted pelagic sediments to their origin.

Despite some successes, however, no clear isotope-based discriminants of tectonic setting have yet been devised, although isotopes (including, most recently, those of Hf and Os) can clearly improve an overall understanding of the petrogenesis of an ophiolite. Trace elements, therefore, remain the discriminants of choice for lavas.

Gabbro Discrimination

Plutonic rocks in ophiolites tend to be much less altered than lavas, which means that some "mobile elements" can be used in their discrimination. Unfortunately, however, the variable and complex processes of crystal cumulation and melt trapping mean that conventional discriminants cannot easily be applied. Nonetheless, fractionation trends can be reliable if they are chosen so that the melt and the crystals plot approximately on the same trends. Serri (1981) used the same elements as Miyashiro (1973) and Glassley (1974), though a slightly different projection. Serri plotted gabbros on a graph of TiO_2 against a Mafic Index [MI = $FeO_{tot}/(FeO_{tot}+MgO)$] to identify two ophiolite types, which he termed high-Ti ophiolites and low-Ti ophiolites. He interpreted the high-Ti ophiolites as those formed at mid-ocean ridges, and the low Ti ophiolites as "oceanic crust generated by spreading processes occurring above a dehydrating subducted oceanic plate in the early stage of opening of intra-oceanic back-arc basins."

Serri's further observation was that these two geochemically-defined ophiolite types were matched by differences in the order of crystallization and hence the type of plutonic rock. These differences, originally recognized by Rocci et al. (1975), were extended by Riccio (1977) and Church and Riccio (1977) into a four-fold classification of ophiolites based on crystallization sequence:

(A) (ol+chr)-opx-cpx-plag
(B) (ol+chr)-cpx-plag-opx
(C) (ol+chr)-cpx-opx-plag
(D) (ol+chr)-plag-opx-cpx

Serri (1981) pointed out that these differences in order of crystallization must be a function of the chemistry of the lavas, and whether the gabbros were of high-Ti (ocean ridge-type) and low-Ti (subduction-related) type. Beccaluva et al. (1983) extended Serri's definition to include a very-low-Ti type, which was subduction-related and associated with boninite lavas. They also made the important link between orders of crystallization and ophiolite type. They noted that the very-low-Ti ophiolite type followed Church and Riccio's orders A and C, giving them an associated cumulate sequence made up of a thick ultrabasic unit of olivine and two pyroxenes in varying proportions, with an overlying sequence of gabbro norite. The low-Ti ophiolite type (which included the Troodos Massif) followed Church and Riccio's order B, giving an ultrabasic unit mainly of olivine and clinopyroxene overlain by a gabbro norite sequence. The high-Ti type followed Church and Riccio's order D, comprising a thin olivine-rich (dunite) ultrabasic sequence overlain by olivine-plagioclase (troctolite) and then gabbro (sensu stricto).

Serri (1981) and Beccaluva et al. (1983) had to use lava geochemistry to develop their plutonic rock discriminants because so few cumulate rocks from known settings had been collected. Detailed ground-truthing of this method began when Bloomer and Hawkins (1983) compared the orders of crystallization of their dredged rocks from the Mariana fore-arc with orders of crystallization in ophiolites. They confirmed the link between subduction zone magmas and early crystallization of pyroxenes.

The reason for the different order of crystallization in low- and high-Ti ophiolites was only discussed in general terms, although the greater degree of melting and higher water content in subduction environments were generally considered responsible for earlier crystallization of pyroxenes with respect to plagioclase feldspar. The point, therefore, is that there is a clear link between subduction processes (increase in degree of melting, or melting of depleted sources) and both lava chemistry (low Ti and Y at a given degree of crystallization) and order of crystallization in the plutonic rocks.

Few attempts were made to use mineral chemistry as a discriminant. However, Browning (1984) did instigate the use of a plot of anorthite content of plagioclase (An) versus forsterite content of olivine (Fo), a projection developed further by Thy (1987). For a given value of An, SSZ lavas have lower Fo.

The granitic rocks from ophiolites, though minor in proportion, had also received attention, and their diversity was the subject of several papers. Pearce et al. (1984b) included them in their granite discrimination. Plagiogranites from ophiolites with subduction affinities typically had lower Y and Nb concentrations than those with ridge affinities, and plotted as volcanic arc granites (VAG), rather than ocean ridge granites (ORG).

Peridotites

Discrimination of ophiolitic peridotites in a modern framework started with Nicolas and Jackson (1972) and Menzies and Allen (1974). They both studied the so-called Alpine peridotites from the Mediterranean region and recognized that they could be separated into two subtypes, a lherzolite-harzburgite subtype and a harzburgite subtype. [Boudier and Nicolas (1985) subsequently gave these the acronyms LOS (lherzolite ophiolite subtype) and HOS (harzburgite ophiolite subtype). Nicolas (1989) renamed them LOT (lherzolite ophiolite type) and HOT (harzburgite ophiolite type).] They discriminated between these on a triangular Al_2O_3-CaO-MgO (ACM) plot, the more residual harzburgite subtype plotting closer to the MgO apex. They explained the differences in terms of geodynamic processes, but not to the presence or absence of subduction. Instead, they considered the more fertile lherzolite-harzburgite subtype to be the residue from melting in small ocean basins, and the harzburgite subtype to be the residue from melting at an established mid-ocean ridge. There was, of course, a very good reason why no link had been made to subduction: a significant number of peridotites had been recovered through dredging at ocean ridges, but there simply were no samples from arcs or marginal basins.

Developments of discriminants initially focused on the harzburgite and lherzolite peridotite types. Because ACM plots were alteration-sensitive, attention switched to the chemically resistant chrome spinels (e.g., Malpas and Strong, 1975; Coleman, 1977). It did, however, take some time for effective discriminant diagrams to be developed. Studies instead focused on the origin of the peridotites; whether they were melt residues, diapirs, or cumulates; and whether they had similar origins to mantle xenoliths.

The realization that harzburgite was a common rock type in subduction-related settings became apparent through inner trench wall dredging. However, the connection between peridotite type and geochemical affinities of the associated lavas provided the best clue. Thus, Beccaluva et al. (1983, p. 307) reported:

> In many ophiolites, parental basalts and mantle ultramafics may be interpreted in terms of generated melts and refractory residua. These are of lherzolitic type in high-Ti ophiolites, whereas mantle harzburgite/dunite commonly occur in low-Ti and very-low Ti ophiolites.

The culmination of the peridotite studies of the 1970s and early 1980s is the paper by Dick and Bullen (1984). They addressed the discrimination of ophiolitic peridotites through a series of projections, the most used being Cr# versus Mg# in chrome spinels. Chrome spinels are remarkably resistant to weathering and alteration, so this discriminant was both easy to obtain and easy to apply.

Dick and Bullen found that ocean ridge (abyssal) peridotites all occupied a well defined field with Cr# ranging from 0.6 to 0.1, as did their associated lavas. In contrast, lavas and plutonic rocks from arcs and layered intrusions typically have Cr# >0.6. Dick and Bullen reported that spinels from "Alpine-type peridotites" and their associated lavas could be divided into three types: Type I with Cr# <0.6, Type III with Cr# >0.6, and Type II with Cr# that spanned the 0.6 discriminant boundary. In terms of setting, they related Type I to mid-ocean ridges (including most back-arc basins), Type III to the earliest stages of arc formation, and Type II to composite settings such as an island arc overlying oceanic crust. The Troodos Massif was Type III on this classification, and the Semail ophiolite was Type II. Dick and Bullen concluded (p. 72):

> Based on analogy to spinels in lavas and plutonic rocks of known provenance, we feel in agreement with Miyashiro (1973) that the provenance of the Type III peridotites is related to the earliest stages of arc-formation on oceanic crust environments which may be preserved in the tectonized material found in the fore-arc regions of many modern island arcs.

Dick and Bullen (1984) also provided the petrogenetic explanation for their observations, namely that the Cr# of the spinels is a function of the degree of melting that the mantle has undergone. Above subduction zones, the added water means that the degree of melting is higher, so the Cr# in the peridotite residue from melting is greater. Moreover, it fits in with the mineralogy of the peridotites. Type I peridotites typically (though not always) leave residues that still contain some clinopyroxene (lherzolites and clinopyroxene-rich harzburgites). Type III peridotites, by contrast, contain very little clinopyroxene as a result of the greater melting (clinopyroxene-poor to clinopyroxene-free harzburgites).

Dick and Bullen's work was the prelude to several other peridotite discriminants. Some extended the range of tectonic settings under consideration (e.g., Bonatti and Michael, 1989), and some replaced Mg# with a more effective axis (e.g., the Arai (1994) plot Cr# against forsterite content of olivine). These all have the same explanation, namely that subduction induces more melting (or melting of more depleted mantle).

DEVELOPMENT OF THE SUPRA-SUBDUCTION ZONE DEFINITION

Thus, by the early 1980s, the Y-Cr, Ti-V and Th-Ta-Hf discriminant diagrams (and their various morphs) were all effective in recognizing subduction signatures in lavas and dikes. The Ti-MI diagram could fingerprint gabbros and the Cr–Mg# diagram was effective at fingerprinting peridotites. Other methods, including mineral compositions and isotope systematics, could add further information. With the exception of a few small improvements, the main methods of discrimination were in place by this time. It was also apparent that there were links between tectonic setting and rock type. Moreover, by this time, a substantial database had been built up, both on ophiolite complexes and on modern analogues. It was clearly the right time to synthesize the data and provide a model for characterizing ophiolites, and it is no coincidence that a series of such papers were published almost simultaneously.

The syntheses were not, however, entirely straightforward to write. The principal impediment was that some ophiolites remained controversial, and these included the world's two biggest and best-exposed ophiolites, the Troodos Massif of Cyprus and the Semail ophiolite of Oman. Both of these were important for analogue studies of mid-ocean ridges, and the role of subduction in their origin became a major issue.

The problem with the Troodos Massif remained that, if one accepted (as most did by this time) that it formed at a spreading axis above and behind a subduction zone, it was difficult to explain the absence of an associated island arc. All modern analogues, Scotia Sea Site 24, the more arc-like lavas of the Western Pacific marginal basins, and even the fore-arc terranes, had associated island arcs. The concept of spreading at the initial stages of subduction was popular, but there was still no modern analogue where subduction had recently initiated.

The Semail (Oman) ophiolite debate was more complex. Two groups began working in Oman in the mid-1970s. The UK led by Ian Gass (of which I was part), worked in the north, where the lavas were best exposed. The USA group, led by Bob Coleman and Cliff Hopson, worked in the south, where the lower crust and upper mantle were best exposed. In the north, a late basalt-andesite-dacite sequence with distinct subduction chemistry on all discriminants formed small volcanic edifices above the ophiolite, and we suggested that they might represent an incipient arc (Pearce et al., 1981; Alabaster et al., 1982). The underlying ophiolite was close to MORB in its geochemistry, but we did detect a small subduction signature based on Y-Cr covariations. In the south, there were no upper lavas, and the gabbros were equivalent to those sampled in the main ocean basins, and so there was no indicator of subduction. To the USA group, the ophiolite was typical of lithosphere formed at a fast-spreading mid-ocean ridge unrelated to subduction (e.g., Coleman, 1981). The USA group rejected a subduction link for the same reason that the setting of the Troodos Massif continued to be debated: there was no chain of arc volcanic edifices to prove a subduction-related setting geologically.

Finding a term to describe ophiolites with a subduction-related geochemistry but no associated chain of arc volcanoes proved a surprisingly difficult problem. We did not view as accurate terms such as "fore-arc ophiolite," "back-arc ophiolite," "pre-arc ophiolite," or "island arc ophiolite" because there was no arc to pre-date or post-date. Moreover, even in ophiolites that were associated with island arc activity, it was usually impossible to tell geochemically or geologically where the ophiolite originally lay with respect to the arc. "Marginal basin ophiolite" was equally inappropriate, because many marginal basins were floored by crust of MORB composition formed before subduction started. Thus, a term was needed that described the subduction influence in generic terms without defining exactly where it lay within the subduction system.

Resolution of this semantic problem began when John Malpas (1981, personal commun.) introduced the term "supra-Benioff zone" to explain our inferred setting of formation of the Semail ophiolite, and this was first used in a paper on Oman geochemistry by Alabaster et al. (1982). The term "supra-subduction zone (SSZ) ophiolites" evolved from this and was formally named and defined by Pearce et al. (1984a, p. 77) as follows:

> Supra-subduction zone (SSZ) ophiolites have the geochemical characteristics of island arcs but the structure of oceanic crust and are thought to have formed by sea-floor spreading directly above subducted oceanic lithosphere. They differ from "MORB" ophiolites in their mantle sequences, the more common presence of podiform chromite deposits, and the crystallization of clinopyroxene before plagioclase which is reflected in the high abundance of wehrlite relative to troctolite in the cumulate sequence. Most of the best-preserved ophiolites in orogenic belts are of this type.

Drawing on the work so far described, we demonstrated that geochemical discriminant diagrams could be used together with information on the order of crystallization and nature of mantle peridotite to distinguish two ophiolite types: a MORB type and an SSZ type. According to our paper, SSZ ophiolites could occupy one of several settings:

- The initial stages of spreading (pre-arc ophiolites)
- The spreading-arc transition
- The arc-back-arc spreading transition

To unravel the precise setting of any given ophiolite, if possible at all, would (we argued) require a combination of geochemistry, lava stratigraphy, and field geology. We proposed that the geochemical stratigraphy of the lavas (e.g., subduction-zone affinity increasing upward for the spreading arc transition, but downward for the arc-back-arc spreading transition) might be one important characteristic.

At about the same time, Leitch (1984) divided what he termed "arc related ophiolites" into four classes:

- Type A: ophiolites derived from oceanic lithosphere in existence prior to island arc inception and trapped within the arc system at the onset of overthrusting
- Type B: ophiolites derived from oceanic lithosphere formed by rifting of the overriding plate after the start of slab-related magmatic activity
- Type C: ophiolites produced at the inception of island arc formation
- Type D: ophiolites produced by slab-related magmatism during arc evolution

As explained above, I view SSZ as a better term than "arc-related" because some ophiolites have no arc to which to relate. Nonetheless, Leitch's concept and our own are very similar. Leitch's Type A is actually a MORB ophiolite according to our definition, having been incorporated in the subduction system without having any genetic relationship to a subduction zone. Type B is an SSZ ophiolite, which is equivalent to pre-arc ophiolites as we defined them. Type C is an SSZ ophiolite created at the start of subduction by near-trench processes. Type D is an SSZ ophiolite, which encompasses our spreading-arc and arc-spreading transitions.

These papers represent syntheses of the work of many scientists since the Penrose Conference definition was published in 1972 (Anonymous, 1972). By 1984, it was clear to almost all geoscientists that ophiolites had diverse affinities and that many, and probably most, had subduction affinities. Enough data had accumulated that several groups of scientists were able more-or-less independently to make the subduction link, define the geochemical and petrological characteristics of subduction-related ophiolites, and define the types of setting at which they formed. The question remained, however: to precisely what setting above a subduction zone did a given ophiolite belong, and how could one tell? And what can SSZ ophiolites then tell us about global dynamics and subduction processes? These now became important questions for ophiolite scientists.

DEVELOPMENT OF THE SUBDUCTION INITIATION MODEL

One of the most significant advances after 1984 was the development of the subduction initiation model for SSZ ophiolites. This model does not apply to all SSZ ophiolites, but may apply to many, including some of the largest and best preserved. Ideas essentially evolved along three tracks, all requiring rifting and spreading as the first manifestation of crustal accretion following initiation of subduction and all assuming that, given time and sufficient lithosphere to subduct, the new lithosphere would form the substrate to subsequent arc volcanism.

- Rifting and extension of lithosphere of the overriding plate at the locus of normal arc magmatism following subduction initiation
- Rifting of young, near-trench lithosphere of the overriding plate following subduction initiation at an old-young lithosphere boundary
- Rifting of young, near-trench lithosphere of the overriding plate following subduction initiation at an active ridge-transform boundary

The hypothesis that spreading might predate arc volcanism was originally developed by Pearce (1975), Pearce et al. (1981), and Alabaster et al. (1982). Its aim was to explain the aforementioned observation that ophiolites such as the Troodos Massif and Semail ophiolite of Oman had the geochemical characteristics of island arcs, but the structure of oceanic crust and no associated arc edifice or overlying volcanogenic sediment. Our view was that they did not evolve into an arc proper because there was not enough oceanic lithosphere to subduct. We argued that many ophiolites (including Troodos and Semail) formed by closure of small oceans, and so froze the arc-basin system in its early, extensional stages of formation.

Drilling and dredging of the Western Pacific trenches supported the concept of extension associated with subduction initiation, but changed the perception that it must take place some distance behind the trench. The important observation was that the ophiolite sequences in the inner trench wall formed very soon after subduction initiation. Thus, either spreading must have taken place close to the trench in the first place, or 100 km or more of old, MORB-like lithosphere in the fore-arc had to be scraped off the inner trench wall and subducted. Karig (1982, p. 571) was one of the first to raise doubts:

> Although it is almost certain that some oceanic arc systems were initiated along transforms or fracture zones, it is less obvious that this process traps a 60–100 km wide belt of typical oceanic crust between the trench and arc.

Of course, this crust need not be trapped; it could be lost by trench erosion or development of a second subduction zone. While not impossible, this was unlikely and so ophiolite formation by extension at the locus of normal arc volcanism did not survive much longer as a model. Whatever model did apply had to explain extension before arc volcanism, the common presence of boninites, and the creation of new oceanic crust near the trench.

Hawkins et al. (1984), started from a different perspective, that of Western Pacific marginal basins. They also emphasized the importance of rollback-driven extension during the initiation and evolution of arc-basin systems, pointing out that this enabled ophiolites to originate in fore-arc, intra-arc, and back-arc settings. They also demonstrated that spreading before active arc volcanism was a common feature of arc-basin systems. Like us, they formed the earliest, extensional lithosphere behind the trench in response to upwelling of hot mantle. They then made the key, additional deduction that the locus of this crustal accretion must be nearer the trench than the active arc. Their argument was that boninites require a depleted mantle source and shallow depths of melt segregation, which in turn implies an origin at shallow subduction depths. In their words:

> [Mantle counterflow following subduction initiation] heats up the serpentinised peridotite, causes an uparch of the lithosphere and promotes dilation of a zone in the fore-arc. Boninite magmas, derived from melting of the peridotite, are the first melts to leak out along the zone of fore-arc dilation. Although the actual depth of boninite generation cannot be determined at this time, a depth of 50 km or less for melt-residue separation has been proposed. Thus, if a relation to the subduction process is inferred, boninite eruption may occur in (or be restricted to) the fore-arc region. (Hawkins et al., 1984, p. 194)

The Hawkins et al. (1984) mechanism still placed the first-formed oceanic lithosphere some distance from the trench, however. Leitch (1984) went a step further and proposed a mechanism for generating oceanic lithosphere still closer to the new trench:

> Where, after initiation of subduction, convergence keeps apace with rollback of the subduction hinge the rocks on the leading edge of the overriding plate will form the basement. However, if roll back rate exceeds convergence rate extensional conditions exist that may lead to ophiolite development in the forearc region. It is envisaged that in this situation asthenosphere displaced by the sinking slab flows around the leading edge of the slab into the region above it. Partial fusion produces basaltic melts that rise to form a magma body similar to that beneath one side of a mid-ocean rift, and new lithosphere fills the space between the retreating subduction hinge and the edge of the upper plate (p. 192–194.)

The Izu-Bonin-Mariana fore-arc provided the natural laboratory for investigating subduction initiation models. Although subduction initiation was of Eocene and not Recent age, the system was the only one to have retained the geometric elements of subduction initiation and so it was the nearest to an analogue for this ophiolite type. If we could understand the Mariana system, we should make significant advances in our understanding of ophiolites.

Uyeda and Ben-Avraham (1972), Hilde at al. (1977), and Hussong and Uyeda (1981) had already noticed that the Western Pacific arc terranes were orthogonal to the relict spreading axis in the West Philippine Basin. This led them to propose that subduction initiated at a transform fault associated with a change in Pacific plate motion. In this model, old Pacific lithosphere was juxtaposed against the young West Philippine Basin lithosphere of the Philippine plate at the time of subduction initiation. Although initiation at a transform fault was more or less consensus, the plate reconstruction was not. For example, Seno and Maruyama (1984) required a plate between the Pacific

Plate and Philippine Plate (their New Guinea plate) at the time of subduction initiation. Casey and Dewey (1984) raised the additional possibility that the transform was not pure strike slip, but contained active ridge-transform-ridge segments at which subduction could more readily initiate.

Casey and Dewey (1984) also made the link to boninite genesis by pointing out that subduction at a ridge or transform between two ridge segments would initiate melting beneath hot, shallow, and depleted lithosphere—all the criteria for boninite formation. Usefully, the model also explained how new ocean crust could be generated almost at the trench itself, as this region was weak and underlain by asthenosphere at shallow depth. The Casey and Dewey model and variants of it initially proved attractive. For example, Boudier et al. (1988) explained the Oman ophiolite by subduction beginning at an active ridge. In this way, they argued, it could begin life as a MORB ophiolite and evolve into a SSZ ophiolite, thus reconciling the ongoing debate about its tectonic setting of formation. This currently remains a matter of debate.

The second phase of drilling in the Western Pacific also contributed to our understanding of subduction initiation and its link to ophiolites. ODP Leg 125 drilled holes in fore-arc serpentinite seamounts and the outer arc high of the Izu-Bonin-Mariana fore-arc (Fryer et al., 1989) and Leg 126 drilled holes in the Izu-Bonin fore-arc basin (Taylor et al., 1990). Hole 786B, drilled during Leg 125 in the outer-arc high of the Izu-Bonin fore-arc, was particularly informative. It penetrated an arc edifice into the underlying oceanic crust, reaching sheeted dikes (the first drilled in SSZ crust). Both the arc edifice and the underlying, possibly oceanic, crust were boninitic in composition.

Our interpretation of the ODP Leg 125 drill core (Pearce et al., 1992) was that the fore-arc crust formed by subduction beneath the ridge or young crust of the West Philippine Basin. The boninites carried an unusual geochemical signal in which Zr was strongly enriched relative to many other elements, and Sr/Y ratios were high. We interpreted this as an "adakitic" slab-melting fingerprint, which would then support the Casey and Dewey model because this required subduction of very young lithosphere.

At around the same time, Stern and Bloomer (1992) published their model for the link between subduction initiation and ophiolite formation. They favored the original models of Uyeda and co-workers, in which older, colder, and thicker Pacific oceanic lithosphere is juxtaposed against younger, hotter, and thinner West Philippine Basin lithosphere before subduction starts. In terms of mechanism, their starting point was the fore-arc extensional model of Hawkins et al. (1984) and, particularly, the Leitch (1984) Type C ophiolite model. The Stern and Bloomer (1992) model provided the link between Leitch's model and the Uyeda picture of subduction initiation in the Western Pacific. They extended the Leitch ideas as follows:

> Melting in such an extensional environment would lead to infant-arc crust formation by sea-floor spreading. This spreading would in many ways be similar to that of mid-ocean ridge and back-arc basin spreading regimes with two significant differences. First spreading is likely to be poorly organised, with many discrete ridge segments and asymmetric spreading. The infant arc crust nearest the precursor transform fault might be first to form, although this may be replaced by younger infant-arc crust during later rifting events. (Stern and Bloomer, 1992, p. 1626)

The important component in their model was the buoyancy contrast between the young, hot lithosphere of the West Philippine Basin in the west and the old, cold Pacific lithosphere in the east. Their idea is that, on initiation of subduction, the older, colder slab sinks and the trench rolls back, thus creating extension close to the trench and allowing asthenosphere to rise into the space created. Stern and Bloomer used the term "arc infancy" to describe this setting. Bloomer et al. (1995) developed this concept further, linking it to the fore-arc drilling from ODP Legs 125 and 135. They concluded (p. 1):

> This early or "infant" arc volcanism was characterised by the eruption of very depleted boninitic and arc tholeiitic lava compositions and occurred in extensional environments. This infant arc volcanism was built on, or displaced, the pre-existing oceanic crust and had igneous production rates much higher than those of mature arcs—eruption rates on the order of those from in slow-spreading ridges. This initial arc volcanism is unlike that developed during the "normal or mature phases of arc activity and is a plausible mechanism for developing supra-subduction zone ophiolites.

Geologically, it is impossible to distinguish between the Uyeda model and the Casey and Dewey model because the evidence (the crust immediately outboard of the incipient subduction zone) has all been subducted. Pearce et al. (1999) tested the two models using isotopic fingerprinting of the earliest supra-subduction zone magmas. The starting point was the Hickey-Vargas (1991) discovery that the marginal basins of the Western Pacific exhibit an "Indian" Pb isotope signature, whereas the subducting Pacific Plate exhibits a "Pacific" signature. In the Uyeda model, therefore, the subduction signature should be Pacific, and the mantle signature Indian. In the Casey and Dewey model, the subduction and mantle signatures should be the same unless subduction initiation fortuitously began at a mantle domain boundary. In the event, the Pb signature was Pacific and the Hf signature was Indian, clearly supporting the Uyeda, and Stern and Bloomer, model of Pacific plate subduction beneath the West Philippine Basin.

Overall, therefore, we can use the Mariana analogue to build up quite a detailed picture of how ophiolites might form at the start of subduction. But is this the only analogue?

RIDGE-TRENCH INTERSECTION (RTI) MODELS FOR SSZ OPHIOLITE FORMATION

Subduction initiation models for SSZ ophiolite formation require that trench rollback take place in the early stages of subduction and that this will lead to seafloor spreading near the trench above the nascent subduction zone. Near-trench seafloor spreading is therefore a direct consequence of rollback that is linked to subduction initiation. The RTI models have a very different mechanism because the subduction zone imparts a subduction characteristic to ridges that are near-trench for reasons unrelated to subduction initiation. In some cases, as I shall explain, subduction initiation may take place at an RTI. RTI intersections capable of producing SSZ ophiolites can be divided into three types:

- Subduction beneath a ridge
- Subduction of a ridge (SSZ ophiolite formation in the fore-arc)
- Subduction of a ridge (SSZ ophiolite formation in the subducting plate)

In the first two of these, the active spreading takes place in the fore-arc. In the third, the spreading takes place in the subducting plate.

Subduction Beneath a Ridge

Ridge-trench intersections have many possible geometries. The first to be invoked as settings for ophiolite genesis is the class that involves subduction beneath a ridge. This setting was first invoked for ophiolite emplacement by Dewey, 1976, and then for anomalous, near-trench magmatism by Marshak and Karig, 1977. Subsequently, Karig (1982) and Casey and Dewey (1984) focused on its potential importance for ophiolite generation. Typically, the spreading axes are orthogonal to the trench, in contrast to subduction initiation models, where the spreading is trench-subparallel. There are many such examples at the present time, mostly at the edges of arc-trench systems, such as the northern termination of the Lau Trench, the southern termination of the Mariana Trench, the southern termination of the Vanuatu Trench, and both north and south terminations of the South Sandwich Trench. With these in mind, Casey and Dewey concluded:

> Therefore, whilst some ophiolites may have "island arc" petrological affinities, they should not necessarily be discounted as the end products of the sea-floor spreading process. Ophiolite formation by sea-floor spreading, whether at a normal mid-ocean ridge or at a back-arc spreading centre that traverses a usually non-volcanic forearc region, would seem to best explain the geologic character of many obducted ophiolite complexes. (Casey and Dewey, 1984, p. 286)

Compositionally, these settings provide good analogues for some ophiolites. The principal rock types are island arc tholeiites, back-arc basin basalts, and boninites, especially those of high-Ca type. Those studying dredged rocks from modern analogues have commented on their similarity with many supra-subduction zone ophiolites, including the Troodos Massif. For example, Falloon et al. (1987, p. 487) interpreted the dredged boninitic rocks from the northern termination of the Tonga Trench as follows:

> [These rocks] are similar to low-Ti ophiolitic basalts such as those of the Upper Pillow Lavas of the Troodos ophiolite, Cyprus. The dredged Tongan high-Mg lavas are therefore an in situ occurrence of a low-Ti ophiolitic lava suite, and support an intra-oceanic island arc origin for the Troodos and other ophiolites with these lavas.

Falloon et al. (1987) interpreted the setting of boninite formation as an island arc, but it is probably more complicated than that. Both the ridge (Northern Lau Spreading Center) and arc (Tofua arc) converge at that point, and it is not clear whether the lithosphere is oceanic or arc-like. The southern termination of the Vanuatu arc similarly converges on the southernmost spreading center of the North Fiji Basin. The submarine islands have the composition of high-magnesium andesites (Monzier et al., 1993). The southern termination of the Mariana system (Crawford et al., 1986; Stern et al., 1989) and the southern and northern terminations of the Scotia Sea (Leat et al., 2000; Fretzdorff et al., 2002) both contain depleted island arc tholeiites resembling those found in many SSZ ophiolites.

In each of these settings, there is the potential to modify the mantle by addition of a subduction component before it rises beneath the ridge. In addition, the residual lithosphere at that ridge would be hot, and therefore able to further melt by fluid addition, to give boninites. Finally, because the setting is at the fracture-zone edge of a subduction system, it would be the first to be emplaced by continent collision.

It is also important to note that the reconstruction of the Western Pacific at the time of subduction initiation had an RTI where the West Philippine Basin spreading center intersects the embryonic subduction zone. Therefore, over some of its length at least, subduction initiation and RTI mechanisms can overlap.

Subduction of a Ridge: SSZ Ophiolite Formation in the Fore-arc

The second type of RTI invoked for ophiolite genesis is that of ridge subduction. The concept of ridge subduction beneath accretionary complexes as a means of explaining near-trench magmatism was put forward by Marshak and Karig (1977). They also demonstrated how the migration of triple junctions could produce the trench-parallel belts of near-trench magmatism observed in Sumatra, Alaska and Japan. Miyake (1985) published one of the first papers to investigate in detail the potential link between ridge subduction and ophiolite genesis. He studied the Shionomisake igneous complex, which formed autochthonously in the fore-arc basin on Honshu in the Miocene. Miyake identified two of the characteristic geochemical features of this type of setting: a MORB character when plotted on diagrams such as Ti-Cr (which are based on degree of melting) and TiO_2-FeO/MgO (which also depend on oxygen fugacity). He also identified enrichment in Th and LREE, but, having no Ta or Nb data, was not able to attribute this to a SSZ character. He concluded:

> The Shionomisake igneous complex is analogous petrologically and petrochemically to abyssal igneous association, though the basic rocks are more enriched in LREE and Th than N-MORB and are associated with relatively more voluminous acidic rocks than …the oceanic crust. The very existence of the Shionomisake igneous complex and other igneous masses in the modern forearc basins suggest another template for the formation of ancient ophiolite complexes. (Miyake, 1985, p. 32)

The Taitao ophiolite in Southern Chile presents an even better example, being younger (Plio-Pleistocene) and having a more complete ophiolite structure. It is located in the fore-arc above the site of Chile Ridge subduction. Forsyth et al. (1986) demonstrated that the Taitao ophiolite has a composition intermediate between MORB and SSZ character on a Ti-Cr plot and they also noted a high proportion of silicic rocks compared with normal oceanic crust. Kaeding et al. (1990) and Lagabrielle et al. (1994) carried out more complete geochemical studies. They reached similar conclusions, namely that ridge subduction leads to decompression melting of MORB mantle, but with the top of the melting column located beneath the continental edge so that the degree of melting is less than normally experienced at mid-ocean ridges. Moreover, the resulting enriched MORB then undergoes extensive assimilation and fractional crystallization in the crust to produce the high proportion of silicic rocks and the enrichments in Th and LREE.

A series of subsequent papers found near-trench plutonic and ophiolite complexes of various ages around much of the Pacific Rim. In Japan and Alaska, in particular, ridge subduction took place beneath accretionary complexes rather than continental crust. The current view is that a wide range of ophiolites and related rock types can be emplaced in fore-arc terranes. These may be derived both from crust formed outboard of the trench and emplaced in the fore-arc (as first envisaged by Dewey, 1976) and from in situ injection of basic magma into the accretionary complex (e.g., Lytwyn et al., 1997, 2000).

Both subduction and crustal assimilation are capable of giving an apparent subduction signature on plots such as Th-Hf-Ta, particularly for the most fractionated rocks. Whether or not this type of ophiolite should be termed SSZ is a semantic problem. The key question should be whether or not the mantle source has a subduction signature. If the mantle source lay beneath the subducting plate and has flowed into the zone of melting without residence in the mantle wedge, then the ophiolite is strictly of MORB type (albeit contaminated by crust). If the mantle source has flowed laterally from the adjacent mantle wedge into the zone of melting, then it is strictly of SSZ type. Evidence to date is ambiguous, and it is quite possible that both MORB and SSZ mantle sources are potentially available, i.e., that both ophiolite types are present.

Subduction of a Ridge: SSZ Ophiolite Formation Before Subduction

Another scenario for SSZ ophiolite formation is when subduction-influenced mantle can melt to form oceanic crust of apparent SSZ affinity before it is subducted. This effect was first recorded in the Woodlark Basin, where the spreading center approaches the Solomon Trench. The crust formed in this setting has a distinct SSZ character (Perfit et al., 1987; Johnson et al., 1987). The Solomon Island region is complicated by the fact that the subduction zone originally faced south, and then changed polarity to its present northerly direction. In consequence, it is possible that the SSZ composition is not related to the subduction of the ridge, but to the presence of mantle that once overlay the earlier subduction zone. Perfit et al. (1987, p. 114) conclude:

> The Woodlark Basin is apparently chemically zoned orthogonal to the current locus of subduction. Crust farther than 150 km from the subduction zone is normal MORB. Nearer the subduction zone, the submarine volcanic rocks acquire an increasing arc-like chemistry…The chemical zonation is difficult to explain in terms of the current plate configuration but may be explicable if the mantle beneath the Woodlark Basin was previously affected by subduction of reversed polarity.

The Woodlark Basin has proved an attractive analogue for SSZ ophiolite genesis. In fact Saleeby (1982) invoked the analogue for the Sierra foothills ophiolites well before Perfit et al. and Johnson et al. published the analyses of their dredged samples. Following the publication of the analyses, Dilek and Moores (1990) carried out a more detailed assessment of the merits of the eastern Woodlark Basin as an SSZ ophiolite analogue, concluding that it was a viable option for some Eastern Mediterranean ophiolites.

Subsequently, Klein and Karsten (1995) identified a similar signature where the Chile Ridge enters the South American Trench. Here, reversal of subduction polarity was clearly not a factor. They recognized the potential significance to ophiolite studies, as follows:

> …the Chile Ridge lavas are the first mid-ocean ridge basalts with convergent-margin characteristics suggests that caution is warranted in using trace-element systematics to identify the provenance (mid-ocean ridge or supra-subduction zone) of ophiolites. (Klein and Karsten, 1995, p. 52)

The implication of their observation is that asthenosphere can flow from the mantle wedge and beneath and along the subducting mid-ocean ridge to impart a SSZ chemistry. There are, though, differences with most SSZ ophiolites: although elements such as Th and LREE are enriched relative to Nb and other HFSEs, the rocks still plot as MORB on diagrams such as Cr-Y, that are based on degree of melting or oxygen fugacity. This setting does, however, provide a small piece of ammunition for those still holding out for a mid-ocean ridge origin for all ophiolites.

BACK-ARC BASIN ANALOGUES

Following the discovery of Site 24 of the East Scotia Sea, the detailed geochemical mapping of the various marginal basins that have been carried out over the past 20 years has revealed that all back-arc basins had highly variable compositions ranging from MORB to SSZ type, with all gradations in between. A key site is the Valu Fa Ridge at the south of the Lau Basin. It has an arc-like chemistry (Jenner et al., 1987), but an oceanic crustal structure and a sub-axial magma chamber. Andesite-dacite lavas are exposed at the ocean floor. More regional geochemical mapping showed a progressive increase in SSZ character from MORB in the center of the basin to the Valu Fa Ridge in the south as the arc is approached (Pearce et al., 1995).

Gradual accumulation of data essentially showed that back-arc basins could have MORB or SSZ character according to the precise setting of the fragment of oceanic lithosphere with respect to the subducting plate and the direction of mantle flow. For example, in the Central and Southern Lau Basin, the subduction affinities increase toward the south, where the spreading center converges on the arc. In the East Scotia Sea, as already noted, subduction signatures are highest in the north and south, where mantle flows onto the system over the subducting plate (Leat et al., 2000; Fretzdorff et al., 2002). In the Mariana Trough, all parts of the spectrum between MORB and SSZ compositions have been identified, with a general increase to the north as the ridge changes to a rift zone and then merges with the arc itself (e.g., Stolper and Newman, 1994; Gribble et al., 1998).

Within this phase of data accumulation, a major and unexpected advance was made during ODP Leg 135. Scientists discovered that much of the Lau Basin is floored not by new oceanic lithosphere formed by back-arc spreading, but by strongly attenuated arc lithosphere (Parson and Hawkins, 1994). In other words, the sequence of rifting and drifting that applies to continental separation also applies to arc separation. From the ophiolite perspective, it raises the question of whether some fragments of SSZ ophiolite represent the products of true back-arc spreading or whether they result from rifting of arc terrane. Given that many MORB ophiolites represent incipient spreading of "normal" oceans, it would not be surprising to find their equivalents in marginal basins. A further point of note is that the rifting process also gives rise to magmatism by decompression. If the rifting is advanced, and the subduction zone distal, the overlying magmas can be of MORB composition while the underlying oceanic lithosphere is of SSZ type.

All the scenarios listed above assume that, if subduction is sufficiently long-lived, an arc and back-arc basin will result. This need not be the case, however. Moores et al. (1984) pointed out that oblique subduction could lead to the formation of an active ridge-transform system above a subduction zone, without associated arc volcanoes. They proposed that this process could explain the absence of arc volcanoes in many Eastern Mediterranean SSZ ophiolites and cited the Andaman Sea as a modern analogue. This is an attractive hypothesis, but still has to be tested by sampling and analysis of Andaman Sea lavas.

"LIFE CYCLES" OF SSZ OPHIOLITES

Although space has restricted this article to the identification and origin of SSZ ophiolites, Shervais (2000) has presented a more holistic synthesis, incorporating information on their evolution and emplacement. He discusses what he terms the "life cycle" of SSZ ophiolites. There are five stages to his cycle:

- Birth (formation in a nascent or reconfigured subduction zone)
- Youth (continued mantle wedge melting and crustal accretion)
- Maturity (onset of arc volcanism)
- Death (sudden cessation of subduction, usually because of continent collision)
- Resurrection (emplacement of the ophiolite onto a passive continental margin)

Shervais (2000) explains this sequence in more detail in paragraph [13]:

> These events generally progress in an orderly fashion from birth through death and resurrection, but not all ophiolites display all stages of this life cycle. In particular some SSZ ophiolites never reach maturity but skip directly to death and resurrection. In others, death and resurrection are coincident, with no evidence for a prolonged interval between these events. The "birth" and "youth" stages seem to be common to all SSZ ophiolites and reflect their original formation in the upper plate of a subduction zone.

In many respects, this life-cycle concept began with the tectonic diagrams of Dewey and Bird (e.g., 1971), who were (as recounted earlier) the first to examine the possibility that ophiolites might form in marginal basins. Shervais' synthesis incorporates the 30 years of work that have subsequently been carried out to define and explain the origin of SSZ ophiolites. It is interesting to compare these papers, which are currently among the first and last articles written about subduction-related ophiolites. The comparison shows how far ideas on subduction-related ophiolites have changed over the period of time discussed in this paper. For example, in Dewey and Bird (1971), subduction-related ophiolites are restricted to back-arc and intra-arc basins, whereas fore-arcs contain trapped ocean crust once formed at mid-ocean ridges. In Shervais (2000), back-arc and intra-arc basins are much less important: it is the fore-arcs that provide the source of most subduction-related ophiolites, and subduction initiation that is the principal mechanism for their formation.

A KUHNIAN ANALYSIS OF THE EVOLUTION OF IDEAS ON SSZ OPHIOLITES

Kuhn (1962) postulated that scientists, at any one time, adhere to a paradigm—a set of fundamental beliefs. Under conditions of "normal science," this paradigm shifts very slowly. Under conditions of "extraordinary science," however, the paradigm shifts rapidly and we have a "scientific revolution." The revolution need not be instantaneous but may be preceded by years of debate. Kuhn's ideas on scientific revolutions have already been applied with apparent success to the development of the plate tectonic hypothesis (e.g., Hallam, 1973). In this context, global tectonic studies have been, since the mid-1960s, in a period of "normal science" following the plate tectonic revolution.

Development of ideas on ophiolites can be viewed on one level as part of the post-plate tectonic "mopping-up" operation whereby geological features are reinterpreted in terms of the new paradigm. As a subject on their own, however, they reveal their own paradigm shifts. The first of these in recent times (but predating the period discussed in this paper) was the shift from ophiolites as components of geosynclines to fragments of oceanic lithosphere. This shift was extremely rapid and occupied the immediate post-plate tectonic period, culminating in the Penrose Conference definition published in 1972 (Anonymous, 1972).

The second shift, discussed in much detail here, was from ophiolites as fragments of oceanic crust formed at mid-ocean ridges to ophiolites as fragments of oceanic crust formed at supra-subduction zone ridges. This shift was slower and, as discussed in this paper, developed through geological studies on ophiolites, development of analytical and techniques and geochemical methods, and drilling and dredging of potential analogues at sea. It was the product of some 12 years (1972–1984) of debate and data acquisition, and culminated in the supra-subduction zone concept. In fact, 1984 saw a series of key papers that established this concept, not just my own that defined the term (Pearce et al., 1984a), but others that placed this group of ophiolites clearly in a subduction context (e.g., Leitch, 1984; Hawkins et al., 1984; Casey and Dewey, 1984; Dick and Bullen, 1984).

The third (post-1984) stage of evolution of ideas is the post-SSZ ophiolite stage. The SSZ definition makes no statement about the precise setting of the ophiolite other than its link with subduction. A period of "normal science" is now taking place to pinpoint the precise settings in which these could happen. This could be viewed as a "mopping up operation," but that description would hide a series of small revolutions that have led to the establishment of subduction initiation and ridge-transform intersections as prime candidates for SSZ ophiolite formation, and have raised the possibility that strongly attenuated arc terranes and oblique subduction present other candidates for SSZ settings.

A BAYESIAN ANALYSIS OF THE EVOLUTION OF IDEAS ON SSZ OPHIOLITES

It is also possible to analyze the chain of events using Bayesian methods, specifically the Bayes Decision Rule. This is because the assignment of a given ophiolite to its most probable tectonic setting of formation involves decision-making processes. Decision making requires two components: a knowledge base comprising the evidence, and an inferencing engine comprising the decision-making method, in this case the Bayes Decision Rule (see Pearce, 1987 for a more detailed explanation). The Bayes Decision Rule can be written as:

$$p\left(T_{\mathrm{j}}\middle|E_{\mathrm{i}}\right)=\frac{p\left(E_{\mathrm{i}}\middle|T_{\mathrm{j}}\right)p\left(T_{\mathrm{i}}\right)}{p\left(E_{\mathrm{i}}\right)} \qquad (1)$$

where $p(T_{\mathrm{j}})$ is the a priori probability of the unknown sample x belonging to tectonic setting T_{j}; $p(E_{\mathrm{i}}/T_{\mathrm{j}})$ is the likelihood that the unknown sample x belongs to setting T_{j}, given the evidence E_{i}; $p(E_{\mathrm{i}})$ is the total probability of the piece of evidence, E_{i}; and $p(T_{\mathrm{j}}/E_{\mathrm{i}})$ is the posterior probability of the unknown sample x belonging to setting T_{j}, given the evidence E_{i}.

To apply this rule for ophiolites, we start with the a priori probabilities (the probabilities before any discrimination criteria are applied). Then, for the first piece of geochemical, geological, or petrological evidence, we use equation 1 to determine the posterior probability of each setting, i.e., the probabilities after that piece of evidence has been considered. This posterior probability is then treated as the a priori probability for consideration of the next piece of evidence, and so on. The eventual outcome is a set of probabilities that the ophiolite in question belongs to each of the designated magma types.

Two other points are important in making the assignment. First, it is possible to incorporate the measure of belief into the equation. Measure of belief of a given piece of evidence (E_i) can be written (MB/E_{i}), and follows a scale of 1 (complete belief) to 0 (no belief, equivalent to nonconsideration of the evidence). The posterior probabilities then become:

$$p\left(T_{\mathrm{j}}\middle|E_{\mathrm{i}}\right)=\frac{p\left(E_{\mathrm{i}}\middle|T_{\mathrm{j}}\right)p\left(T_{\mathrm{i}}\right)\left(MB\middle|E_{i}\right)}{p\left(E_{\mathrm{i}}\right)}-\left(1-MB\middle|E_{i}\right)p\left(M_{\mathrm{j}}\right) \qquad (2)$$

The second point has to do with whether or not the assignment can be made with confidence. Essentially, the most likely setting is the one with the highest probability. For this assignment to be made with confidence, the value of this probability has to lie above a statistically determined threshold.

Now consider the situation at the time of the Penrose ophiolite definition. Essentially, the database at the time comprised only three potential settings for creating oceanic igneous crust: mid-ocean ridge, island arc, and oceanic island.

The knowledge base in the 1960s comprised crustal structure, the sheeted dike evidence for extension, and the rock associations. If all existed (as in completely developed ophiolites, such as the Troodos Massif), a mid-ocean origin was reasonable and inevitable. If only some components were present (as in some fragmentary ophiolites), then the overall probability may not exceed the threshold, so that the conclusion may not be made with confidence. If pieces of evidence were present but in a state that they had to be inferred (as in other fragmentary ophiolites), then a mid-ocean ridge origin was possible only if the MB of the various pieces of evidence were high.

When geochemistry became available (in the 1970s), ophiolites such as the Troodos Massif gave mixed signals. Geological evidence gave highest probabilities for the mid-ocean ridge setting, whereas geochemical evidence gave the highest probability to the island arc setting. In detail, this should mean that no overall probability would exceed the threshold, so that no definite conclusion could be made. However, measure of belief, subjectively applied, could become highly significant. If a geologist could set the MB of the geochemical evidence to 0, but the MB of geological evidence to 1, then a mid-ocean ridge origin possible. Similarly, a geochemist could set the MB of the geological evidence to 0, but the MB of geochemical evidence to 1, so making an island arc origin possible. This, of course, is the essence of the Troodos controversy, with two groups questioning the validity of the evidence used by the other.

The problem was that the tripartite division of tectonic settings did not fully describe the possibilities. By 1975, the knowledge base had increased and the possible settings had become four: mid-ocean ridge, island arc, oceanic island, and marginal basin ridge.

Essentially, the marginal basin setting would have similar probabilities to mid-ocean ridges for geological pieces of evidence, but probabilities overlapping those of island arcs for geochemical lines of evidence. Thus, an ophiolite with ridge geology and arc geochemistry could exceed the probability threshold as a marginal basin ophiolite. Even so, the controversy could (and, to a certain extent still does) continue for anybody wishing to set a low MB for some of the lines of evidence. It could also reasonably continue for ophiolites for which the geochemical signals were insufficiently strong (such as the Semail ophiolite) and those that were too fragmentary for confident application of geological criteria.

In detail, however, this was not efficient. A marginal basin ridge could chemically span the spectrum of compositions from arcs (if subduction-zone influenced) to ridges (if not subduction-zone influenced). A much more effective discrimination thus is achieved by making a further subdivision of magma types into MORB ridge, SSZ ridge, island arc, and oceanic island.

This was the effective recommendation of the Pearce et al. (1984a) paper. By this time, too, the knowledge base had increased enough that the petrology and geochemistry of all components of the ophiolite sequence could be used in the discrimination.

The post-1984 work then focused on whether the MORB ridge and SSZ ridge could be subdivided in a way that would improve decision-making. This work has made it possible to define tectonic settings as:

<table>
<tr><th>MORB ridge</th><th>SSZ ridge</th></tr>
<tr><td>Major ocean</td><td>Subduction initiation</td></tr>
<tr><td>Ocean margin</td><td>Subduction beneath a ridge</td></tr>
<tr><td>Plume-influenced ridge</td><td>Attenuated arc</td></tr>
<tr><td colspan="2">Back-arc basin</td></tr>
<tr><td colspan="2">Ridge subduction</td></tr>
<tr><td colspan="2">Oblique subduction</td></tr>
</table>

Clearly, however, neither geochemistry alone nor the combination of geology and geochemistry can always separate these settings at above-threshold probability. The aim must still be to recognize the SSZ characteristics and then examine the petrogenesis and geological setting in some detail to make the final assignment.

SUMMARY

1. The concept of ophiolite formation in marginal basin settings was first proposed by Dewey and Bird in 1971. They presented a set of geological criteria for distinguishing ophiolites formed in marginal basin ridges from those formed at mid-ocean ridges.

2. The use of immobile elements to fingerprint ophiolites began with Cann (1970) and continued with Pearce and Cann (1971, 1973). The projections used at the time had a large overlap between island arc and mid-ocean ridge basalts, and so did not contradict a mid-ocean ridge origin for ophiolites.

3. The first use of geochemical criteria to demonstrate a subduction-related setting was that of Miyashiro (1973), who proposed an island arc origin for the Troodos Massif, on the basis of major element fractionation trends. This attracted much criticism because of the absence of geological evidence and fact that his criteria were sensitive to weathering and metamorphism.

4. Improvements in immobile element discrimination supported and extended many geochemical aspects of Miyashiro assertion. However, they did not explain how a fully developed ophiolite such as the Troodos Massif could have subduction-zone geochemistry but ocean-crust structure and no associated arc or arc-derived sediments. It led to the inference that the Troodos Massif and comparable ophiolites formed in a marginal basin setting. Even so, debate continued because of the absence of a modern analogue.

5. Exploration of marginal basins in the late 1970s helped locate these potential analogues. Back-arc basins continued to yield rocks with compositions close to those of mid-ocean ridges, with the notable exception of East Scotia Sea Site 24. More significantly, the RV *Dimitry Mendeleev* cruise and drilling on DSDP Legs 59 and 60 recovered all components of the ophiolite section from the Tonga and Mariana fore-arcs—and these had the necessary subduction signature. They also recovered the first boninites from the ocean floor, which led to the recognition of the essential link between fore-arcs, boninites, and oceanic crust with subduction characteristics.

6. By the early 1980s, accumulation of petrologic and geochemical data had demonstrated that there were two principal types of ophiolites, one with subduction geochemistry, early crystallization of clinopyroxene, and harzburgitic residual mantle, and another with MORB geochemistry, early crystallization of plagioclase, and lherzolitic-harzburgitic residual mantle. Most differences could be explained by the subduction influence on magma genesis: addition of subduction-mobile elements, increased fluid-induced melting, and increased oxygen fugacity.

7. The term "supra-subduction zone (SSZ) ophiolites" was devised to describe the larger group because, although the geochemical and petrological link to subduction was evident, the

precise setting was rarely clear. Moreover, terms such as "arc-related" did not take into account the observation that oceanic crust with a subduction signature could exist without any associated arc. This definition, published in 1984 at the same time as a number of equivalent syntheses, is an important landmark in the evolution of ideas on ophiolites. Before 1984, the emphasis was on debating and establishing the subduction link to ophiolites. After 1984, the emphasis was on establishing the precise settings in which SSZ ophiolites form, and the mechanisms by which they do so.

8. Subduction initiation soon became the setting of choice for deriving many of the SSZ ophiolites. The principal question was the precise mechanism. The absence of relict crust between the ophiolite and the trench favors a model in which spreading takes place near the trench itself. Two models were proposed and investigated: subduction initiation at an active ridge-transform system, and subduction initiation at a transform separating young and old oceanic lithosphere. In the type example of the Izu-Bonin-Mariana system, data favors the second of the two models, hence the mechanism for ophiolite formation summarized by Stern and Bloomer in 1992.

9. Subduction initiation did not emerge as the only mechanism for producing oceanic lithosphere in a fore-arc-type setting. Ridge-trench intersections can achieve this, either by subduction beneath a ridge or subduction of a ridge. Other settings hitherto unconsidered also were proposed, including oblique subduction and attenuation of arc lithosphere at the margins of back-arc basins.

10. A recent synthesis by Shervais (2000) demonstrates how those SSZ ophiolites formed by subduction initiation in fore-arcs can be considered to follow a "life cycle" from birth, through youth, maturity, and death, to resurrection.

11. Evolution of ideas can be considered in both a Kuhnian and Bayesian context. From a Kuhnian perspective, the definition of SSZ ophiolites was the final event in a paradigm shift that depended on a series of advances in geochemistry, marginal basin exploration, and land-based geology. This paradigm shift—from ophiolites as fragments of lithosphere created at mid-ocean ridges to lithosphere created mainly at a variety of subduction-related settings (some with no Recent analogues)—took ~10 years to achieve. From a Bayesian perspective, the assignment of an ophiolite to its correct tectonic setting is a question of probabilities, in which the necessary and correct knowledge base and decision-making apparatus has to evolve before the probability of assignment can exceed the decision-making threshold and give a robust interpretation.

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I thank the many ophiolite workers, geochemists, and marine geologists with whom I have discussed ophiolite problems over the past 30 years. In writing this review, I have attempted to be objective in acknowledging the achievements of all people and groups involved, but there are only so many references I can cite and I cannot fully submerge my personal perspective. I therefore take this opportunity to acknowledge the work of numerous scientists not mentioned here who have contributed to the development of ideas on ophiolites and their relationship to subduction zones. I am also grateful to Yildirim Dilek, John Shervais, Paul Robinson, and Bob Stern for their constructive comments. This is contribution 5, School of Earth, Ocean, and Planetary Sciences, Cardiff University.

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