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Ophiolites, historical contingency, and the Wilson cycle

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Historical explanations take the form of narrative: E, the phenomenon to be explained, arose because D came before, preceded by C, B, and A. If any of these earlier stages had not occurred, or had transpired in a different way, then E would not exist (or would be present in a substantially altered form, E′, requiring a different explanation). Thus, E makes sense and can be explained rigorously as the outcome of A through D. But no law of nature enjoined E; any variant E arising from an altered set of antecedents, would have been equally explicable, though massively different in form and effect. I am not speaking of randomness (for E had to arise, as a consequence of A though D), but of the central principle of all history—contingency. A historical explanation does not rest on direct deduction from laws of nature, but on an unpredictable sequence of antecedent states, where any major change in any step of the sequence would have altered the final result. This final result is therefore dependent, or contingent, upon everything that came before—the unerasable and determining signature of history. (S.J. Gould, 1989, p. 283)

ABSTRACT

Lithologic assemblages termed "ophiolites" were at the heart of the mid-twentieth century "plate tectonics" paradigm shift when they were widely accepted as representing sections of the oceanic crust created during the early stages of "Wilson cycles." However, the past four decades have seen lengthy, if acrimonious, debates about this enigmatic phenomenon, fueled by a growing body of evidence for their association with processes of lithosphere subduction. Today, the core of the debate continues to be the coexistence of structural evidence for seafloor spreading and the chemical and petrographic signatures of subduction. More recently, the discussions have acquired a philosophical flavor, following the suggestion that a "historically contingent" model could allow subduction-related geochemical indications to be reconciled with processes at active mid-ocean ridges. Offering powerful, if not controversial insights into the nature of biological and cultural change, historical contingency is an appropriate context for resolving dilemmas in interpreting earth history, including the subject of this paper, the so-called ophiolite conundrum. Here, an actualistic model for Tethyan ophiolites is offered for testing against the geological record and contingent factors absent or underrepresented today. The model is based on processes observed in the Mediterranean and western Pacific regions and is developed on the premise that "proto-ophiolites" form as accreting forearc complexes during sub-cycles of basin opening and arc-trench rollback in closing, pre-collision stages of Wilson cycles. Rollback appears to be triggered by spontaneous subduction nucleation and may be driven by lateral mantle flow. If a rollback episode successfully evades the "jaws" of a plate collision (as observed in the western Pacific), forearc accretion may proceed indefinitely or until mantle flow dissipates. On the other hand, entrapped by a continental plate collision, forearcs are preferentially preserved in an ensuing orogeny, given their relative buoyancy relative to conjugate backarc basin

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lithosphere. The case for studying the ophiolite conundrum from a historically contingent perspective is supported in principle, but remains accountable to petrologic constraints and evidence from the geological record.

Keywords: ophiolite, Wilson cycle, mantle, subduction zone, back-arc basin, plate collision, earth history.

INTRODUCTION

Hailed in the 1960s as one of several keys to validating the plate tectonics hypothesis, ophiolites are still considered by many as an unresolved enigma. A substantial amount of circular reasoning has dogged their study, reflecting both a skewed attention to the evidence and some basic philosophical differences. On the assumption that ophiolites represent oceanic crust, they were adopted as a model template for interpreting mid-ocean ridge dynamics and petrogenesis (Gass, 1968; Moores et al., 1968; Moores and Vine, 1971; Moores, 1974, 1982a; Nicolas and Violette, 1982). While this view persists, with substantial justification (Nicolas, 1997; Dilek et al., 1999; Benoit et al., 1999, Moores et al., 2000; Nicolas and Boudier, 2000), it had met nevertheless with serious difficulties in the mid-1970s, as the expanding database revealed key differences between ophiolites and typical sections of oceanic crust. The first of these, a series of prescient observations by Miyashiro (1973, 1975a, b, c), was that calcalkaline lithologies are a common component of ophiolites, evidence for subduction-related affinity that was initially downplayed or rejected outright by "ocean crust" protagonists (Gass et al., 1975; Moores, 1975; Hynes, 1975; cf. Miyashiro, 1977).

Further misgivings followed the revelations of early age-dating studies (e.g., Dallmeyer and Williams, 1975; Lanphere et al., 1975) and were reinforced by later research (e.g., Hacker, 1994; Parlak and Delaloye, 1999; Bill et al., 2001; Corfield et al., 2001; Costa and Caby, 2001; Dimo-Lahitte et al., 2001), that ophiolites were formed only a few million years prior to their emplacement, suggesting they may have been generated in marginal basins at later rather than early stages of ocean basin opening. By the early 1980s, a growing consensus seemed able to accept the existence of both "oceanic" and "supra-subduction" ophiolites as the rule, rather than the exception (Pearce et al., 1981, 1984), leading to what Moores et al. (2000) refer to as the "ophiolite conundrum." Debate concerning their relative significance continues with relatively little sign of consensus.

At the present time, the conundrum is best summed up as the problem posed by the coexisting structural evidence for seafloor spreading, imbricated pillow lava and plutonic sequences, sheeted dike complexes that are unambiguously associated with extensional tectonics, and show the chemical and petrographic indications of subduction-related magmatism—enrichments in H_2O and large-ion lithosphile element (LILE), depletions in high-field strength elements (HFSE), calcalkaline lithologies, and refractory mantle sequences, all of which are exclusive to compressive, subduction-related plate margin environments. However, while the majority of ophiolite specialists probably accept a generic association of ophiolites with convergent plate margins, ascribing their "oceanic" attributes to seafloor spreading in marginal basin settings (see Höck et al., 2002), Moores et al. (2000) appealed to the notion of historical contingency, a compelling view of biological evolution (Gould, 1990), to lend much-needed weight to the exclusively mid-ocean ridge ophiolite model.

CHANGING VIEWS OF EARTH HISTORY

The relationship between natural order and history has fascinated scholars since classical times. It was, however, the theories of William Smith, James Hutton, and Charles Darwin that laid the basis for a conceptual revolution that led to modern views of earth history. Smith's "Statigraphic Principle" embodied in his geological map of England and Wales and part of Scotland, published in 1815, and Hutton's "Principle of Uniformitarianism" (codified as "the present is the key to the past" with "no vestige of a beginning, no vestige of an end," published in his *Theory of the Earth* in 1795) provided the intellectual bedrock for Charles Darwin's theory, "The Evolution of Species" (1857) and, eventually, Alfred Wegener's "Theory of Continental Drift" (1912). In each case, these profoundly radical proposals were the cause of considerable pain among contemporary thinkers and, as with most intellectual paradigm shifts, the principal source of pain was resistance to the particular notion in question. While uniformitarianism is a truism for the physical sciences, it remains an important "law" in modern geoscience. At the Royal Society of Edinburgh, Hutton contended that catastrophic happenings were not responsible for Earth's landforms, which he believed had developed over unimaginable periods of time through a variety of slow processes. Above all, he rejected contemporary biblical interpretations that viewed Earth as having been created supernaturally via catastrophic events such as the biblical Flood.

Despite the lack of enthusiasm for uniformitarianism among Hutton's peers, Sir Charles Lyell published his "Principles of Geology" (1830–1833), a compendium of compelling geological evidence from the British Isles and Europe that supported Hutton's ideas. It was, moreover, implicit in Darwin's proposal that the diversity of Earth's biota results from the uniform modification of genetic traits over long periods of time. Darwin's theory evolved along two divergent paths, however, each offering potentially radical perspectives for the interpretation of earth history. The first of these, historical contingency, describes how the historical particulars of a given group of biological entities have influenced their current diversity in lineage and form, as explored through the use of phylogenetic inference. The second approach invokes "generative constraints" that affect ontogenetic process (how entities are made) and constrains the possible realizations of form, as explored through developmental biology and, more recently, studies of protein structure.

In the earth sciences, by analogy, generative constraints may be taken to be equivalent to explaining phenomena in terms of mineralogy and crystal chemistry (bonding, ligand fields, atomic site occupancies, and so on), while historical contingency can be considered as a modifier to the uniformitarian view that clearly dominated Darwin's thinking. Perhaps the most salutary example was provided by Gould (1989), who proposed that biota preserved in the Burgess Shale, British Columbia, provide a perfect illustration of the contingency challenge to Darwinian evolution, and observed that, in his view, the history of life records a "staggeringly improbable series of events, sensible enough in retrospect and subject to rigorous explanation, but utterly unpredictable and quite unrepeatable" (p. 289–290)—a far cry from Darwin's vision of inherent predictability, so dear to the ordered philosophies of the nineteenth century.

Today, the inherent unpredictability of scientific progress is self-evident and in essence conforms to Gould's perception of organic evolution. Whether such a perspective is helpful in explaining earth evolution as a whole depends on the extent to which the "fundamental laws" of our geological forefathers faithfully pre-ordain the geological record. In other words, can we view the development of our planet as a series of "staggeringly improbable" events, "utterly unpredictable and quite unrepeatable," but "explicable in retrospect," or should this view be subordinated to, or at least integrated with, the principles upon which Darwin's theory was constructed? A fundamental tenet of contingency theory is that an interpretative context is rarely that of an opposing interpretation. For example, conflict between catastrophists and uniformitarians in the early nineteenth century is redundant if the agreed context is a dynamic Earth as an interactive component in an evolving solar system. Historical contingency and classic uniformitarianism may therefore be compatible if they share the same contextual parameters. For most earth scientists today, these include the laws of thermodynamics, kinetics, and radioactive decay, along with the apparent tendency of our planet to behave as a self-regulating, steady-state system, rather than (in geological terms) a "runaway" chain reaction. If, on the other hand, earth evolution is viewed as inherently catastrophic, the effects of unpredicted (and unpredictable) events clearly outweigh those implied by conventional uniformitarian models. In either case, actualistic models developed on the basis of active geodynamic processes, in conjunction with experimental and theoretical insights, are still amenable to testing against the geological record and remain a valid approach to studying earth history. If such models are successful, a meaningful context probably exists for identifying and evaluating historically contingent factors. Alternatively, they can be reconfigured according to new contextual parameters if they fail.

In a seminal paper, Moores et al. (2000) addressed the ophiolite conundrum with a view toward reconciling ophiolite genesis with processes that characterize the global mid-ocean ridge system. Contending that debate of the conundrum hitherto has ignored historical contingency, Moores et al. (2000) observed that a correct interpretation of geochemical source "signatures" in mid-ocean ridge magmas is fundamentally contingent on prior histories of mantle convection and lithospheric plate motions, which vary *a priori* with time. Accordingly, they cite incidences of ridge subduction and the propagation of spreading centers into regions affected by subduction, and proposed that magmatic sources of apparent supra-subduction affinity may be tapped by ocean ridges along with those more familiarly characterized by mid-ocean ridge basalt (MORB) and rarely, oceanic island basalt (OIB). They further argue that ophiolites showing structural evidence for seafloor spreading should be interpreted as such, regardless of apparent indications of geochemical "fingerprints" (Pearce, 1991; Pearce et al., 1992b), the latter being explicable by a variety of contingent factors. In the present paper, the ophiolite conundrum is further scrutinized as a basis for evaluating historical contingency and the extent to which it qualifies conventional uniformitarian approaches.

AN ACTUALISTIC MODEL

Mantle Flow and the Wilson Cycle

The Wilson cycle was proposed as a way to explain opening and closing phases of ocean basins throughout earth history, in terms of: (1) continental breakup in response to subcratonic asthenosphere upwelling; (2) subsidence and sediment accumulation at thinned passive margins with the inception of seafloor spreading; (3) continued seafloor spreading on a scale comparable to that of the Atlantic, Pacific, and Indian oceans; (4) subduction inception within the basin itself or at one of its passive margins in response to distal plate collisions; (5) the consumption of remnant oceanic lithosphere by subduction, with the approach of continental plates; and (6) orogeny and ophiolite emplacement following continent-continent collision (e.g., Casey and Dewey, 1984) (Fig. 1). Wilson cycles are generally assumed to be driven by a combination of global-scale mantle convection and the effects of "slab pull" forces, as inferred from the near-contemporaneous development of the American cordilleras with opening of the Atlantic Ocean and their colinearity with the Mid-Atlantic Ridge (e.g., Russo and Silver, 1996). While studies of ophiolitic bodies played a significant part in validating Wilson cycles (Casey and Dewey, 1984; Robertson, 1994; Xiao et al., 2000), it was assumed that they represent opening, rather than closing, stages of such cycles. Given the factors that appear to preclude an exclusively ocean ridge provenance, the broader significance of ophiolites is still open to question. In fact, mantle convection paths may be quite complex toward the end of a Wilson cycle,

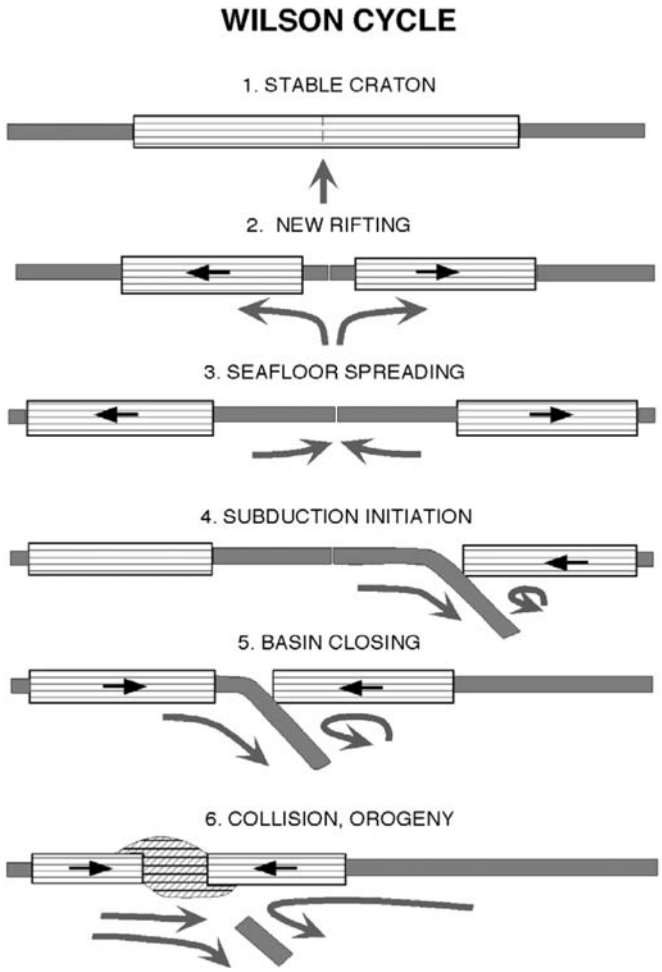

Figure 1. Schematic Wilson cycle stages, simplified from Casey and Dewey, (1984). (1) Breakup of a continent in response to subcratonic asthenosphere upwelling. (2) Rifting and development of thinned passive margins with the inception of seafloor spreading. (3) Continued seafloor spreading on a scale comparable to that of the Atlantic, Pacific, and Indian oceans. (4) The termination of basin opening in response to distal plate collision(s) triggering subduction inception at one or another passive margin. (5) Consumption by subduction of remnant oceanic lithosphere as continental plates converge. (6) Continent-continent collision, leading to orogeny and eventual exhumation and denudation of orogen roots.

when asthenosphere flow may be considered as both a driver of and a passive response to lithospheric plate motions.

This possibility may be considered in relation to collisions of the Afro-Arabian and Indian plates with Eurasia. In both cases, a process of collision-induced mantle perturbation may be inferred from the coupled kinematics of escaping continental lithosphere and newly formed marginal basins, together with spatially- and temporally-related igneous activity. (See discussions by Flower et al., 1998, 2001.) The role of mantle flow is supported by S-wave splitting data (e.g., Yang et al., 1995; Russo and Silver, 1996; Hung and Forsyth, 1999; Murdie and Russo, 1999), seismic tomography (Wortel and Spakman, 2000), and the evidence from isotopic mantle flow tracers (Flower et al., 1998, 2001). It was postulated that the approach to and eventual collision of Arabia and India with Eurasia led to the lateral extrusion of asthenosphere, in turn driving the escape of mobile continental blocks such as Eurasian Sundaland and Anatolia, with conjugate opening of marginal basins (Flower et al., 1998, 2001; cf., Briais et al., 1993; Jolivet and Faccenna, 2000). These "mirror-image" collision responses highlight the broader regional histories of these regions, and suggest that the initiation of subduction and arc-trench rollback intrinsically characterize mantle responses to the closing stages of a Wilson cycle in a constrained spatial-temporal framework.

"Proto-ophiolites" and the Forearc Analog

Because ophiolites appear to show distinctive spatial-temporal correlations with distal plate tectonic events, the question of where "proto-ophiolites" (modern or recently formed ophiolitic assemblages destined to be entrapped in orogens) are formed is fundamental. Following publication of the seafloor spreading hypothesis (Vine and Matthews, 1963), Hess (1965) proposed that ophiolites represent fragments of the oceanic crust, an observation supported by "single-chill" sheeted dikes, pervasive listric faulting, and imbricated pillow lava sequences recorded in the Troodos, Vourinos, and other ophiolites (Gass, 1968; Moores et al., 1968; Moores and Vine, 1971; Moores and Jackson, 1974). This view prevailed until the early 1970s, when the first inklings of a conundrum appeared. Miyashiro (1973) reported that in addition to MORB, calcalkaline magmatic lithologies are widespread in ophiolites, an observation which was initially downplayed and in some cases refuted (e.g., Gass et al., 1975; Hynes, 1975; Miyashiro, 1975a, b, c; Moores, 1975), cf. (Miyashiro, 1973, 1975a, b, c, 1977). In response, it was argued that calcalkaline attributes were probably an artifact of seafloor hydrothermal alteration and therefore not significant (Gass et al., 1975; cf. Pedroni et al., 1999; Gillis and Banerjee, 2000). By the 1980s, however, ocean crust protagonists had conceded ground by accepting that some ophiolites at least may have been generated in subduction-related marginal basins (e.g., Pearce et al., 1984), permitting a partial rapprochement between these positions. This view was supported by observations that MORB-like cumulates and peridotitic melt residua had been intruded or underplated by calcalkaline melts (Pearce et al., 1984; Batanova and Sobolev, 2000), and that ophiolitic lava sequences often grade upward from MORB-like to calcalkaline compositions with little or no eruptive hiatus (Alabaster et al., 1982; Pearce et al., 1984; Smewing et al., 1984).

Reports of ultramafic or strongly mafic boninite eruptives in ophiolite (Cameron et al., 1979; Upadhyay 1980; Capedri et al., 1981; Dobretsov and Kepezhinscas, 1981; Hibbard and Wright, 1982; Barringer, 1983; Walker and Cameron, 1983) were a further challenge because these rocks had hitherto been considered unique to intra-oceanic forearc settings (Cameron et al., 1979). The implication of a forearc analogy proved, however, to be critically significant. Building on the work of Casey and Dewey (1984) and Leitch (1984), Stern and Bloomer (1992) proposed that ophiolites are fundamentally linked to the inception of new subduction, whose magmatic products, typified by boninite, are commonly preserved in the lower parts of forearcs and their conjugate remnants, detached by backarc basin opening (Bloomer et al., 1995; Pearce et al., 1995; Hawkins and Castillo, 1998) (Figs. 2 and 3). On the basis of available information, Stern and Bloomer (1992) observed that ophiolites lack features that *preclude* a forearc analogy, an observation that is as valid today as it was ten years ago.

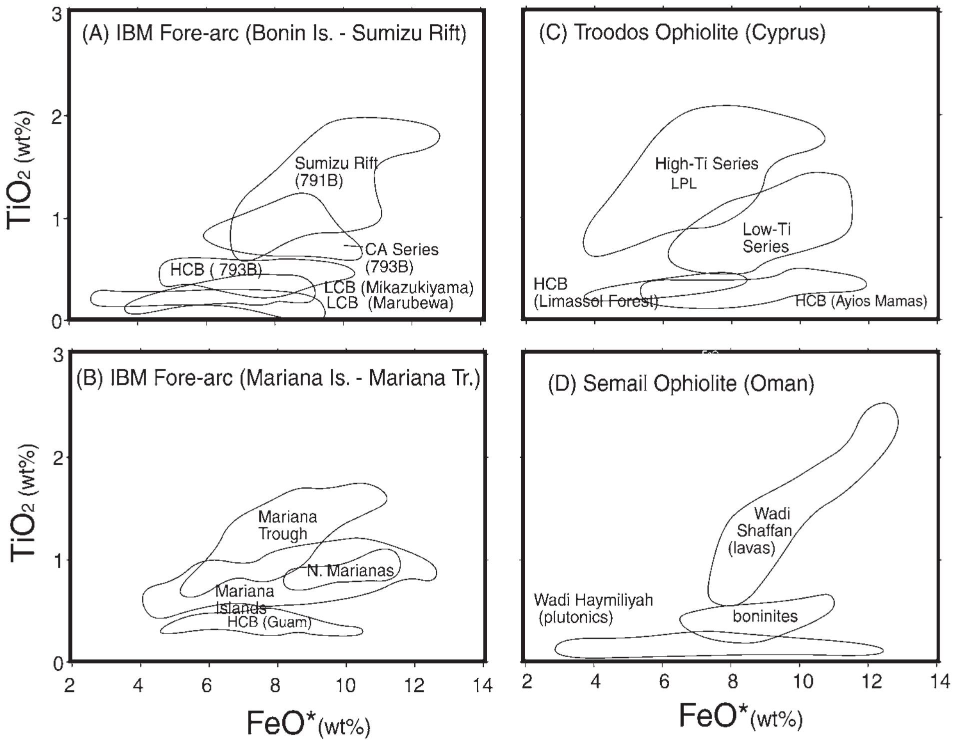

Figure 2. Variation of TiO_2 versus FeO* (in wt%) for eruptive and intrusive lithologies sampled from typical forearcs and ophiolites. (A) Bonin arc-forearc and backarc Sumisu Rift (Izu-Bonin-Mariana system [IBM]) (Pearce et al., 1992a; Taylor et al., 1994). (B) Mariana arc-forearc (Reagan and Meijer, 1984; Stern et al., 1989) and backarc Mariana Trough (Gribble et al., 1998). (C) The Troodos ophiolite, Cyprus (Flower and Levine, 1987; Gibson et al., 1987; Rogers et al., 1989; Bednarz and Schmincke, 1994; Portnyagin et al., 1997). (D) The Semail ophiolite, Oman (Lachize et al., 1996; Einaudi et al., 2000).

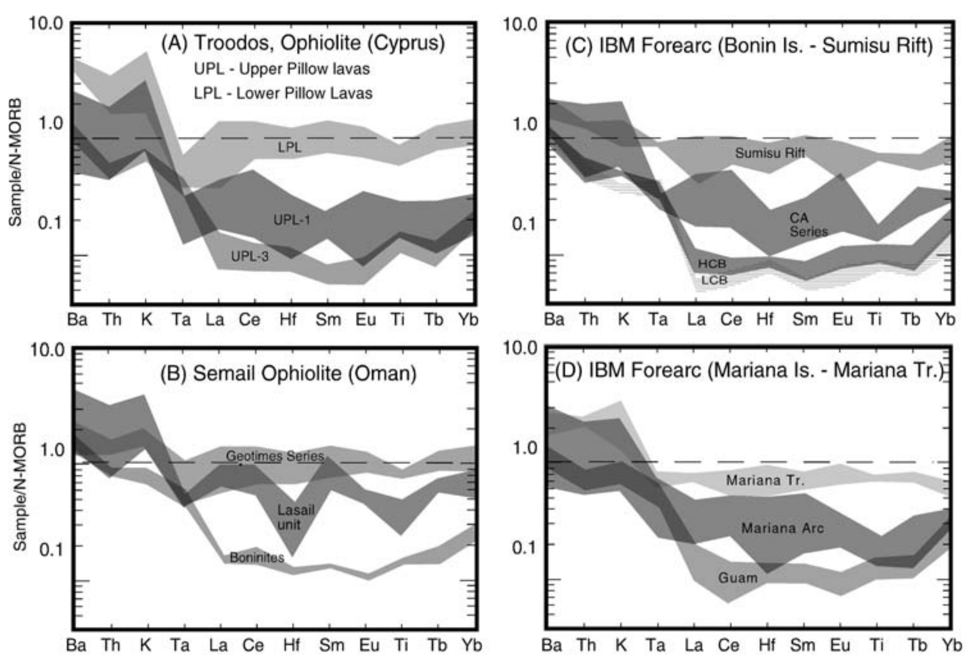

Figure 3. MORB-normalized incompatible element distributions for typical forearc and ophiolite lithologies. A: Troodos ophiolite, Cyprus—Upper Pillow Lavas (series 1 and 3), and Lower Pillow Lavas (Flower and Levine, 1987; Gibson et al, 1987; Rogers et al., 1989; Bedarz and Schminke, 1994; Portnyagin et al., 1996, 1997). B: Semail ophiolite, Oman (Umino et al., 1990; Lachize et al., 1996; Einaudi et al., 2000; Ishikawa et al., 2002). Alley Series volcanics (calcalkaline and boninitic), Geotimes Series volcanics (MORB-type volcanics). C: Izu-Bonin arc-forearc and backarc Sumisu Rift (Izu-Bonin-Mariana system) (Pearce et al., 1992a; Taylor et al., 1994). D: Mariana arc-fore-arc (Reagan and Meijer, 1984; Stern et al., 1989) and backarc Mariana Trough (Gribble et al., 1998).

More recently, Flower et al. (2001) concluded that forearc-like lithologies may range from near-exclusively oceanic types, such as in the western and southwestern Pacific (Stern and Bloomer, 1992; Danyushevsky et al., 1995; Ballantyne, 1991; Ballantyne and Parson, 1992) and the South Sandwich Islands (Pearce et al., 1995), to those in the Mediterranean and Caribbean (Cobiella-Reguera, 1996, 2000; Robertson and Grasso, 1995), which include substantial continental crustal components. Generic forearc components may therefore include MORB basement, boninitic proto-arc (including high-Mg andesite and adakite), calcalkaline arc, MORB-like backarc, and older continental relics. Even where incomplete, such assemblages are commonly juxtaposed with ultra-refractory serpentinized peridotite and other features unique to forearcs, such as serpentinite mud diapirs (Le Pichon et al., 1995a; b; Fryer et al., 2000) and anomalous, high-temperature hydrothermal deposits (Banerjee et al., 2000; Banerjee and Gillis, 2001; Gillis, 2002).

Subduction Rollback in Action

Subduction rollback is conventionally explained as a passive response to down-dip slab compression as determined by the force balance between slab pull, upper plate collision, and "ridge push" effects (Le Pichon et al., 1981). Theoretically, slab-related buoyancy forces exceed those associated with mantle convection, slab motion being largely controlled by its excess density (Royden, 1993a, b). Rollback is expected to continue until oceanic lithosphere input is terminated by the arrival of a continental plate or other obstruction. Most subduction zones behave accordingly, although the slab pull appears insufficient to explain the common coincidence of slab steepening, anomalous arc curvature, and accelerated basin opening. Moreover, the observation that some subducting slabs in Mediterranean and western Pacific arc-backarc systems exhibit tensional rather than compressional stress fields (Seno and Yamanaka, 1998) suggests that slab pull effects are subsidiary to those of trenchward mantle flow (Figs. 4A and 4B). This type of scenario presents a problem for the classic extrusion tectonics model (Tapponnier et al., 1982; 1986), which assumes that basin opening and subduction rollback are passive responses to lithosphere escape (Briais et al., 1993; Le Pichon et al., 1995a; Reilinger et al., 1997). Nevertheless, mantle-driven rollback appears to be the only mechanism capable of explaining the observation that opening of the South China and Aegean Seas began prior to and proceeded at a faster rate than the escape of their conjugate continental blocks (Indochina and Anatolia, respectively) (Seno and Yamanaka, 1998) (Figs 4 and 5).

Rollback cycles in the Mediterranean are relatively short-lived and invariably terminated by the "collapse" (or reconsumption by subduction) of backarc basins following forearc-continent collisions (Royden, 1993a, b; Jolivet and Faccenna, 2000) (Fig. 5). Following the Apulia-Eurasian collision (70–65 Ma), the Betic-Rif, Corsica-Sardinian, Calabrian, and Sicilian terrains were probably bounded by near-continuous, north-vergent subduction that subsequently evolved as discrete rollback episodes (Lonergan and White, 1997; Stampfli et al., 2002). Rollback to the west was probably concomitant with opening of the Alboran

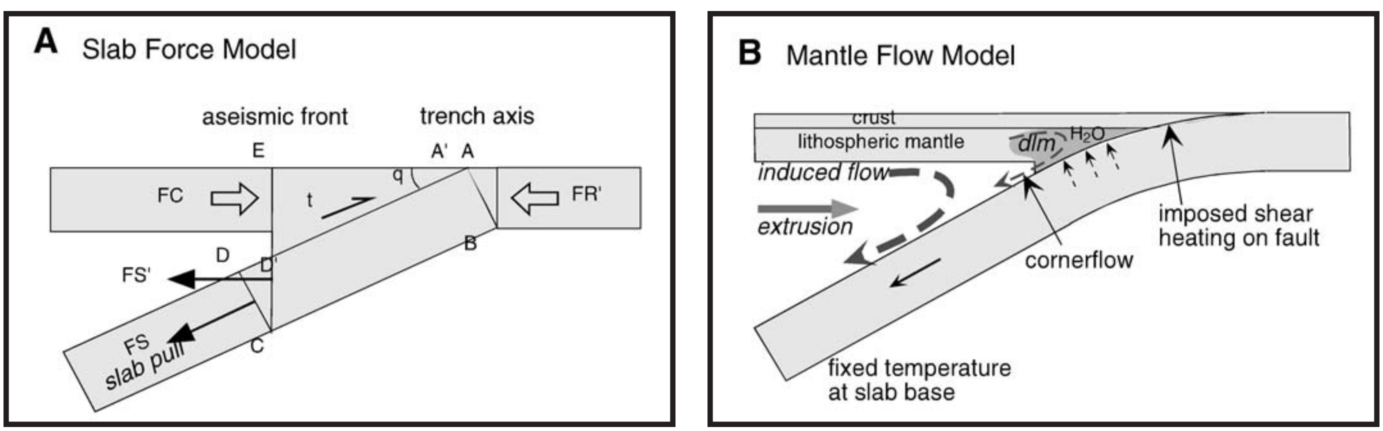

Figure 4. Hypothetical effects of "slab pull" and "mantle extrusion" in retreating arc-trench sectors (examples in Fig. 5). A: Slab force model (after Seno and Yamanaka, 1998). This shows interaction between a subducting slab and overriding plate. Where backarc basin opening represents a passive response to slab-pull effects, the slab shows down-dip compression and arc-trench rollback is relatively slow. However, in cases where basin opening is matched by down-dip extension, as recorded, for example, at the Mariana and Hellenic arcs (Seno and Yamanaka, 1998) (see Fig. 5), rollback is rapid and driven by an exogenous force such as trenchward mantle flow. The dip of the subducting plate is q, AB is the trench axis, and CE the aseismic front. PS′ is the effective ridge push, FS the slab pull, and PC the collision force. FS′ is the horizontal component of traction on CD′ and t is the shear stress at the thrust zone (see Seno and Yamanaka, 1998). B: Mantle flow model 2D (after van Keken et al., 2002). Assuming a constant rate of subduction, two flow filed components are shown: (1) "endogenous" (slab induced), and (2) exogenous (e.g., collision induced). Mantle wedge "cornerflow," combining these elements with ambient shear heating, is believed to allow for delamination of refractory (melt-depleted) lithospheric mantle, fluxed—thereby rheologically altered—by slab-derived fluids. The incorporation of hydrated, refractory peridotite is a potential mechanism, unique to this setting, for generating asthenospheric boninite magma sources (Ngyuyen and Flower, 2003).

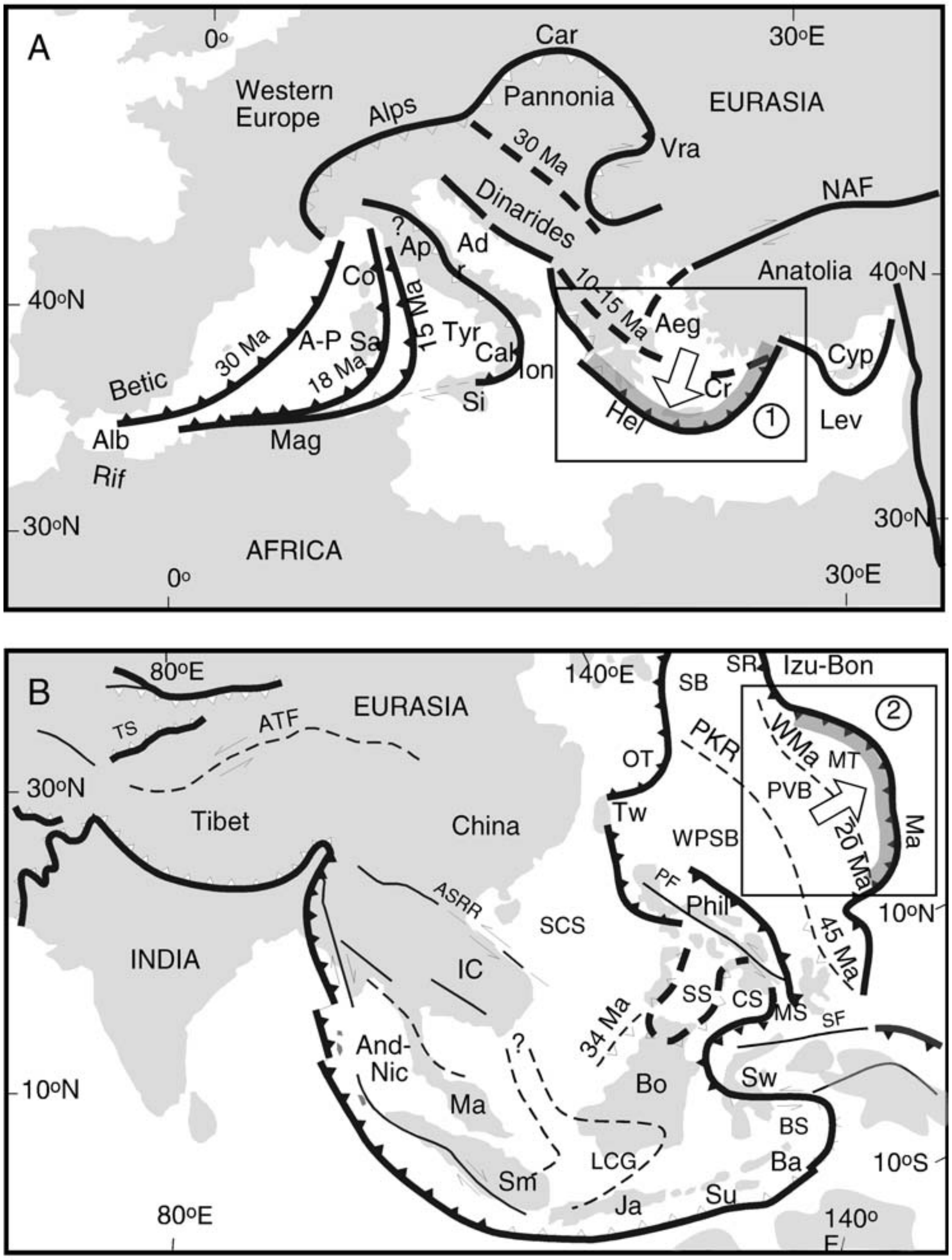

Figure 5. Plate boundary evolution and subduction rollback in active Tethyan domains. (A) The circum-Mediterranean region (after Wortel and Spakman, 2000). Arrows indicate directions of probable slab tearing beneath the Apennine-Calabrian, Hellenic, and Carpathian arcs. Adr—Adriatic Sea, Aeg—Aegean Sea, Alb—Alboran Sea, Ap—Apennines, Cr—Crete, A-P—Algero-Provencal Basin, Bet—Betics, Cal—Calabria, Car—Carpathians, Co—Corsica, Cr—Crete, Cyp—Cyprus, Din—Dinarides, Hel—Hellenic arc/trench, Ion—Ionian Sea, Lev—Levantine Basin, Mag—Maghrebides (from the Rif to Sicily), NAF—North Anatolian Fault, Pan—Pannonian Basin, Rif—Rif, Sa—Sardinia, Si—Sicily, Anat—Anatoia, Tyr—Tyrrhenian Sea. Barbs indicate subduction or thrusting vergence, black suggesting a continuous slab, and white, possible post-collision breakoff. (B) Western Pacific region (after Flower et al., 1998, 2001). Arrows indicate directions of probable slab tearing beneath the Himalayas, Sunda-Banda arcs, and Northern Luzon-Taiwan. TS—Tien Shan, ATF—Altyn Tagh Fault, IC—Indochina, RRF—Red River fault, And-Nic—Andaman-Nicobar Islands, IC—Indochina, Ma—Malay Peninsula, Sm—Sumatra, Bo—Borneo, Ja—Java, Su—Sunda, Ba—Banda, Sw—Sulawesi, Phil—Philippines, Tw—Taiwan, Izu-Bon—Izu-Bonin islands, Ma—Mariana Islands, Wma—West Mariana arc, PKR—Palau-Kyushu ridge, Ru—Ryukyu Islands, SCS—South China Sea, SS—Sulu Sea, CS—Celebes Sea, MS—Molucca Sea, WPSB—West Philippine Sea Basin, BS—Banda Sea, SB—Shikoku Basin, SR—Sumizu Rift, PVB—Parece Vela Basin. Aegean-Hellenic (1) and Izu-Bonin-Mariana (2) rollback systems are indicated (see text; Figs. 4 and 6).

Basin and terminated by collision of the retreating arc with the Betic-Rif system. (Lonergan and White, 1997). Eastward rollback of what became the Apennine-Calabrian arc system occurred in stages with the opening of the Valencia Trough and the Balearic, Algero-Provençal, and Tyrrhenean Sea Basins (Jolivet and Faccenna, 2000). In the eastern Mediterranean, the Cyprus Basin had already begun opening in the Late Jurassic, prior to the Arabia-Eurasia collision, following detachment and northward drift of the Taurus microcontinent. This basin was preserved intact following the post-collision westward escape of Anatolia. Sundering of the Hellenide and Tauride orogens (at 15–10 Ma) led to opening of the Aegean Sea and rollback of Hellenic arc-forearc complexes, with concomitant thinning of continental crust and eventual collision with the approaching African plate. Meanwhile, continued south- and east-vergent subduction of relict oceanic basins led to rapid rollback of the Carpathians and opening of the Pannonian and Transylvanian Basins from 30 Ma to the present.

In contrast, subduction rollback in the western Pacific has been much less constrained by approaching continental plates and continues propagating rapidly to the east (Fig. 5B). Despite controversies regarding kinematic reconstructions of the region, a three-fold scenario for Western Pacific Basin opening is likely: (1) a Paleocene pre-collision stage involving opening of the West Philippine Sea and Celebes Sea Basins; (2) Oligocene to Miocene opening of the South China, Sulu, and Makassar Seas and, to the north and east, the Shikoku and Parece Vela Basins; and (3) a late Miocene to Quaternary stage characterized by opening of the Banda Sea, Okinawa Trough, Mariana Trough, and Andaman Sea. A significant hiatus between the first and second episodes (50–45 Ma) either predates or is contemporaneous with the "hard" collision of India and Asia and a major reorientation of Pacific plate spreading (Lee et al., 1994). A second hiatus (15–10 Ma) appears to match microplate collisions in and around the South China Sea (North Palawan, Reed Bank, Dangerous Grounds) (Pubellier and Cobbold, 1996), while a third (Quaternary) hiatus coincides with consolidation of the Banda Sea (Milsom et al., 1996, 1999); rollback of the Japanese, Izu-Bonin, and west Mariana arcs; initiation of eastward subduction beneath the Philippines and Sulawesi; truncation of the Moluccan Sea (Rangin et al., 1995, 1996, 1999a, b, 2000); the Luzon-Eurasia collision; and the widespread appearance of "dispersed" basaltic volcanism in the western Pacific and in east and southeast Asia (Flower et al., 1998, 2001).

Thus, rollback cycles in active Tethys characteristically begin with splitting of nascent proto-arcs into active and remnant segments that become progressively detached as basin opening and arc rollback proceed, the best example in progress being that of the Izu-Bonin-Mariana (IBM) system in the western Pacific (Figs. 5 and 6). Typically signaled by boninite or high-Mg andesite magmatism (Stern and Bloomer, 1992; Monzier et al., 1993; Sigurdsson et al., 1993; Eissen et al., 1994; Crawford et al., 1997), the initial stages of rollback appear to reflect anomalous mantle thermal conditions (van der Laan et al., 1989; Falloon and Danyushevsky, 2000; Insergueix-Filippi et al., 2000). Rollback is often interrupted by additional arc splitting events, probably

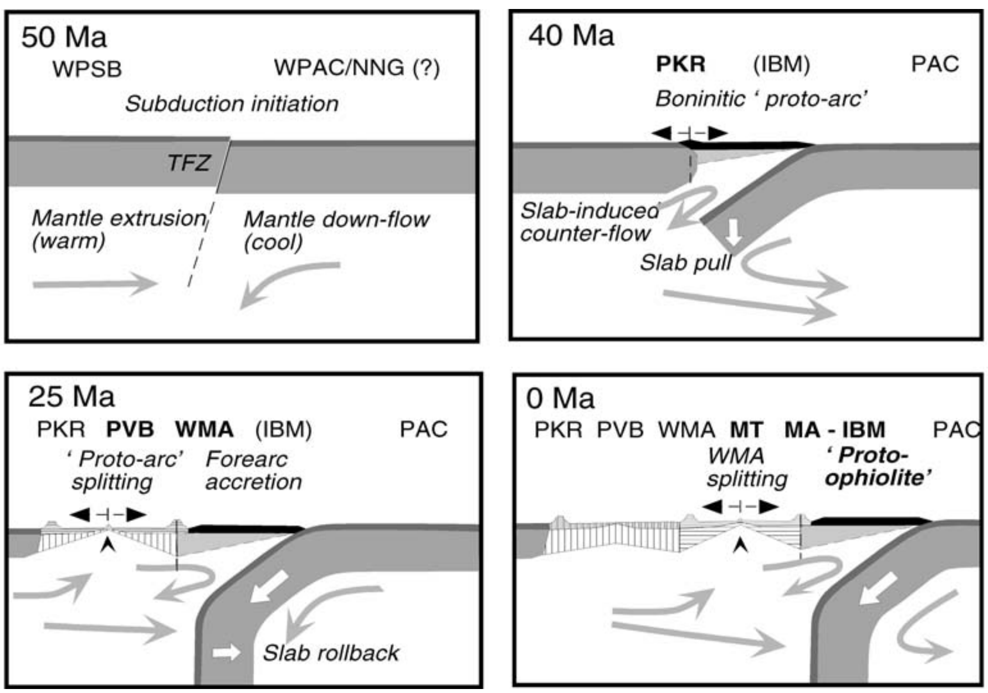

Figure 6. Subduction rollback model, from Bloomer et al. (1995), based on evolution of the IBM forearc and eastern part of the Philippine Sea Plate (following Karig, 1971; Hussong et al., 1981; and Stern and Bloomer, 1992). (A) 50–40 Ma. Subduction initiation beneath West Philippine Sea Basin (WPSB) plate either by the Pacific (PAC) plate or (hypothetical) young North New Guinea (NNG) plate along transform fracture zone in proto-WPSB spreading center. Boninite melt genesis accompanies early forearc development with inception of the calcalkaline arc forming the Palau-Kyushu ridge (PKR). (B) 40–25 Ma. Continued subduction with slab steepening of the Pacific plate, splitting of the Palau-Kyushu arc, Parece Vela Basin (PVB) opening, and rollback of the active West Mariana arc (WMA). (C) 25–0 Ma. Continued subduction, Mariana Trough (MT) opening by splitting of the West Mariana arc, and rollback of the active Mariana arc (MA). (D) 0 Ma. Subduction beneath the modern Mariana arc-trench system with continued MT opening by "unzipping" of the West Mariana-Mariana arc to the north (Iwo Jima). PKR—Palau-Kyushu Ridge, PVB—Parece Vela Basin, WMA—West Mariana Arc, MT—Mariana Trough, MA—Mariana Arc, IBM—Izu-Bonin-Mariana forearc, PAC—Pacific Plate, WPSB—West Philippine Sea Basin, WPAC—Western Pacific, NNG—"North New Guinea" Plate.

in response to plate kinematic adjustments. Evolving forearc terrains thus progressively incorporate proto-arc, arc, backarc, and (in some cases) continental lithosphere fragments (Fig. 6), and may be likened to lithologic "high tide marks" (HTMs), showing large age discrepancies within and between their crust and mantle components (Ishii et al., 1988; Ogawa, 1995; Flower et al., 1998, 2001; Kamp, 1999). If mantle flow is indeed a driver of subduction rollback, the occurrence and spatial-temporal distribution of ophiolites in the geologic record should yield new insights into mantle thermal and dynamic behavior prior to and during plate collisions.

Subduction Nucleation Versus Ridge Subduction

Forearc–Remnant Arc Pairs

The link between ophiolite subduction rollback is further supported by temporal correlations between forearc boninites and their respective proto-arc remnants. Unfortunately, active boninite-high-Mg andesite volcanism is rare, one exception being that occurring at the newly-forming Hunter Ridge proto-arc, located between southernmost Vanuatu (New Hebrides) and the Fiji islands (Falloon and Crawford, 1991; Crawford et al., 1997). Here, boninite-high-Mg andesite activity recently occurred as the southward-propagating North Fiji Basin spreading center became linked by a transform shear zone with newly active subduction (Monzier et al., 1993, 1997); however, numerous examples of coeval boninite and high-Mg andesite in forearc-remnant arc pairs confirm the effects of active rollback in the Mediterranean and western and southwestern Pacific regions (Crawford et al., 1981, 1986). The best-studied example is the Palau-Kyushu Ridge that dissects the Philippine Sea Plate, marking the locus of middle Eocene (50–42 Ma) subduction inception that occurred shortly before the India-Asia collision (45–40 Ma) and reorientation of Pacific Plate motion (ca. 43 Ma) (Stern and Bloomer, 1992; Bloomer et al., 1995; Hawkins and Castillo, 1998). Palau-Kyushu boninites match those in lower horizons of the IBM forearc that conform in all respects to in situ "proto-ophiolites" (Ogawa, 1995; Ishii et al., 1988) (see Figs. 6 and 7).

Similar effects were produced at ca. 25 Ma in the southwestern Pacific by a sharp increase in the angle and rate of Australian convergence with the northwest-moving Pacific Plate (Ballance et al., 1999). Pacific Plate subduction beneath what is now the Lau-Colville Ridge was accompanied by splitting of the Colville and Norfolk-Three Kings proto-arcs, opening of the backarc Norfolk Basin, and relatively rapid (approximately 35 mm/yr^1) eastward retreat of the active Colville-Lau arc (Pearce et al., 1995). While basin opening temporarily ceased at ca. 15 Ma, the newly configured Colville-Coromandel-Taranaki arc was reactivated at ca. 5 Ma and split again, accommodating opening of the Lau-Havre Basin and rollback of the Tonga-Kermadec-Taupo forearc (Ballance et al., 1999).

Mid-Miocene eruptions of high-Mg andesite (ca. 13 Ma) preserved in central and southern parts of the Ryukyu forearc are matched by similar activity in the Fujian-Taiwan region and

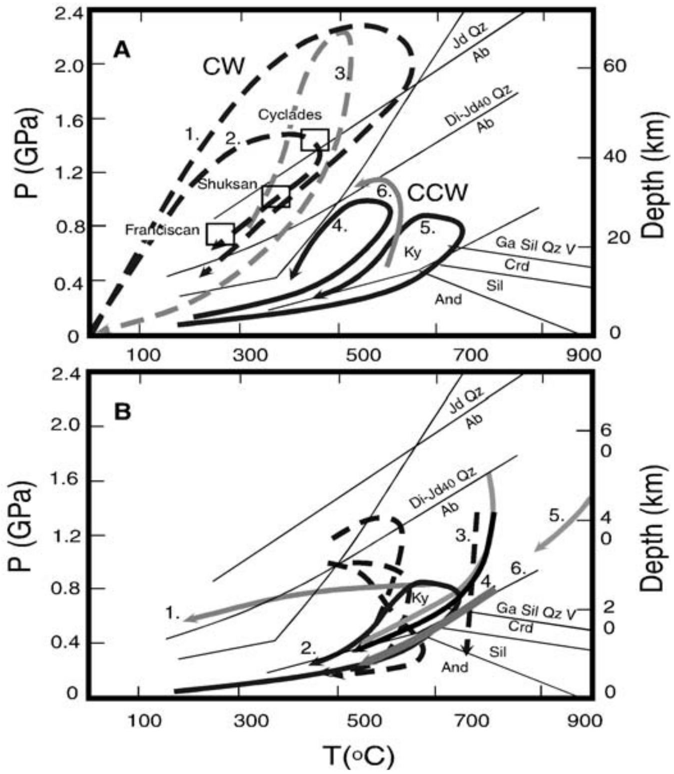

Figure 7. Pressure-temperature-time metamorphic histories in relation to a simplified petrogenetic grid. (A) *P-T*-t curves for sub-ophiolitic metamorphic soles are: 1–5—the Semail ophiolite, Oman (Hacker and Gnos, 1997); 6—the Kiziltepe ophiolite, Turkey (Dilek and Whitney, 1997). Also shown, *P-T* equilibration conditions for ophiolitic blueschist-bearing units from the Shuksan and Franciscan terrains and Cyclades (Aegean) remnant arc. (B) *P-T*-t curves for exhumed post-orogenic peridotites are: 1—the Ronda peridotite (Pearson, 1999), 2—Dabie Shan (Webb and Hacker, 1999).

marks subduction initiation, triggered by collision of the Luzon arc with Eurasia, which led to opening of the Okinawa Trough (Chung et al., 1995; Shinjo, 1999; Shinjo et al., 1999). Similarly, mid-Miocene (14–15 Ma) high-Mg andesite volcanism recorded from the islands of Evia and Skyros between the Hellenic forearc and Cycladean metamorphic core complexes (Lister et al., 1984; Pe-Piper and Piper, 1994; Forster and Lister, 1999; Migiros et al., 2000) corresponds with high-Mg andesite-bearing ophiolite fragments in the Hellenic forearc (Fortuin et al., 1997; Clift and Dixon, 1998). In addition, Oligo-Miocene high-Mg andesite volcanics (ca. 18 Ma) in Sardinia and Corsica, matched by those in Calabrian forearc ophiolite fragments (Beccaluva et al., 1982; Delaloye et al., 1984; Compagnoni et al., 1989), appear to mark proto-arc splitting associated with the inception of Tyrrhenian Sea opening (Morra et al., 1997; Padoa, 1999).

Hot Subduction Initiation

At least two lines of evidence highlight the anomalous thermal character of the mantle associated with subduction nucleation—the presence of boninite and high-Mg andesite eruptives in proto-arc formations, and the inflected "counterclockwise" *P-T*-t histories interpreted from thermobarometric studies of sub-ophiolitic metamorphic "soles" (e.g., Fig. 7). Experimental studies indicate that boninites result from the combined effects of slab-derived fluid flux, mantle decompression, and elevated mantle potential temperatures (van der Laan et al., 1989; Umino and Kushiro, 1989; Falloon and Danushevsky, 2000), consistent with seafloor spreading close to a trench and the coexistence of both upwelling and downwelling asthenosphere (Stern and Bloomer, 1992). Asthenosphere potential temperatures interpolated from H_2O-undersaturated boninite phase equilibria exceed those predicted for "normal" mid-ocean ridges by at least 150–200 °C (van der Laan et al., 1989; Umino and Kushiro, 1989; Falloon and Danyushevsky, 2000), consistent with the conditions simulated by 2D numerical models (Insergueix-Filippi et al., 1998, 2000).

Analogous thermal conditions indicated by thermobarometric data for ophiolite metamorphic soles have been interpreted by some (e.g., Crawford, 2002, personal commun.) to reflect those associated with volcanic passive margin rifting and by others (e.g., Searle and Cox, 1999) MORB-like relics of incipient subduction. Interpolated metamorphic *P-T*-t histories commonly indicate thrusting to depths >60 km with temperature increases to >900 °C, followed by rapid decompression (e.g., curves 4–6, Fig. 7) (e.g., Hacker, 1991; Wakabayashi and Unruh, 1995; Dilek and Whitney, 1997; Hacker and Gnos, 1997; Wakabayashi, 1999; Wakabayashi and Dilek, 2000; Dimo-Lahitte et al., 2001). While some ophiolites slightly post-date their high-temperature soles, most are coeval or slightly older (Parlak and Delaloyne, 1999), consistent with interpretations that sundered forearc and remnant proto-arc components were single entities prior to splitting, and that incipient subduction relics are preserved a priori in forearc proto-ophiolites (Ogawa, 1995; Ishii et al., 1988). Thermochronologic data for metamorphic soles support this model, the best documented examples being the Mirdita ophiolite in Albania (Dimo-Lahitte et al., 2001) and the Semail ophiolite, Oman (e.g., Hacker and Gnos, 1997; Searle and Cox, 1999).

Ridge Subduction

The only serious alternative to subduction initiation is the proposal that ophiolite genesis results from the consumption of recently-active spreading centers at *pre-existing* subduction zones (e.g., Crawford et al., 1986; Hacker and Mosenfelder, 1996; Hacker et al., 1996; Lytwyn et al., 1997). This rests on the presumption that newly formed (<10 my) oceanic lithosphere is too buoyant to be subducted (Cloos et al., 1994) and that high-temperature metamorphic soles represent mid-ocean ridge thermal conditions rather than those associated with "normal" subduction (e.g., Hacker and Mosenfelder, 1996; Hacker et al., 1996). Although the two interpretations are not mutually exclusive, which process dominates appears to hinge on: (1) the bulk compositional character of metamorphic soles, (2) validity of the ophiolite-forearc analog, and (3) possible spatial-temporal correlations between ophiolite formation and regional plate kinematic adjustments. In this light, ridge subduction is the less appealing model, given its absence from currently active rollback episodes. In contrast, several examples of the latter can be shown to have been triggered by subduction nucleation events characterized by boninite or high-Mg andesite volcanism (Lister et al., 1984; Falloon and Crawford, 1991; Stern and Bloomer, 1992; Monzier et al., 1993, 1997; Bloomer et al., 1995; Pe-Piper et al., 1996; Crawford et al., 1997; Hawkins and Castillo, 1998).

The MORB-like compositional character and inflected, counterclockwise *P-T*-t trajectories of many ophiolite metamorphic soles (e.g., Fig. 7, curves 4–6) (Searle and Malpas, 1980; Ghent and Stout, 1981; Malpas and Moores, 1992b; Shallo, 1992; Encarnacion et al., 1995; Hacker and Mosenfelder, 1996; Gnos, 1998; Searle and Cox, 1999; Bebien et al., 2000; Dimo-Lahitte et al., 2001) support the interpretation that they represent relict subducting slab fragments, their relatively steep thermal gradients complementing the inferred association of ultramafic boninite eruptives with fossil transforms, as represented by the Scutari-Pec lineament (Smith and Spray, 1984; Shallo, 1992; Robertson and Shallo, 2000), Arakapas fault zone (Simonian and Gass, 1977; Flower and Levine, 1987; Macleod et al., 1990; Macleod and Murton, 1995), and analogous features in the Semail ophiolite (Smewing, 1981; Boudier et al., 1988; Wakabayashi and Unruh, 1995). Together, both lines of evidence favor the notion that subduction nucleation at near-ridge transform fractures is a common precursor to subduction rollback (Stern and Bloomer, 1992; Monzier et al., 1993; Sigurdsson et al., 1993; Eissen et al., 1994; Crawford et al., 1997).

Subduction Nucleation Models

The underlying causes of subduction inception are also contentious, although critically important to evaluating the significance of ophiolites in the geological record. Is subduction initiated in response to pre-existing lithospheric heterogeneities; is it coupled to mantle flow patterns or thermal character; or does it represent a response to regional plate kinematic changes? If "spontaneous" subduction results from gravitational instabilities associated with pre-existing (e.g., transform) weak zones, a convergent stress field is not a necessary condition. On the other hand, the kinematic responses to distal plate collisions could result in the replacement of an extensional stress field by compression. For any of these cases, however, the observation that proto-arc splitting and backarc basin opening invariably follow subduction initiation events suggests that an overall extensional stress field is inherent, as suggested by Seno and Yamanaka (1998).

Smoot (1997) proposed that subduction nucleation is probably triggered by lithospheric gravitational instabilities resulting from thermal heterogeneities. On the other hand, Niu et al. (2001), citing the exceptionally low densities of refractory forearc peridotite (e.g., Parkinson et al., 1998), suggested compositional rather than thermal buoyancy contrasts may be more significant. While either or both of these factors are plausible, questions still remain as to whether pre-rollback subduction nucleation events are predictable responses to distal plate kinematic adjustments or to changes in the mantle flow field. There is evidence to support both possibilities.

Paleomagnetic data and seafloor magnetic anomaly patterns indicate that compositional boundaries between Indian Ocean and Pacific MORB mantle reservoirs—represented, for example, by the Antarctic-Australia Discordance (AAD) and retreating western Pacific arc systems—reflect a close connection between mantle flow and continental plate motions. DUPAL-like (Indian Ocean type) mantle first appeared following the late Paleozoic disaggregation of Gondwanaland and became the dominant magmatic source as the Tethyan oceans evolved, sharply demarcated from the ambient Atlantic and Pacific mantle reservoirs. As Australia (together with Africa-Arabis, India, and other Gondwana fragments) began its northward motion toward accreting Eurasia, infiltration of Pacific mantle shifted the domain boundary westward (Alvarez, 1990; Christie et al., 1998). To the north, however, as India and Australia approached, and then collided with, southern Eurasia, the domain boundary migrated to the east, as propagating marginal basins and subduction rollback accommodated displaced Indian Ocean mantle (Hickey-Vargas, 1998a, 1998b; Flower et al., 1998).

Despite the absence of active lithosphere subduction at the AAD, the evidence for preferential Pacific margin down-flow suggests that subduction nucleation associated with western and southwestern Pacific rollback episodes may have also occurred at the asthenospheric domain boundaries, implying that mantle flow traction is a significant factor. This does not preclude new subduction being triggered by plate kinematic changes resulting, for example, from collisions between retreating arc-forearc systems prior to their eventual entrapment. Subduction initiation and boninitic proto-arc formation at the Hunter Ridge, at the eastern extremity of the New Hebridies (Falloon and Crawford, 1991), appears to be linked to diachronous evolution of the New Hebrides–North Fiji Basin rollback cycle, initiated following the collision between Ontong Java and the Solomon Islands and interrupted (although not terminated) by collision of the New Hebrides forearc with the d'Entrecasteaux Ridge (Monzier et al., 1993). Following this collision, concomitant subduction and transform fracturing on the southward-propagating North Fiji Basin spreading center (Crawford et al., 1997) accommodates continued arc-forearc retreat (Monzier et al., 1997).

EMPLACEMENT MECHANISMS AND KINEMATIC IMPLICATIONS

The Obduction "Red Herring"

It is commonly remarked that the obduction of newly formed oceanic lithosphere onto passive continental margins (Coleman, 1977; Moores, 1982b; Lippard et al., 1986; Robertson, 1987; Pearce, 1991) is conspicuously absent from Earth at the present time. In contrast, the mantle-driven rollback model implies that ophiolites are emplaced shortly after their formation, following forearc-continent or forearc-forearc collisions, examples of which are briefly reviewed here.

In Kamchatka, lower Eocene oceanic crust and Late Cretaceous boninitic forearc fragments were incorporated during the Oligocene to late Miocene collision with the Aleutian forearc, accompanied by continental subduction, upper plate deformation, and reversed subduction from southeast to northwest (Geist and Scholl, 1994; Geist et al., 1994; Gaedicke et al., 2000). Similarly, the East Taiwan ophiolite was emplaced during diachronous collision between the Luzon arc (Philippine Sea Plate) and continental Eurasia (Teng, 1990; Teng et al., 2000), also interpreted by some (Hsu and Sibuet, 1995; Sibuet and Hsu, 1995) as a forearc-forearc collision with the former Ryukyu subduction system. In the Molucca Sea, a diachronous forearc-forearc collision associated with progressive backarc basin collapse represents the best actualistic example of proto-ophiolite emplacement, a process initiated in Mindanao at 4–5 Ma, between opposite-vergent subduction systems (Moore and Silver, 1983; Lallemand et al., 1998). Prior to ca. 5 Ma, eastern and western Mindanao terrains (respectively of Eurasian and Philippine Mobile Belt affinity) were also separated by collapsing backarc basins, later consumed by dual subduction (Sajona et al., 1994), whereas ophiolites in eastern Mindanao represent a further example of forearc-continent collision (Pubellier et al., 1991, 1999).

Ophiolite emplacement during the diachronous Australia-Sunda collision began at ca. 30 Ma (Audley-Charles et al., 1990; Van Bergen et al., 1993), indentation being initially absorbed by the northern edge, now represented by the Palau-Kyushu Ridge, of what later became the West Philippine Basin, Philippine Sea (Charlton, 2000). An arc-forearc complex destined to form much of the future eastern Philippines, became detached at ca. 24 Ma and removed entirely between ca. 12 and 6 Ma, by left-lateral shearing on the Sorong fault (Charlton et al., 1991a, b). At ca. 18 Ma, subduction initiation in northern New Guinea led to formation of the Maramuni proto-arc. Diverse ophiolites remain in the Sunda-Banda chain, including fragments of Indian Ocean lithosphere as large as the Semail ophiolite, welded to forearcs and commonly thrust over continental Sunda (Harris, 2001).

In western Tethys, as the Mediterranean became "locked" by the collisions of Africa and Arabia with Eurasia, first in southeastern Spain (ca. 30 Ma), then in Iran, marked by the Zagros crush (ca. 25 Ma) (Dewey et al., 1989a, b). Proto-ophiolites became entrapped by the Betic-Rif, Apennine-Calabrian, and Carpathian orogens as rollback was halted by collisions, a process also recorded in the islands of Crete and Cyprus. Metamorphic core complexes and high-Mg andesite eruptives in the Aegean Cyclades (Lister et al., 1984; Pe-Piper et al., 1996) probably represent proto-arc remnants from splitting of the Hellenide orogen (14–15 Ma), analogous to that affecting the Maures Massif that led to the detachment of Corsica-Sardinia (Jolivet et al., 1996, 1998). The Mediterranean Ridge itself evolved as a mud-dominated accretionary wedge (Robertson and Grasso, 1995) becoming trapped at 5–6 Ma, as the Hellenic Arc collided with Africa (Chaumillon and Mascle, 1997).

Analogous basin collapse and forearc collisions had closed the neo-Tethyan Pindos and Antalya Basins by the early Tertiary, the Cyprus Basin (discussed later) surviving into the Quaternary (Eaton and Robertson, 1993). The Africa-Cyprus collision is also very recent, as evidenced by subsidence record of the Eratosthenes Seamount, an inferred crustal fragment immediately to the south of Cyprus, and coupled uplift of the Limassol Forest block (Robertson et al., 1998). Paleomagnetic data indicate that Troodos rotated 90° counterclockwise (Morris et al., 1998), a possible pre-emplacement rollback effect juxtaposing the Arakapas fracture zone against arcuate, strike-slip faults.

Regional Kinematic Implications

The age distributions of Neo-Tethyan ophiolites suggest they belong to discrete temporal clusters, including an Alpine group (200–164 Ma), an "Outer-Hellenic" Pindos-Mirdita group (180–145 Ma), a "Tauride-Zagros" group (98–65 Ma), and a circum-Philippine Sea Plate group (50–43 Ma), etc. (Table 1), conceivably representing discrete subduction initiation-rollback cycles. Gnos et al. (1997), Hall (2002), and others, have observed that ophiolite ages correlate with recorded plate kinematic adjustments, which, in turn, represent regional-scale responses to distal continental splitting and collision events. Although additional paleomagnetic and geochronologic studies are needed to confirm these correlations in much of the Tethyan record, the pattern in active Tethyan regions provides a sufficiently clear basis for developing an actualistic model.

Plate kinematic adjustments in the Western Pacific are recognized at ca. 45, 34, 25, and 5 Ma (e.g., Hall, 2002). Mid-Eocene (50–42 Ma) subduction initiation at the Palau-Kyushu line shortly pre-dated the "hard" collision of India and Eurasia (45–40 Ma) and the ensuing change in Pacific Plate motion (ca. 43 Ma) (Hawkins and Castillo, 1998; Cosca et al., 1998). Construction of the IBM proto-arc began at ca. 50 Ma, giving way to "normal" calcalkaline activity as Pacific Plate motion changed at 42 Ma (Stern and Bloomer, 1992). Ophiolites rimming the Philippine Sea Plate such as the Zambales and Angat in the Philippines, and the ophiolites in Halmahera and northwestern New Guinea (Encarnacion, 1994; Ballantyne and Hall, 1990; Abbott et al., 1994) show similar ages to the IBM proto-ophiolite. Younger ophiolites may also be linked to regional kinematic changes. For example, formation of the late Eocene-early Oligocene (ca. 34 Ma) Palawan ophiolite may correspond to compressional stresses resulting from the coeval initiation of Indochina escape (32–33 Ma) (Leloup et al., 2001) and South China Sea spreading (ca. 30 Ma) (Briais et al., 1993; Encarnacion et al., 2001). Near-coeval formation of the Mindoro and East Taiwan ophiolites, emplaced during the collisions of North Palawan with Mindoro and of the Luzon arc with Eurasia (Rangin et al., 1985) and Mindanao (30–5 Ma) (Sajona et al., 1994), respectively, and those in East Sulawesi (ca. 30 Ma) (Parkinson, 1998), and Antique (Panay) (15–10 Ma) (Tamayo et al., 2001), may also correspond to common regional triggering events, although this is more speculative. A third regional plate kinematic adjustment (ca. 25 Ma) (Hall, 2002) may be

TABLE 1: TETHYAN OPHIOLITE AGES INFERRED FROM RADIOMETRIC AND PALEONTOLOGICAL DATA

Region	Ophiolite body	Time (Ma)
Betic-Calabrian	Betic-Rif	157–145
	Calabria	150–148
	Pyrenees	146–65 ?
Alpine	Balagne Corsica	200–175
	Internal Ligurides	200–165
	Montgenevre Ligurides	198–148
	Eastern Alps	ca. 187
	Ligurides, Corsica	ca. 180
	Queyras, Monte-Viso	175–145
	Gets Nappe	166–165
	Sardinia	ca. 166
Meliata	Meliata-Bodva	160–140
	Meliata-Apuseni	157–140
	Meliata-Pieniny KB	ca. 155
	Meliata-Hallstatt	136–108
Vardar "Inner-Hellenic"	Szarvasko	160–150
	Drina-Ivanjica	157–155
	Kalamaki-Mortero	155–150
	Samothraki, Guevgeli	155–154
	Evros-Lesvos	155–150
	Chalkidiki	150–140
	Makran	156–139
	Masirah	ca. 150
	Zemplen	110–66
Pindos-Mirdita "Outer-Hellenic"	Central Dinarides	190–120
	Albanides	188–168
	Mirdita	175–162
	Pindos	175–155
	Albania	174–160
	Pindos	ca. 165
	Dafnospilia-Kedros	162–153
	Eastern Pontides	160
	Vourinos, Othris	160–145
	Migdhalitsa	160–145
Tauride-Zagros	Zagros	98–75
	Semail	96–85
	Crete	95–75
	Troodos	95–75
	Kutahya	ca. 93
	Mersin	93–92
	Taurides	92–90
	Pozanti-Karsanti	90–94
	Baer-Bassit	90–65
	Central Anatolia	81–65

(*continued*)

TABLE 1: TETHYAN OPHIOLITE AGES INFERRED FROM RADIOMETRIC AND PALEONTOLOGICAL DATA (*continued*)

Region	Ophiolite body	Time (Ma)
Caucasian	Lesser Caucasus	230–225
Ladakh-Tibetan	Ras Koh	ca. 110
	NW Himalaya	ca. 80
	Kohistan	ca. 80
	Muslimbagh	76–65
	Ladakh	ca. 75
	Bela	70–65
	Yarlung-Zangbo	ca. 75
Ailaoshanian	Ailaoshan-Shuangguo Burma-Baoshan	362–328
	Jinshajiang	340–294
	Song Ma	338–290
	Bangxi-Chenxing Hainan	333
Lincangian	Baoshan-Lincang	240
	Yangtze-Lincang	210
Protosundian	Camarines Norte	ca. 140
	Meratus-Bobaris	ca. 140
	E. Sulawesi	140–115
Zambalian	Palau-Kyushu	47–45
	Zambales	50–42
	Angat	50–42
	Halmahera	50–42
Nanhaian	Palawan	ca. 34
	East Taiwan	ca. 34
	Mindoro	ca. 34
Celebian	Mindanao	30–5
	E. Sulawesi	ca. 30
	Antique-Panay	15–10

Note: Source references in Danishwar (2003).

linked to collisions of the New Guinea passive margin with the East Philippines-Halmahera-South Caroline arc system and the Australian (Bird's Head) margin, and a possible combination of factors, including further changes in Pacific Plate motion and arc-continent and arc-arc collisions in the Philippines and Indonesia.

Mesozoic and Paleocene ophiolites in the Philippines that pre-date IBM subduction initiation potentially represent rollback episodes triggered by plate collisions prior to that between India and Asia. For example, the mid to Late Cretaceous Central Cordilleran ophiolite in northern Luzon may share a common provenance with coeval ophiolites in northwestern New Guinea, signalling inception of the (present-day) West Philippine Sea or the Celebes Sea Basin (Leroy et al., 1996). Ophiolites marking distal Philippine Sea Plate boundaries highlight the potential extent and rapidity of collision-induced kinematic changes and the extreme caution required in interpreting the ophiolite record in older orogenic belts.

THE NEO-TETHYAN RECORD: TESTING THE "ROLLBACK" MODEL

The actualistic model developed (Figure 8) is predicated on the forearc analog for proto-ophiolites that is believed to characterize late, pre-collision stages of a Wilson cycle. It is contended that ophiolites represent subduction-resistant forearc assemblages entrapped in orogens following their collisions with other mobile arcs or continental plates. This model is supported by several lines of evidence: (1) the structural, lithologic, and geochemical resemblances of ophiolite to modern forearc and remnant arc terrains; (2) an association of boninitic proto-arcs with fossil transforms and their unique high-temperature character; (3) the evidence for rapid mantle-driven subduction rollback of fragmented successions of proto-arc, arc, and backarc lithosphere; (4) the common presence of relatively unmetamorphosed MORB-like basement (layers 1–4); (5) amphibolite-facies sub-ophiolitic metamorphic soles showing counterclockwise *P-T*-t histories consistent with incipient subduction; (6) age relationships suggesting that ophiolites characterize "late" rather than "early" stages of Wilson cycles (with implications for paleomagnetic plate reconstructions); and (7) the temporal coincidence of ophiolites with local and distal plate kinematic adjustments.

Several additional points may be emphasized. Tethyan ophiolites repeatedly show attributes that are rare or absent from modern spreading centers and "normal" subduction zones, but that are unique to forearcs. Features that preclude the forearc proto-ophiolite analogy have not been reported as yet. The better-preserved ophiolites invariably show developmental trends from mid-ocean ridge- to subduction-related lithologies, evidenced (e.g.) by the intrusion and underplating of lherzolitic mantle and MORB-type plutonics by boninitic and calcalkaline melts and by lava sequences showing the same stratigraphic progression with little or no eruptive break. Relatively untectonized basement sequences show classic ocean ridge attributes such as sheeted dike complexes, *en echelon* gabbroic complexes, and imbricated MORB-like pillow lavas. Below, the model is adopted as a template for interpreting neo-Tethyan ophiolite examples from Liguria, Albania (Mirdita), Cyprus (Troodos), Oman (Semail), and the Philippines (Zambales), pending publication of more detailed, comprehensive evaluations (e.g., Dilek and Flower, 2003). These are briefly reviewed in terms of their lithologic, structural, and geochemical diversity and judged, where possible, according to their internal and external chronological relations.

Liguria

Ophiolites of the Western Alps, Sardinia-Corsica, and the Apennines, that represent the Jurassic-Cretaceous Ligurian ocean, typically comprise small-volume gabbro and basalt sequences with frequent stratigraphic contact of sediments with peridotite or gabbro sequences (Lagabrielle and Lemoine, 1997). Sheeted dike complexes are mostly lacking. Despite the overall MORB-like character of Northern Apennine ophiolites, Os and Nd isotopic

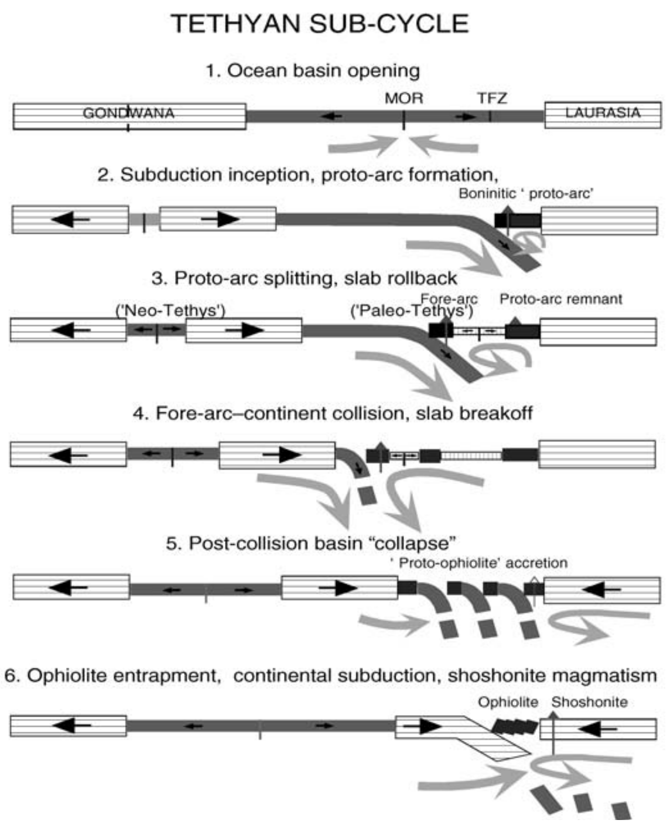

Figure 8. Mantle-driven Tethyan sub-cycle during late (pre-collision) stages of a Wilson cycle (see Fig. 1). (1) Continental plates separate as Paleo-Tethys begins opening; passive asthenosphere upwells beneath spreading axis to produce MORB-like oceanic lithosphere. (2) Laurasia blocks continued Paleotethys opening; new subduction is initiated at weak (e.g., transform) zone, with boninite magmatism forming a proto-arc on the overriding MORB plate, followed by "normal" calcalkaline arc volcanism; neo-Tethyan rifting is initiated in Gondwana. (3) "Cimmeria" microcontinent detaches from Gondwana as Palo-Tethys continues subducting; MORB-like backarc extension and arc-forearc rollback occur in response to the compression of Tethyan asthenosphere beneath Laurasia and Cimmeria. (4) Continued "Cimmerian" microcontinent migration leads to oblique collision and diachronous breakoff of the paleo-Tethyan ocean slab, accompanied by enhanced continental sediment subduction; deflected asthenosphere flow field leads to shoshonite and potassic granite magmatism derived from continent-contaminated asthenosphere. (5) Neo-Tethys continues to open until relict MORB-like backarc lithosphere is completely subducted and progressively detached from the overriding continental plate. (6) Neo-Tethys ceases opening as paleo-Tethyan basin collapse is completed, and new subduction is initiated, mélange of relict arc-forearc-backarc (ophiolite) is entrapped in the ensuing continent-continent orogeny.

compositions of the Liguride peridotites indicate significantly greater depletions than those at modern ridge systems (Rampone et al., 1996; Snow et al., 1996, 2000), while clinopyroxene and whole-rock Sr and Zr depletions relative to REE (Rampone et al., 1996) and a positive Os-Nd isotopic correlation are consistent with the addition of crustal components (Snow et al., 2000). These features led Rampone et al. (1998) and Rampone and Piccardo (2000) to conclude that the Ligurian peridotites represent relict continental lithospheric mantle, attributing its presence to the effects of continental breakup.

An alternative possibility is that, rather than representing a Red Sea–type rifted basin, the presence of refertilized, refractory peridotite may be a sign of incipient subduction that preceded subduction-related proto-arc activity. This interpretation is consistent with the unusually high equilibration temperatures (1150–1250 °C) interpreted for the Liguride peridotites and subsolidus re-equilibration histories that indicate high temperature–low pressure retrograde metamorphism prior their final emplacement (Rampone et al., 1996). It is also supported by the evidence for Jurassic intra-oceanic subduction in Corsican ophiolites and for subsequent (mid-Cretaceous) subduction of the European continental margin beneath the Adria plate (Malavieille et al., 1998). Eocene closure of the remnant Ligurian Basin that separated proto-Corsica from Adria led to a second orogenic phase and the entrapment of unmetamorphosed ophiolites over the previously exhumed (Corsican) high-pressure belt. Malavieille et al. (1998) suggested that this may be a typical effect where a continental collision is preceded by intraoceanic subduction.

Other Liguride remnants, such as the Montgenevre ophiolite in the Western Alps, were relatively unaffected by the Alpine orogeny, and preserve evidence of pre-collision intra-oceanic deformation. MORB-like gabbros yield isochron ages of 198 ± 22 Ma, older than those recorded for other Western Alpine ophiolites (ca. 165 Ma) (Costa and Caby, 2001), but close to 180 Ma ages of eclogitized gabbros from the Ligurides and Corsica. Zircon ages of 156 ± 3 and 148 ± 2 Ma for calcalkaline diorites and plagiogranites that intrude gabbros and peridotites (Costa and Caby, 2001) correlate well with stratigraphic ages (160–140 Ma) of the overlying radiolarian sediments, suggesting a life span for Ligurian ophiolites of up to ca. 30 Ma

Albania (Mirdita)

Mid to Late Jurassic ophiolites in Albania comprise subparallel eastern and western belts overthrust onto the Paleozoic Korabi (Pelagonian) block during Africa-Eurasian plate convergence (Shallo et al., 1987; Shallo, 1992; Hoxha and Boullier, 1995a, 1995b; Nicolas et al., 1999). These ophiolites probably developed within the neo-Tethyan Pindos-Mirdita marginal basin, which propagated northward as the Korabi microcontinent separated from Apulia, eventually becoming trapped by one of several diachronous arc-continent collisions (Robertson and Shallo, 2000).

The western Albanian ophiolites show fertile lherzolitic mantle sections overlain by MORB-like plutonics, sheeted dikes, pillow lavas, and minor plagiogranites (Cortesogno et al., 1998) and underlain by an amphibolite-facies metamorphic sole (Bebien et al., 2000; Dimo-Lahitte et al., 2001). These lithologies resemble those of the MORB-like Alpine-Liguride ophiolites and the Pindos ophiolite to the south, and clearly suggest a mid-ocean ridge provenance (Beccaluva et al., 1994a; Nicolas et al., 1999). In contrast, the "eastern" ophiolites are dominantly calcalkaline in character (e.g., Shebenik, Kukes) and include ultramafic boninites and refractory harzburgitic mantle sections (Hoxha et al., 1993a; Manika et al., 1997) resembling those of the Vourinos and Eastern Othris complexes to the south (Beccaluva et al., 1994b; Bebien et al., 1997); however, the commonly-observed intrusions of calcalkaline and boninite dikes into MORB-like (plagioclase-bearing) plutonic lithologies suggest that both ophiolite types in Albania are closely related (Cortesogno et al., 1998) and reflect the initiation of west-vergent subduction in oceanic lithosphere formed at a recently-active spreading system (e.g., Bebien et al., 1998).

This view is reinforced by the MORB-like character of coeval metamorphic soles (Gjata et al., 1992) which young northward from ca. 174 to 160 Ma (Dimo-Lahitte et al., 2001) and record rapid counterclockwise *P*-*T*-t paths (Gjata et al., 1992; Dimo-Lahitte et al., 2001; Bebien, et al., 2000). Intra-oceanic detachment and ophiolite emplacement were clearly near-contemporaneous with preceding or ongoing seafloor spreading. A fossil transform related to, or at least similar to, the northern Albanian Scutari-Pec lineament, is indicated by anisotropic mantle fabrics in the northern Kukes section, implying that the latter represents the eastern limb of a NNW-SSE fossil spreading axis (Hoxha et al., 1993a, 1993b; Hoxha and Boullier, 1995a, 1995b). Irrespective of whether Pindos-Mirdita was an intra-continental or intra-oceanic basin, there is little doubt that oceanic spreading, unaffected by subduction, characterized its initial development (Beccaluva, 1994; Nicolas et al., 1999). If seafloor spreading was interrupted by newly initiated subduction at a ridge transform, it would appear that the collision of a boninitic proto-arc (or retreating arc-forearc complex) with Pelagonia occurred shortly thereafter. Uplift, fragmentation, and partial burial of the proto-ophiolitic forearc beneath flysch (Shallo, 1992) would have been succeeded in the Eocene-Oligocene by collision between Korabi-Pelagonia and Apulia, at which point the ophiolite was thrust over the Korabi margin.

If this interpretation is correct, the MORB-like "western" ophiolites represent remnants of Pindos-Mirdita oceanic basement, whereas the inception of west-vergent subduction and ensuing development of the near-contemporaneous (162–174 Ma) is recorded by "eastern" ophiolites. The latter may be interpreted as relict proto-arc fragments formed at or close to the Pindos-Mirdita spreading axis, where subduction was nucleated at an active transform fracture zone, possibly represented by the present-day Scutari-Pec lineament (Bebien et al., 2000, Dimo-Lahitte et al., 2001). Their eventual collision with Pelagonia can be ascribed to the collapse (closure) of Pindos-Mirdita, possibly following a sequence of proto-arc splitting and arc-forearc rollback. Subsequent formation of the Periadriatic "foredeep" and Tirana Depression in the Miocene and Plio-Quaternary occurred as the continued convergence of Africa and Eurasia was accommodated by southward rollback of the Hellenic margin (Robertson et al., 1995).

Cyprus (Troodos, Mamonia)

To the south and east, Late Cretaceous ophiolites associated with the Pontide, Anatolide, and Tauride orogenies (Table 1) suggest that analogous conditions prevailed in other neo-Tethyan basins. Of these, the Troodos (Cyprus) and Semail (Oman) ophiolites are the most extensively studied. The Troodos Massif comprises a lithologic "sandwich" of variably refractory peridotite, layered, and massive plutonics, sheeted dikes, and pillow lavas with a pelagic sedimentary carapace (Moores and Vine, 1971; Robinson et al., 1983, 1984; Malpas and Robinson, 1997; Robertson, 1991; Eaton and Robertson, 1993). Age data for plagiogranites (92–90 Ma) (Mukasa and Ludden, 1987) suggest that the ophiolite post-dates the Late Jurassic initiation of Cyprus Basin opening (Garfunkel, 1998), whereas the succession of MORB-like, boninitic, and calcalkaline lithologies is strongly indicative of a forearc provenance. There is no metamorphic sole exposed and the ophiolite is underlain by continental crust (Makris et al., 1983).

Batanova and Sobolev (2000) recognize two distinct mantle sequences, consisting of spinel lherzolite (veined by dunite and clinopyroxene-bearing harzburgite) and refractory, clinopyroxene-poor harzburgite, respectively. The composition of spinel lherzolites suggest they are residual to MORB melt extraction and, while not parental to calcalkaline or boninitic magmas, were probably modified by the latter, as evidenced by veins of dunite and harzburgite (Batanova and Sobolev, 2000). Structural relationships of layered cumulates, massive gabbros, and sheeted dikes (Malpas and Robinson, 1997) suggest that seafloor spreading was largely steady-state (Allerton and Vine, 1987), with periodic shifts in the axial rift (Varga and Moores, 1985). "Lower" and "Upper" pillow lava series record a progression from dominantly MORB-like to calcalkaline and high-Ca boninitic character (Robinson et al., 1983; Schmincke et al., 1983). Hydrothermal deposits include massive sulphides and associated stockworks, often located at the overlying lava-sediment interface (Robertson and Boyle, 1983). Relict fragments of the Cyprus Basin are preserved in the Kyrenia Range in northern Cyprus, bounded on the north by a carbonate platform and on the west and southwest by tectonized MORB-like crust and pelagic sediment, part of the present-day Mamonia Complex (Robertson, 1991; Eaton and Robertson, 1993). The latter was interpreted as a deformed passive margin sequence sutured to Troodos during the Late Cretaceous (Bailey et al., 2000). Detailed mapping and microstructure studies in Mamonia suggest that an episode of pro-grade metamorphism (90–88 Ma) was followed by coeval retrograde hydration and dextral transtension, and serpentinite diapirism (83–73 Ma), prior to its exhumation at ca. 65 Ma (Malpas et al., 1992a).

Evidence for subduction nucleation in southern and southeastern Cyprus includes the presence of accretionary wedge lithologies in the Limassol Forest area (Eaton and Robertson, 1993), and high-Ca boninites associated with the Arakapas fault, a possible fossil transform (e.g., Simonian and Gass, 1977; Flower and Levine, 1987; Rogers et al., 1989; MacLeod and Murton, 1995). Similarities between extensional detachment faults in the Limassol Forest area, immediately south of the Arakapas Fault, and those in the "inside corners" of modern ocean-ridge-transform intersections appear to confirm this interpretation (Cann et al., 2001). Accordingly, the Limassol Forest block would have been formed in the western "inside corner" of the ridge-transform intersect, having spread eastward until it passed a second spreading axis. At this point magmatic crust north of the Arakapas Fault would have become welded to the Limassol Forest block as the fault evolved as a transform fracture zone. While this interpretation is supported by dike orientations by and magmatic and mantle flow fields inferred from rock fabric studies (Abelson et al., 2001, Borradaile and Lagroix, 2001), the evidence of boninite magmatic activity along the Arakapas Fault appears to confirm that a subduction nucleation event was in progress.

Formation of the Troodos ophiolite can be linked to opening of the Cyprus Basin, which began in the Mid to Late Jurassic. Despite continuing convergence of Africa and Eurasia, seafloor spreading in the Cyprus Basin continued into the Late Cretaceous, at which time (92–90 Ma) the Troodos proto-arc was formed in response, presumably, to subduction nucleation at a near-axial transform fracture zone. Proto-arc splitting and rollback of its active portion led to collision of the overriding plate with the Arabian platform at 74–70 Ma (Robertson, 2002) since when, it appears, north-vergent subduction migrated from the evolving proto-ophiolite belt to the northern edge of the basin as the Cyprus Basin began to collapse (Yilmaz, 1993). Meanwhile, the westward escape of Anatolia following the Mid-Cenozoic collision of Arabia with the Cimmerian continent (Sengör et al., 1984) and kinematic constraints imposed by opening of the Aegean Basin (Le Pichon et al., 1981, 2002; Eaton and Robertson, 1993) precluded further collapse of the basin. Such a scenario explains several hitherto-puzzling features—preservation of the Cyprus Basin, the absence of regional emplacement-related deformation in its ophiolitic forearc (Troodos-Mamonia), and the lack of post-Cretaceous magmatism at the present-day plate boundary (Moores and Vine, 1971; Malpas and Robinson, 1997; Robertson, 1991; Eaton and Robertson, 1993).

Oman (Semail)

The neo-Tethyan Semail ophiolite is the largest in the world and probably the best subaerial analog for oceanic lithosphere. There is broad agreement that the petrologic and structural attributes of the Semail ophiolite resemble those of lithosphere formed at a fast-spreading ocean ridge (Pallister and Hopson, 1981; Pallister and Knight, 1981; Pearce et al., 1981, Alabaster et al., 1982; Pallister, 1984; Umino et al., 1990; Nicolas et al., 1994, 1996; Nicolas and Boudier, 1995; Umino, 1995), as exemplified by MORB-like compositions of the Geotimes Volcanic Unit (Pearce et al., 1981; Alabaster et al., 1982; Ernewein et al., 1988; Umino et al., 1990), sheeted dikes (Nicolas and Boudier, 1991), and layered plagioclase-rich gabbros (Pallister and Knight, 1981; Browning, 1984; Benn et al., 1988; Ernewein et al., 1988; Juteau et al., 1988a, b; Nicolas et al., 1988a, b). Jousselin and Mainprice (1998) and Jousselin et al. (1998) corroborated this interpretation with structural data demonstrating the presence of a fossil subaxial mantle diaper. However, further investigation revealed an incipient second developmental stage, evidenced by the intrusion of ultramafic and calcalkaline magmas into MORB-like basement plutonics (Benn et al., 1988; Ernewein et al., 1988; Juteau et al., 1988a, 1988b), the eruption of boninites and calcalkaline tholeiites (Alabaster et al., 1982; Ernewein et al., 1988; Umino et al., 1990; Ishikawa et al., 2002), and subsequent intrusion of calcalkaline plutons, as in the Haylayn Massif and Sumail nappe regions (Pallister and Hopson, 1981; Pallister and Knight, 1981; Benn et al., 1988; Juteau et al., 1988a, b; Lachize et al., 1996; Schiano et al., 1997). The intrusives are mostly (although not always) discordant with older MORB-like layered rocks (Benn et al., 1988; Juteau et al., 1988a, 1988b; Umino, 1995) and comprise a suite of dunite, wehrlite, olivine gabbro, and diorite cumulates, and a series of lherzolite, gabbro-norite, two-pyroxene diorite, and trondhjemite (Umino et al., 1990). Previously interpreted as remobilized melt-cumulate emulsions (Pallister and Knight, 1981), these lithologies appear to reflect boninitic parent magmas (Umino et al., 1990; Schiano et al., 1997; Ishikawa et al., 2002). Evolved calcalkaline rocks also dominate in the succeeding Alley Volcanic Unit (Pearce et al., 1981; Alabaster et al., 1982; Ernewein et al., 1988) complemented by large (up to 10 km^2) intrusions of gabbro, diorite, and trondhjemite (Umino et al., 1990) genetically related to the ultramafic intrusives (Lachize et al., 1996; Schiano et al., 1997). Boninites also appear as lavas and dikes in the Alley volcanic sequence (Umino et al., 1990; Ishikawa et al., 2002), unconformably overlying, and in some cases cross-cutting, the Geotimes unit. The most recent Semail activity produced alkali basalts between ca. 85 and 90 Ma (Lachize et al., 1996).

As elsewhere, the Semail metamorphic sole is MORB-like in character (Searle and Malpas, 1980, 1982; Searle and Cox, 1999) and post-dates the ophiolite by <4 m.y. (Hacker and Gnos, 1997). Its interpolated *P-T*-t path shows peak temperatures of 775–875 °C and pressures of ca. 1.1 GPa, implying a rapid, albeit short-lived, subduction history. To explain these conditions, Boudier et al. (1998) suggested that subduction triggered within ca. 5 m.y. of ridge accretion was a counterpart to the obduction of oceanic lithosphere detached from the dying spreading axis. *P-T*-t paths for sub-ophiolitic continental rocks suggest that the Arabian margin, a potential source for two-mica, garnet-, tourmaline-, cordierite- and andalusite-bearing granites was also subducted to >70 km depth (Searle and Cox, 1999). In summary, it is abundantly clear that the bulk of the Semail ophiolite represents oceanic lithosphere, as contended by Nicolas and coworkers. It seems reasonable to conclude that subduction was initiated at 95–93.8 Ma, as indicated by the appearance of boninite volcanism (Umino et al., 1990; Umino, 1995; Kinoshita et al., 2002) and plagiogranite (adakite) intrusions (Pallister and Knight, 1981; Benn et al., 1988; Searle and Cox, 1999) following the cessation of active spreading. It is unclear whether proto-arc formation led, in turn, to an episode of subduction rollback; however, there is little doubt that calcalkaline magmatism that produced the

Lasail arc edifice ceased at ca. 87 Ma, following collision between the evolving arc-forearc complex and the Arabian continent. This was followed at ca. 85 Ma by subduction (to depths of 78–90 km) of Arabian continental crust, and then by partial melting of subducted, eclogite-facies crust, the latter as evidenced by intrusions of two-mica, cordierite-bearing granites in mantle harzburgite and cumulate sequences between 85 and 76 Ma (Searle and Cox, 1999).

Philippines (Zambales-Angat, Palawan)

The Zambales complex is one of several mid-Eocene ophiolites that rim the Philippine Sea Plate, and comprises several constituent parts (Encarnacion et al., 1993a, 1993b; Encarnacion and Fernandez, 2001). To the north, the Acoje block comprises a boninitic to calcalkaline proto-arc sequence that is bordered to the south by the "transitional MORB"-like Coto block. Farther south, the San Antonio arc terrane is separated from the Coto block by the left-lateral West Luzon shear zone (Evans and Hawkins, 1989; Hawkins 1989, 1993; Evans et al., 1991; Yumul et al., 1998a, 2000; Yumul, 2001; Encarnacion et al., 1999), apparently translated southward from the northern part of the complex (Encarnacion et al., 1993a). The Acoje and Coto blocks (44–45 Ma) appear to be near-coeval with the Angat ophiolite (ca. 48 Ma), 100 km to the east in the southern Sierra Madre, suggesting they shared a common mid-Eocene provenance (Encarnacion et al., 1993a). The recognition of older, Late Cretaceous ophiolitic lithologies southeast of the main Angat body (Encarnacion et al., 1993a) suggests that the Zambales-Angat ophiolites record opening of a backarc basin following the buildup of an Eocene arc that developed on pre-existing Cretaceous basement, and, moreover, that both ophiolites represent autochthonous Luzon basement (Geary et al., 1989; Encarnacion et al., 1993a; Yumul et al., 1998b). Interestingly, the somewhat different petrologic structure of the younger (ca. 34 Ma) ophiolite on the island of Palawan implies a similar pattern. Despite its MORB-like character, upper sequence lavas show incipient calcalkaline affinity, resembling those of peripheral parts of the Mariana and Lau Basins (Encarnacion et al., 1995). The concurrence of ophiolite and metamorphic sole ages (Encarnacion et al., 2001) supports their formation close to a spreading axis while the geochemical evidence for subduction inception is matched by the evidence for subsequent arc splitting and subduction rollback associated with development of the Cagayan-Sulu backarc system (Pubellier et al., 1991; Rangin, 1991; Serri et al., 1991; Spadea et al., 1991).

Similar petrologic-stratigraphic patterns are observed in ophiolites associated with Meso- and Paleo-Tethyan sutures in Central Eurasia, Iran, and Anatolia, and additionally, the Caribbean and Scotia Seas, and many of the older Phanerozoic cordilleras. Significantly, boninitic proto-arc sequences developed on MORB-like basement are recorded from all major Archean greenstone belts (e.g., Bateman and Costa, 2001; Polat and Kerrich, 2001; Parman and Grove, 2001; Puchtel and Brugmann, 2001), reinforcing validity of the subduction initiation-rollback model and the uniformitarian precept on which it is based.

HISTORICAL CONTINGENCY IN PERSPECTIVE

The contention of Moores et al. (2000) that ocean ridge source "signatures" are contingent on mantle convection and plate migration histories is undeniable and, with other factors, requires careful consideration in uniformitarian interpretations; however, despite the recognition of mantle isotopic heterogeneity as convincing evidence for long-term domain mixing, their conclusion that some ophiolites, at least, may be generated at mid-ocean ridges rests on two exceptional present-day cases—the Woodlark Basin, where spreading ridge magmas tapping subduction-contaminated mantle appear to have followed a change in subduction vergence (Perfit et al., 1987; Crawford, 2002, personal commun.), and the South Chile Rise, where a similar effect is produced by active ridge axis subduction (Sturm et al., 2000). It is reasonable to ask whether these and other contingent attributes are: (1) consistent with, even if not currently observed in, present-day proto-ophiolites, and (2) intrinsic to ophiolites through the known geological record. In fact, both of these examples are rare, and at least three obstacles appear to preclude their inclusion in a generic model for ophiolites.

It is hard to reconcile refractory mantle sources capable of yielding calcalkaline and boninitic magmas with mid-ocean ridge spreading systems. At the present time, elevated mantle potential temperatures needed to produce such magmas from their requisite refractory sources (as deduced from experimental studies) are confined to the loci of inferred "plume-ridge" interactions (McKenzie and Bickle, 1988) characterized largely by "fertile" OIB-like mantle source products. The apparently unique association of boninite and high-Mg andesite with initial stages of arc-trench rollback is consistent with the notion that such magmas are incompatible with mid-ocean ridge settings. It is, therefore, reasonable to suggest that while potentially significant, the idea of unpredictable contingencies in earth history need not preclude a uniformitarian approach to studying ophiolites. It is noted, finally, that the continued study of features such as the Woodlark and Mariana backarc spreading centers is likely to yield vital insights related to the development of actualistic subduction rollback models as a basis for interpreting the Tethyan record.

CONCLUSIONS

Geodynamic and petrologic studies in tectonically active sectors of the Tethyan belt suggest that unique combinations of features, rare or absent from ancient and modern mid-ocean ridges or subduction zones, have repeatedly characterized ophiolites for >2.5 b.y. These include basement sequences with typical oceanic crustal features, near-coeval MORB-like, high-temperature metamorphic soles often showing inflected, counterclockwise *P-T*-t paths; boninitic proto-arcs succeeded by calcalkaline and MORB-like eruptive sequences; refractory peridotite; and the associated effects of serpentinitic mud diapirism and high-temperature "epidosites."

Taken together, these features preclude exclusively mid-ocean ridge, "normal" arc, or backarc basin provenance for ophiolites, whereas they uniquely match those of proto-ophiolites in modern forearc settings. These appear to evolve in response to subduction nucleation—often at mid-ocean ridge transforms—signaled by boninitic and related magmatism and high-temperature hydrothermal activity, and to evolve in response to one or more episodes of arc splitting and basin opening.

Subduction nucleation may be triggered by thermal or compositional heterogeneities in the lithosphere or, more plausibly, by temperature differences across asthenospheric domain boundaries. On the other hand, subduction rollback appears to reflect sub-horizontal mantle flow, whether directly in response to collision-induced extrusion, mantle plume upwelling, or accelerated differential plate motion. In most cases rollback episodes are terminated by forearc-forearc and forearc-continent collisions ~10–30 m.y. after their commencement.

If a rollback episode successfully evades orogenic entrapment, proto-ophiolitic forearc accretion may continue indefinitely. On the other hand, if entrapped by a collision following one or more episodes of basin collapse, forearcs tend to resist subduction (in contrast to backarc basin lithosphere) and are readily preserved as ophiolites. It is, therefore, not surprising that the obduction of oceanic crust is absent from modern passive margins.

Ophiolite genesis occurs during "sub-cycles" of basin opening and arc-trench rollback at closing stages of a Wilson cycle. Modern subduction initiation precedes or is near-coeval with "hard" plate collisions and their respective plate kinematic responses. Similar relationships are discernible in Tethyan (and prior) geological record, where temporal correlations may be discerned between ophiolites and distal plate kinematic changes. If—as seems to be the case—traditional ocean ridge and supra-subduction models are only "correct" when considered together, then the ophiolite conundrum is a false dichotomy.

Historical contingency has undeniable potential as an aid to interpreting earth history; however, the Moores et al. (2001) model for ophiolite genesis is in conflict with both *a priori* petrologic constraints and the ophiolite record through geological time. Refractory mantle sources of the type yielding calcalkaline and boninitic magmas at newly-forming convergent plate margins are unlikely to have been generic to mid-ocean ridge settings. Moreover, such near-ubiquitous ophiolite components appear to be exclusive to subduction nucleation stages of rollback cycles. The model also fails because it requires us to believe that only ocean crust formed over previously modified mantle is eligible for emplacement, whether by obduction or other process, while "normal" MORB lithosphere is emplaced in accretionary complexes.

After more than 30 years, the ophiolite conundrum provides a sobering example of how ambient context (the late 1960s paradigm shift of advent of plate tectonic theory) of an observation (the enigma of ophiolites) may determine the rationale for its interpretation (as a model for seafloor spreading, "linchpin" component of plate tectonics). If, as is suggested in this paper, the conundrum is a false dichotomy—if ophiolites intrinsically are *in part* formed at spreading axes and *in part* subduction-related—then we may tentatively conclude that the debate has been fruitful.

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