What constitutes 'emplacement' of an ophiolite?: Mechanisms and relationship to subduction initiation and formation of metamorphic soles

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Abstract: Ophiolites have long been recognized as on-land fragments of fossil oceanic lithosphere, which becomes an ophiolite when incorporated into continental margins through a complex process known as 'emplacement'. A fundamental problem of ophiolite emplacement is how dense oceanic crust becomes emplaced over less dense material(s) of continental margins or subduction–accretion systems. Subduction of less dense material beneath a future ophiolite is necessary to overcome the adverse density contrast. The relationship of subduction to ophiolite emplacement is a critical link between ophiolites and their role in the development of orogenic belts. Although ophiolite emplacement mechanisms are clearly varied, most existing models and definitions of emplacement concern a specific type of ophiolite (i.e. Oman or Troodos) and do not apply to many of the world's ophiolites. We have defined four prototype ophiolites based on different emplacement mechanisms: (1) 'Tethyan' ophiolites, emplaced over passive continental margins or microcontinents as a result of collisional events; (2) 'Cordilleran' ophiolites progressively emplaced over subduction complexes through accretionary processes; (3) 'ridge–trench intersection' (RTI) ophiolites emplaced through complex processes resulting from the interaction between a spreading ridge and a subduction zone; (4) the unique Macquarie Island ophiolite, which has been subaerially exposed as a result of a change in plate boundary configuration along a mid-ocean ridge system. Protracted evolutionary history of some ocean basins, and variation along the strike of subduction zones may result in more complicated scenarios in ophiolite emplacement mechanisms. No single definition of emplacement is free of drawbacks; however, we can consider the inception of subduction, thrusting over a continental margin or subduction complex, and subaerial exposure as critical individual stages in ophiolite emplacement.

Ophiolites have been recognized as on-land fragments of oceanic crust since the advent of plate tectonics (e.g. Gass 1968; Dewey & Bird 1970; Moores 1970; Coleman 1971; Moores & Vine 1971). Incorporation of ophiolites into continental margins is a significant component of the tectonic evolution of orogenic belts and has been broadly defined as 'ophiolite emplacement' or 'ophiolite obduction' (e.g. Moores 1970; Dewey & Bird 1970, 1971; Coleman 1971). Scientific evaluation of ophiolite emplacement has played a key role in the formulation of plate tectonic theory, because ophiolites provide a critical link between the seafloor spreading evolution of oceanic plates and their demise at subduction zones and because the mechanisms of their incorporation into land constitute a first-order tectonic problem in plate tectonics.

Ophiolite emplacement mechanisms were once a subject of vigorous debate, particularly with respect to the derivation of an ophiolite from the lower (Coleman 1971) versus upper plate (Temple & Zimmerman 1969; Dewey & Bird 1970, 1971; Moores 1970) of a subduction system (Fig. 1). In the past two decades, however, controversy regarding the tectonic setting of ophiolite formation has greatly overshadowed any debate over emplacement mechanisms (e.g. Moores *et al.* 2000 and references therein). The widespread acceptance of the suprasubduction zone (SSZ) ophiolite concept (e.g. Robinson *et al.* 1983; Pearce *et al.* 1984) has contributed to the swinging of the majority opinion on ophiolite emplacement toward the model of emplacement from the upper plate of a subduction system (e.g. Dewey 1976; Moores 1982; Searle & Stevens 1984) (Figs 1 and 2). Regardless of their original tectonic setting of igneous formation, ophiolites became incorporated into continental margins through complex interactions of lithospheric plates and hence the mechanisms of ophiolite emplacement should be expected to vary depending on the age, thickness and thermal state

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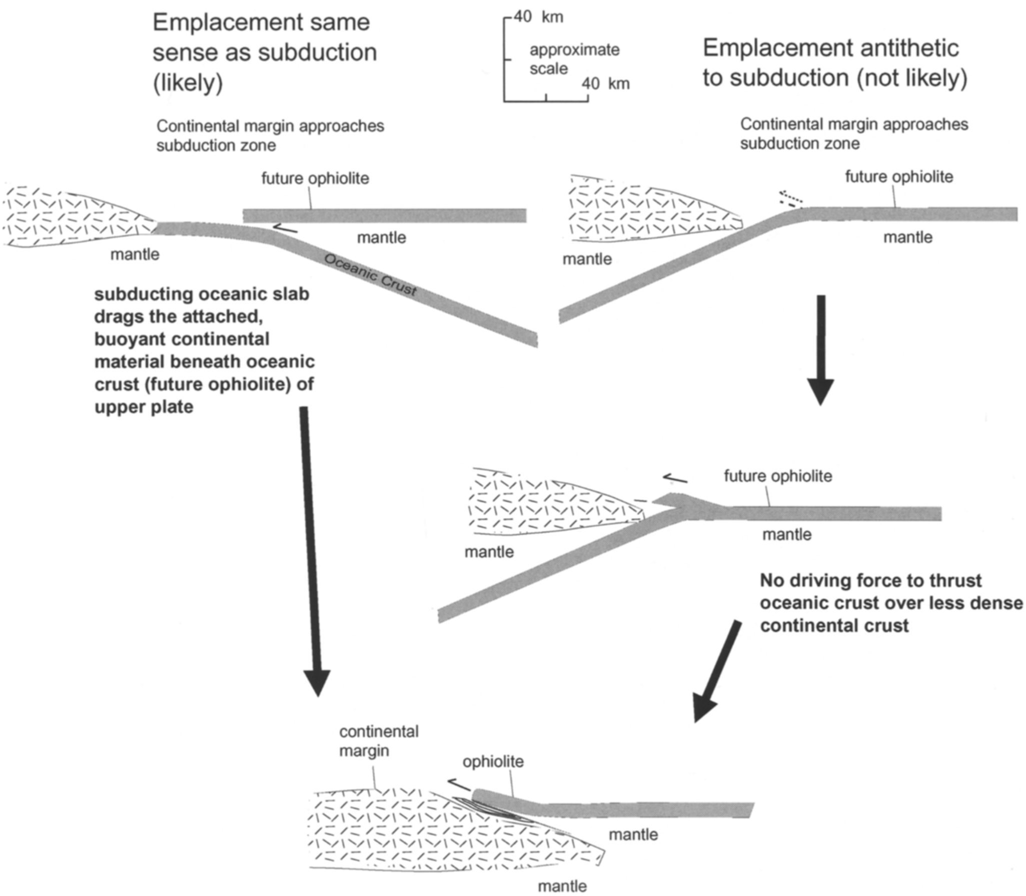

Fig. 1. The preferred model of emplacing an ophiolite over a continental margin (same thrusting sense as subduction) contrasted with emplacement antithetic to the subduction polarity. Although these diagrams illustrate the case for Tethyan ophiolites, the same principles apply to Cordilleran ophiolites emplaced over subduction–accretion complexes (see Fig. 4).

of oceanic crust, the nature and geometry of plate boundaries involved, and the size and character (i.e. oceanic versus continental, microcontinent, island arc, seamount, etc.) of the interacting plates. Although ophiolite emplacement mechanisms have been debated for several decades, most of the arguments concern a specific type of ophiolite and do not apply to different types of ophiolites around the world.

In this paper we examine the existing ideas and models on ophiolite emplacement mechanisms to better document the nature and order of the processes involved in the incorporation of fossil oceanic crust into continental margins as ophiolites. We define four prototypes of ophiolites based on their emplacement mechanisms, which deviate from each other as a result of different plate interactions in the past. We then present a critical evaluation of the models on subduction initiation and metamorphic sole development, both of which constitute two major phases in ophiolite emplacement. Finally, we discuss the emplacement mechanisms of the four prototypes of ophiolites.

Ophiolite prototypes

We follow in this paper the 1972 Penrose definition of an ophiolite (Penrose Conference Participants 1972) for simplicity, although we realize the obvious shortcomings of this restricted definition in ophiolite classification (Dilek 2003), because the discussion of various tectonic environments of ophiolite genesis is not directly relevant to emplacement mechanisms. Our discussion of ophiolites excludes thrust slices or blocks of pelagic sedi-

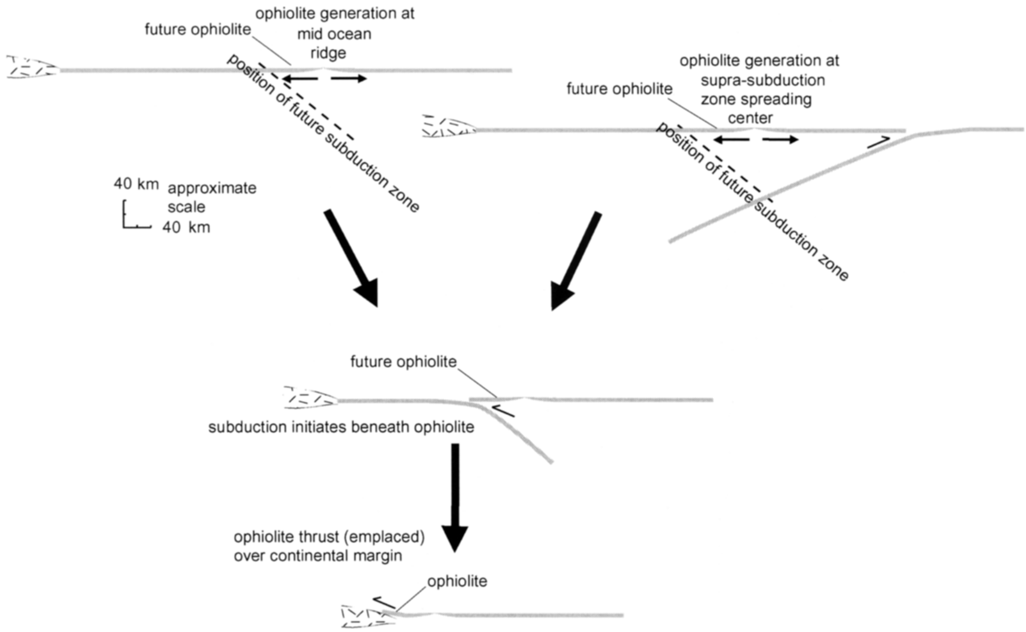

Fig. 2. Illustration that ophiolite emplacement and the environment of the emplacement do not constrain the tectonic setting of ophiolite genesis. Any type of ophiolite, whether it be nascent arc, interarc, backarc or mid-ocean ridge generated, can be emplaced over a continental margin or subduction–accretion complex.

mentary rocks, basalt and variably serpentinized ultramafic rock that are intercalated within accretionary wedges. Exposures of ophiolitic rocks in subduction–accretion systems are not treated as ophiolite complexes in this paper because: (1) accretionary wedge ophiolitic rocks most commonly comprise small blocks or thrust sheets of basalt with or without overlying chert or limestone; (2) serpentinite, although locally present as moderately large bodies or sheets (up to several kilometres of structural thickness and 30 km in along-strike length), seldom occurs in the same block or thrust sheet with basalt and chert; (3) gabbro or sheeted dykes are extremely rare in accretionary wedge sheets or blocks; (4) the largest dimensions of most thrust sheets of ophiolitic rocks in accretionary wedges are less than 10 km, whereas Penrose-type ophiolites can extend for hundreds of kilometres along-strike; (5) different scraps of oceanic rocks within the same accretionary wedge can vary greatly in age and origin. The lack of large ophiolite sheets, containing thick plutonic sections, in subduction complexes, is consistent with the conclusion of Cloos (1993) that all downgoing oceanic crust is subducted except for a few topographic highs from which basalt and pelagic sediments may be offscraped. Ultramafic rocks within accretionary wedges may be the off-scraped remnants of peridotite-cored uplifts formed at ridge–transform intersections (Coleman 2000).

We distinguish four prototypes of ophiolites based on their emplacement mechanisms and the nature of their underlying tectonic basements: (1) Tethyan; (2) Cordilleran; (3) ridge–trench intersection (RTI); (4) Macquarie Island-type. Moores (1982) recognized the differences between the Tethyan and Cordilleran types and provided several lines of criteria for their distinction that we follow herein. RTI ophiolites are special because both their igneous evolution and tectonic emplacement are strongly controlled by the spatial and temporal interactions between mid-ocean ridges and subduction zones (e.g. Forsythe & Nelson 1985; Lytwyn *et al.* 1997). The close association and interaction of ridges with trenches during the formation of RTI ophiolites are unrelated to subduction initiation. The Macquarie Island-type ophiolite presents a unique case (Varne *et al.* 1969, 2000) whereby relatively *in situ* and young oceanic crust has been exposed subaerially as a result of changing plate boundary configurations. Depending on the interpretation of the tectonic setting of the Macquarie Island ophiolite, an argument could be made that this ophiolite is subaerially exposed but not emplaced.

The terms Cordilleran and Tethyan traditionally carry geographical connotations, but we emphasize that we define 'Cordilleran' and 'Tethyan' ophiolites on the basis of their emplacement mechanisms, not their location. For example, the Brooks Range ophiolite, of Alaska in the North American Cordillera, has been emplaced over a continental margin (Wirth *et al.* 1993) reminiscent of Tethyan-type ophiolites, and hence we consider it a Tethyan ophiolite for the purposes of our discussion of emplacement. Some ophiolites in the Sierra Nevada of California, also part of the North American Cordillera, have been emplaced over continental margins or island arcs (e.g. Moores 1970; Moores & Day 1984) much as in Tethyan examples, and therefore we also would consider them as Tethyan ophiolites from the standpoint of their emplacement. On the other hand, the Cretaceous ophiolites of Neo-Tethys in the eastern Pontide belt of Turkey clearly have a protracted emplacement history typical of subduction–accretion systems in the Pacific Rim (Yilmaz *et al.* 1997), and we consider these ophiolites as Cordilleran in character regarding their emplacement histories.

We briefly summarize the characteristic features of these four ophiolite prototypes below and discuss their emplacement mechanisms in a later section.

Tethyan-type ophiolites

Tethyan ophiolites structurally overlie passive continental margins and their crystalline basement, microcontinental fragments, or island arcs. Tethyan ophiolites in the eastern Mediterranean region commonly display a Penrose-type complete pseudostratigraphy (defined as having upper-mantle rocks, cumulates, gabbros, sheeted dykes, volcanic rocks) and include some of the classic ophiolites of the world (e.g. Troodos ophiolite, Dilek *et al.* 1990b; Robinson & Malpas 1990; Oman ophiolite, Searle & Cox 1999; Dilek *et al.* 1998; Bay of Islands ophiolite in Newfoundland, Casey *et al.* 1981). Ligurian-type ophiolites exposed in the western Alps and Apennines have Hess-type oceanic crust with MORB affinities (Dilek 2003, and references therein) and are also considered as Tethyan based on their emplacement mechanisms. Extrusive sections of most Tethyan ophiolites do not have volcaniclastic rocks that are typical of volcanic arcs (e.g. Dilek & Moores 1990, and references therein), but the upper-crustal rocks in many Tethyan ophiolites display the geochemical characteristics of subduction zone environments (e.g. Pearce 1975; Alabaster *et al.* 1982; Rautenschlein *et al.* 1985; Umino *et al.* 1990; Jenner *et al.* 1991). Metamorphic soles, thin (<500 m thick) sheets of high-grade metamorphic rocks, are present beneath most Tethyan ophiolites (e.g. Williams & Smyth 1973; Spray 1984; Jamieson 1986; Dilek *et al.* 1999). There is a significant break in metamorphic pressure between the ophiolite, which commonly exhibits negligible burial metamorphism, and the structurally underlying metamorphic sole (reviewed by Wakabayashi & Dilek 2000).

Cordilleran-type ophiolites

Cordilleran ophiolites structurally overlie subduction–accretion complexes and range from rare complete ophiolite sections to those missing one or more of the major ophiolite lithologies (e.g. Irwin 1977; Saleeby 1992; Coleman 2000). Volcaniclastic and intermediate to silicic volcanic rocks that are generally associated with island arc development are widespread in the extrusive sections of Cordilleran ophiolites. Upper-crustal rock units in Cordilleran ophiolites display island arc tholeiite to calcalkaline chemical affinities indicating a subduction zone origin of their magmas (Shervais & Kimbrough 1985; Shervais 1990; Saleeby 1992). The existence of volcaniclastic rocks, including some subaerial depositions, indicates the construction of volcanic arc edifices during the evolution of these ophiolites. Cross-cutting field and geochronological relations from the Jurassic ophiolites in the Sierra Nevada foothills in California show that the arc construction had occurred on and across a pre-existing, multiply deformed and heterogeneous oceanic basement (Dilek *et al.* 1990a, 1991). Metamorphic soles are present beneath many Cordilleran ophiolites, although in some cases the sole has been nearly completely dismembered (e.g. Platt 1975; Brown *et al.* 1982; Cannat & Boudier 1985; Wakabayashi & Dilek 2000). Blueschist-facies rocks are also present structurally beneath many Cordilleran ophiolites (e.g. Ernst 1971; Platt 1975; Brown *et al.* 1982; Ernst 1988). There is a significant break in metamorphic pressure between the ophiolite, which commonly exhibits negligible burial metamorphism, and the structurally underlying metamorphic sole or blueschist-facies rocks (e.g. Platt 1986).

Ridge–trench intersection (RTI) ophiolites

Ridge–trench intersections are common in plate tectonics and may cause anomalous near-trench igneous activity (Marshak & Karig 1977), which may result in oceanic crust or ophiolite formation (Casey & Dewey 1984). Ridge–trench intersection (RTI) ophiolites may have a complete or nearly complete pseudostratigraphy. Accretionary wedge materials may be present both structurally above and below RTI ophiolites (e.g. Lytwyn *et al.* 1997). The ridge–trench intersections are associated with low-pressure, high-temperature metamorphism of the rocks structurally above (and inboard) of the ophiolite (e.g. Sisson & Pavlis 1993; Brown 1998). Examples of this type of ophiolites include the Resurrection Bay and Knight Island ophiolites in Alaska (Lytwyn *et al.* 1997) and the Taitao ophiolite in Chile (Forsythe & Nelson 1985; Nelson *et al.* 1993; Lagabrielle *et al.* 2000). The petrology and geochemistry of the ultramafic, gabbro and dyke sections of the Taitao ophiolite in Chile display a mid-ocean ridge basalt (MORB) affinity whereas the geochemistry of extrusive rocks, which are interpreted to have erupted after the spreading centre had intersected with the trench (LeMoigne *et al.* 1996), indicates a mixed MORB and island arc tholeiite affinity (LeMoigne *et al.* 1996). The degree of decompressional melting of MORB mantle, caused by ridge subduction, was apparently less rigorous than that typically occurring at mid-ocean ridges because of the capping of the melting column by the continental edge. This phenomenon, combined with crustal assimilation and fractional crystallization of enriched MORB melt, produced more silicic rocks in the extrusive sequence of the Taitao ophiolite (Kaeding *et al.* 1990; Lagabrielle *et al.* 1994). Sheeted dykes and lavas from the two Alaskan ophiolites have geochemistry similar to that of MORB with some arc influence that has been attributed to intersection of the spreading centre with a subduction zone and a slab-free window (Lytwyn *et al.* 1997). Although only two ridge–trench ophiolite localities have been described to date, this type of ophiolite may be more common in the rock record (van den Beukel & Wortel 1992).

Macquarie Island ophiolite

The Macquarie Island ophiolite is exposed on the 37 km × 5 km Macquarie Island, which is situated about 950 km SSW of New Zealand and 1500 km SSE of Tasmania along the transform boundary between the Indo-Australian and Pacific Plates (Varne *et al.* 1969, 2000). Exposures on Macquarie Island comprise a complete, Penrose-type ophiolite including basalts (making up nearly two-thirds of the exposures) with intercalated sedimentary rocks, sheeted dykes, gabbro and ultramafic rocks. The basaltic rocks display MORB and enriched MORB (E-MORB) chemistry, and plate motion reconstructions place the site of ophiolite generation at a mid-ocean ridge spreading centre (Varne *et al.* 2000).

The Macquarie Island ophiolite differs from Tethyan- and Cordilleran-type ophiolites in that it structurally overlies either *in situ* oceanic crust (Varne *et al.* 2000) or suboceanic mantle (Daczko *et al.* 2002), rather than a continental margin or a subduction–accretion complex. A metamorphic sole is not exposed. If such a sole were present, it would be beneath the present level of exposure.

Igneous ages of the Macquarie Island ophiolite, determined from $^{40}Ar/^{39}Ar$ step heating ages of two different basalt outcrops, range between 9.7 and 11.5 Ma (Duncan & Varne 1988). These ages are consistent with the estimated age of the ophiolite from plate motion models, magnetic anomaly patterns and the ages of associated sedimentary rocks (Varne *et al.* 2000). The generation of oceanic crust in the Macquarie Island ophiolite apparently occurred at slow rates (5–10 mm a^{-1} half-spreading rate) during the waning stages of sea-floor spreading activity at a mid-ocean ridge (Varne *et al.* 2000).

Goscombe & Everard (2001) suggested that, following generation of the 'Macquarie Island oceanic crust' and associated extensional faulting in the vicinity of the spreading centre, the ophiolite was subject to transtensional deformation, possibly during transition from the spreading environment to a transform environment. The transtension was followed by transpressional deformation along the transform fault plate boundary. In contrast, Daczko *et al.* (2002) interpreted all structures on Macquarie Island, including active ones, to be extensional or transtensional. Greenschist-grade lower pillow lavas and sheeted dykes have yielded $^{40}Ar/^{39}Ar$ step heating ages of 6.5–7.2 Ma, interpreted to indicate cooling at the end of greenschist-grade hydrothermal metamorphism (Duncan & Varne 1988). The transform plate boundary along which Macquarie Island is situated became transpressional at or after 5 Ma (Varne *et al.* 2000; Goscombe & Everard 2001).

Development of metamorphic soles and subduction initiation: a critical part of ophiolite emplacement

Structure and evolution of metamorphic soles

Initiation of subduction and formation of metamorphic soles have been linked to the ophiolite emplacement process. Some researchers have explicitly defined the inception of subduction and consequent development of a metamorphic sole beneath an ophiolite as emplacement, or at least the first stage of emplacement (e.g. Williams & Smyth 1973; Malpas 1979; McCaig 1983; Jamieson 1980, 1986; Hacker *et al.* 1996).

Subophiolitic metamorphic soles, or simply metamorphic soles, are thin (<500 m thick), fault-bounded sheets of highly strained high-grade metamorphic rocks that structurally underlie many ophiolite complexes (e.g. Williams & Smyth 1973; Jamieson 1986). The higher-grade parts of the metamorphic soles are composed mainly of metabasic rocks of oceanic affinity, with minor metamorphosed pelagic sedimentary rocks. Many soles display inverted metamorphic field gradients and an inverted ocean crustal sequence. The high-grade parts of such soles appear to grade structurally downward from metagabbros to metabasalts to metamorphosed pelagic sedimentary rocks (Jamieson 1986).

The pressure–temperature ($P-T$) conditions of metamorphism for subophiolitic soles are consistent with high-temperature metamorphism beneath hot suboceanic mantle. Metamorphic soles are thought to form at the inception of oceanic subduction beneath the hot sub-ophiolitic mantle of the hanging wall, as suggested by estimated $P-T$ conditions of their metamorphism, their oceanic protoliths, and the presence of an ophiolite structurally above them (e.g. Williams & Smyth 1973; Malpas 1979; Nicolas & Le Pichon 1980; Spray 1984; Jamieson 1986) (Fig. 1). The inverted temperature anomaly responsible for the high-grade metamorphism of the sole decays quickly (<2 Ma) as subduction continues (Peacock 1988; Hacker 1990, 1991; Hacker *et al.* 1996). Thus the high-grade metamorphism of the sole can occur only at the inception of subduction because the hanging wall would be too cold to cause high-grade metamorphism thereafter. As a result of thermal insulation from continuing subduction, the metamorphic rocks of the sole cool rapidly through the blocking temperature of commonly applied isotopic dating methods such as $^{40}Ar/^{39}Ar$ (Wakabayashi & Dilek 2000). Because of this rapid cooling, the metamorphic age of the sole closely approximates the inception of subduction (e.g. Spray 1984; Peacock 1988).

Pressures of metamorphism associated with metamorphic soles are higher than can be explained by the structural thickness of material found above them (Wakabayashi & Dilek 2000), indicating that: (1) the amount of underthrusting represented by metamorphic soles is considerable (burial depths range from 20 to 40 km); (2) normal faulting must have occurred between the ophiolite and the sole after sole development, to exhume the sole to the present field relationship with the ophiolite. Alternatively, the relationship of the ophiolite structurally above the high-P metamorphic sole can be explained by multiple thrusting events instead of normal faulting (e.g. Cowan *et al.* 1989; Ring & Brandon 1994). However, thrusting, in contrast to normal faulting, requires the erosional removal of all material originally present between the ophiolite and sole, an enormous volume of ultramafic material. Large volumes of syn-exhumational ultramafic sediments have not been observed to be associated with ophiolites and their soles. The absence or scarcity of metaclastic rocks in the higher-grade (earliest formed) part of metamorphic soles indicates that the ocean floor at the site of subduction initiation lacked terrigenous sediment cover. This observation suggests either that sites of subduction initiation were far from a major landmass, or that sufficient submarine topography was present to shield the nascent subduction zone from terrigenous sediments.

In addition to the inverted temperature gradient recorded in metamorphic soles, an inverted pressure gradient is also observed (Jamieson 1986; Gnos 1998), indicating that the sole is a composite of slices formed at different times, brought together by thrust faulting (Casey & Dewey 1984; Gnos 1998). The structurally lower (lower-grade) parts of soles were probably scraped off the subducting oceanic plate some time after the structurally higher (higher-grade) parts of the sole were formed.

The inferred origin of metamorphic soles, as products of subduction initiation, suggests that they may offer insight into how subduction begins, at least in the cases that result in development of metamorphic soles and subsequent emplacement of ophiolites. The high temperature of metamorphism as reflected by mineral assemblages in sole rocks and the small age difference between soles and overlying ophiolites indicate that ocean crust was young (generally 5 Ma or younger) and hot at the inception of subduction (e.g. Spray 1984; Jamieson 1986; Hacker *et al.* 1996; Dilek *et al.* 1999). No soles have been found that predate the ophiolites found structurally above them, so if such ophiolites were of SSZ origin (as has commonly been interpreted), they must have been formed above an older subduction zone than the one that began with the formation of the sole (Wakabayashi & Dilek, 2000). Thus, SSZ ophiolites must have been emplaced above a separate, younger, subduction zone than the one they formed over.

The inverted ocean crustal sequence exposed in the high-grade parts of soles is not compatible with an ordinary sequence of underplating or offscraping during subduction initiation that would produce a right-side-up ocean-floor stratigraphy within each thrust sheet. The inverted ocean-floor sequence found in metamorphic soles suggests that subduction might have started as the down-bowing of young oceanic crust that developed into an overturned fold (Fig. 3). The inferred overturning of the flexure at the inception of subduction is consistent with the model of Mueller & Phillips (1991), who have suggested that foundering of dense oceanic lithosphere alone cannot initiate subduction; an external force is needed. The overturned limb of the progressively forming oceanic flexure becomes thinned by numerous thrust faults as the fold develops into a young subduction zone and the future ophiolite, as well as the sole, are left on the upper plate of this system (Fig. 3). Oceanic rocks in the overturned, fault-thinned limb are subject to high-temperature metamorphism beneath the hot suboceanic mantle; this configuration forms the high-grade metamorphic sole with an 'inverted' sequence of oceanic crust. The actual subduction break is the main structure of what may be a broader shortened zone in the oceanic lithosphere.

Subsequent continuous subduction leads to offscraping under lower-temperature conditions, as the hanging wall rapidly cools. The structurally lower parts of the sole may include metaclastic material that may indicate the approach of a continental margin in the lower plate (as in Tethyan ophiolites), or the development of an arc–trench depocentre in the upper plate (as in Cordilleran ophiolites). Anticlockwise $P-T$ paths of metamorphism from both intact (Hacker & Gnos 1997) and dismembered (Wakabayashi 1990) metamorphic soles show evidence of a pressure increase with cooling. This can most easily be achieved if the upper plate of the nascent subduction zone is imbricated (tectonically thickened) after subduction has begun and the metamorphic sole has started to cool (e.g. Wakabayashi 1990).

Exhumation of metamorphic soles

Following sole metamorphism, the higher-grade part of the sole is exhumed relative to the overlying ophiolite. This differential exhumation appears to be accommodated by a normal fault above (low-P ophiolite on higher-P sole) and by thrust faults below (inverted pressure gradient in

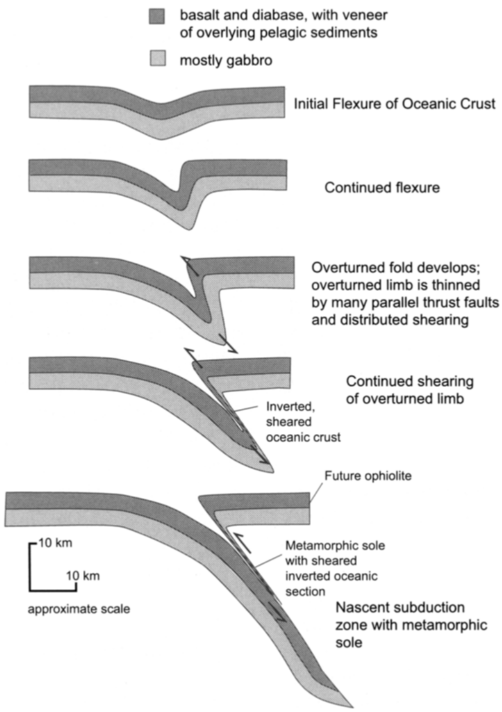

Fig. 3. Model for inception of subduction. The width of the subophiolitic sole is exaggerated in this view so that it is visible. Additional imbrication of the upper plate may occur, leading to the increasing burial with cooling noted in some metamorphic soles. The new subduction zone generally forms in young oceanic crust (near a spreading centre) and may exploit a pre-existing zone of weakness. There may be a density contrast across this zone of weakness with older, more dense material on the side that subducts. Such density contrast would be greatest across a fracture zone, but smaller contrasts may be present across zones of normal faulting in the oceanic crust.

the sole), suggesting an apparent extrusion of the higher-grade part of the sole. Such relations are analogous to those associated with high-pressure metamorphic rocks (blueschists and eclogites) (Wakabayashi & Dilek 2000). The exhumation fault (or faults) structurally above the sole does not necessarily coincide with the contact between the peridotite and the metamorphic sole; it could be somewhere between the sole and the crustal section of the ophiolite (Hacker & Gnos 1997; Wakabayashi & Dilek 2000). Timing of the exhumation of the high-grade part of the metamorphic sole relative to the ophiolite is poorly constrained in many cases. Geochronological and structural data from the Oman ophiolite (e.g. Hacker *et al.* 1996; Gregory *et al.* 1998; Gray *et al.* 2000) suggest that exhumation of the sole relative to the Oman ophiolite occurred probably less than 10 Ma after the metamorphism of the sole rocks. Such an exhumation event would have occurred prior to, or in the earliest stages of, the thrusting of the ophiolite over the Arabian continental margin. For Tethyan ophiolites in general, metamorphic soles were probably exhumed relative to the ophiolite prior to, or during the earliest stages of thrusting onto a continental margin, because the soles and ophiolites commonly are thrust over continental margin sequences as part of the same nappe system (Moores 1982; Searle & Cox 1999).

Subduction initiation models

Mueller & Phillips (1991) showed that the blockage of a subduction zone by buoyant material (island arc, continental fragment, continental margin) is probably the only event capable of generating a large enough external force to initiate a new subduction zone. The conclusions of Mueller & Phillips (1991) are consistent with models of subduction initiation based on field relations in ophiolites (Casey & Dewey 1984), as well as the geodynamic history of the SW Pacific, where the clogging of subduction zones with buoyant material was followed by initiation of new subduction zones (Hall 1996).

Although an external force apparently triggers subduction initiation, a material contrast and a zone of weakness in the oceanic lithosphere may determine the location of the nascent subduction zone (Casey & Dewey 1984). An oceanic spreading centre (i.e. mid-ocean ridge) has been suggested as a site of subduction initiation (e.g. Casey & Dewey 1984; Hacker *et al.* 1996). Initiation of subduction at a spreading centre is consistent with the indistinguishable ages of some ophiolites and their soles (Hacker *et al.* 1996).

Fracture zones separate oceanic lithosphere of differing age and density and are likely sites of subduction initiation (Casey & Dewey 1984; Hawkins *et al.* 1984; Stern & Bloomer 1992). Subduction may be initiating along two segments of the Macquarie Ridge, an oceanic transform, in the SW Pacific Ocean (Collot *et al.* 1995; Frohlich *et al.* 1997), along the Azores–Gibraltar transform fault, and along a fracture zone in the East Caroline Basin (Mueller & Phillips 1991). The age of oceanic crust on the upper plate of a subduction initiated at a fracture zone should become progressively older along the trend of the trench-line, away from the spreading centre. Such a relationship may result in a variation of age of tens of million years over the hundreds of kilometres of oceanic crust that form a future ophiolite. Some ophiolites in the North American Cordillera show large (tens of million years) ranges of igneous ages as well as lithological heterogeneity suggesting a similar scenario; their tectonic evolution is consistent with subduction initiation along a fracture zone (Saleeby 1990, 1992). In contrast, many ophiolite belts that are hundreds of kilometres long, such as the Coast Range ophiolite of California (Hopson *et al.* 1981, 1996) and many Tethyan ophiolites (e.g. Dewey 1976; Juteau 1980; Dercourt *et al.* 1986; Dilek & Moores 1990), show a restricted (generally 5 Ma or less) age range. Such ophiolite belts are inconsistent with subduction initiation along an oceanic transform fault or fracture zone.

Major contrasts in age and density of oceanic lithosphere are also found where new spreading began in older ocean crust (i.e. rift propagation in the Lau Basin; Parson & Wright 1996; Zellmer & Taylor 2001). Such contrasts in lithospheric age and density would be parallel to a spreading centre, as in the case of ridge-parallel normal faults (Dilek *et al.* 1988), which constitute pre-existing zones of mechanical weakness. Initiation of subduction along such a ridge-parallel discontinuity between old and young crust would result in an ophiolite (on the upper plate of the subduction zone) that is older than its metamorphic sole, and that is of relatively consistent age along the trend of the trench-line.

Ophiolite emplacement mechanisms

Proposed models and the problem of emplacing oceanic lithosphere over less dense rocks

The existing ophiolite emplacement models generally fall into four categories (Fig. 1): (1) emplacement by partial subduction of a continental margin beneath the displaced fossil oceanic crust (e.g. Temple & Zimmerman 1969; Dewey & Bird 1970, 1971; Moores 1970); (2) emplacement by antithetic thrusting of oceanic crust from the subducting plate (e.g. Coleman 1971), referred to by some as flake tectonics (e.g. Oxburgh 1972); (3) emplacement by gravity sliding (e.g. Reinhardt 1969; Church & Stevens 1971; Smith & Woodcock 1976); (4) emplacement through intersection of a spreading ridge with a subduction zone (e.g. Forsythe & Nelson 1985; van Beukel & Wortel 1992; Lytwyn *et al.* 1997). The term 'obduction' was first defined by Coleman (1971) to explain ophiolite emplacement through antithetic thrusting along active continental margins. Dewey (1976) used obduction, however, to refer to any type of ophiolite emplacement mechanism, and others have followed this usage (e.g. Searle & Stevens 1984).

How oceanic crust comes to be emplaced over the less dense continental margin material or subduction–accretion complex is the central problem of ophiolite emplacement. A viable emplacement model needs to include a mechanism that overcomes this adverse density contrast. Gravity sliding, in the absence of other processes, requires an unrealistic topographic high on the ocean floor and improbable transport distances necessary to emplace an ophiolite (Dewey 1976; Moores 1982). Gravity sliding might have played a partial role in emplacement of some ophiolites (Searle & Stevens 1984), particularly after collision-induced thrusting caused significant crustal uplift and topographic buildup; these processes might have then produced high gravitational potential energy in the upper-plate rocks that would have triggered downward sliding of ophiolitic packages onto the continental margin sequences in the lower plate (Gregory *et al.* 1998; Gray *et al.* 2000; Gray & Gregory 2003). However, it is unlikely that gravity sliding can be the sole agent or primary mechanism of ophiolite emplacement.

Subduction zones are the only locations on Earth where less dense material is thrust beneath denser material on a large scale. Thus, ophiolite emplacement mechanisms must be spatially associated with subduction. Such a linkage is consistent with the occurrence of metamorphic soles beneath ophiolites. Underthrusting of buoyant material at subduction zones is a consequence of the attachment of such material to the dense downgoing oceanic lithosphere. This includes both passive continental margins or island arcs attached to a downgoing oceanic slab, and accretionary wedge materials that are scraped off the downgoing oceanic slab. Because the pull of the sinking oceanic lithospheric slab is such an important driving force in plate tectonics (e.g. Forsythe & Uyeda 1975), ophiolite emplacement is best viewed as less dense material being dragged (by the descending slab) beneath an ophiolite, rather than the pushing of an ophiolite over less dense material. Consequently, an ophiolite emplaced as part of the upper plate of a subduction system (Temple & Zimmerman 1969; Dewey & Bird 1970, 1971; Moores 1970), is more plausible than emplacement from the downgoing slab (e.g. 'obduction' of Coleman 1971), because in the latter scenario there is no slab to drag the less dense material beneath the ophiolite (Fig. 1). An exception is the subduction of an active spreading centre, which may arrest the subduction of very young, buoyant, oceanic lithosphere and result in emplacement of ophiolites from the downgoing plate (e.g. Forsythe & Nelson 1985; van Beukel & Wortel 1992).

The connection between subduction zones and ophiolite emplacement links ophiolites to the development of orogenic belts. Ophiolites make up the structural 'roof' of palaeosubduction zones, and ophiolite-marked subduction sutures have been considered the most important first-order structures in orogenic belts (e.g. Moores 1970; Moores *et al.* 1999).

Collisional emplacement of Tethyan-type ophiolites

Emplacement of Tethyan ophiolites has been traditionally defined as the thrusting of an ophiolite over a continental margin and/or a crystalline complex of a microcontinent (e.g. Temple & Zimmerman 1969; Dewey & Bird 1970, 1971; Moores 1970; Coleman 1971) (Fig. 4). By this definition, the inception of oceanic subduction (and development of the metamorphic sole) beneath the ophiolite predates the terminal emplacement event (Fig. 4) (Moores 1982). However, some others have defined the inception of subduction as emplacement itself (e.g. Williams & Smyth 1973; Malpas 1979; Jamieson 1980; McCaig 1983). Alternatively, thrusting of an ophiolite over a passive continental margin has been considered but one step in a multi-stage emplacement process, the beginning of which may involve transform fault tectonics (Brookfield 1977) or the inception of subduction (e.g. Casey & Dewey 1984; Jamieson 1986; Hacker *et al.* 1996).

Collision of a passive continental margin leads to the arrest of subduction because the continental material is too buoyant to be subducted (e.g. Temple & Zimmerman 1969; Moores 1970). Subduction jump and a flip of subduction polarity may then follow, creating the field relations noted by Coleman (1971) in which the active subduction

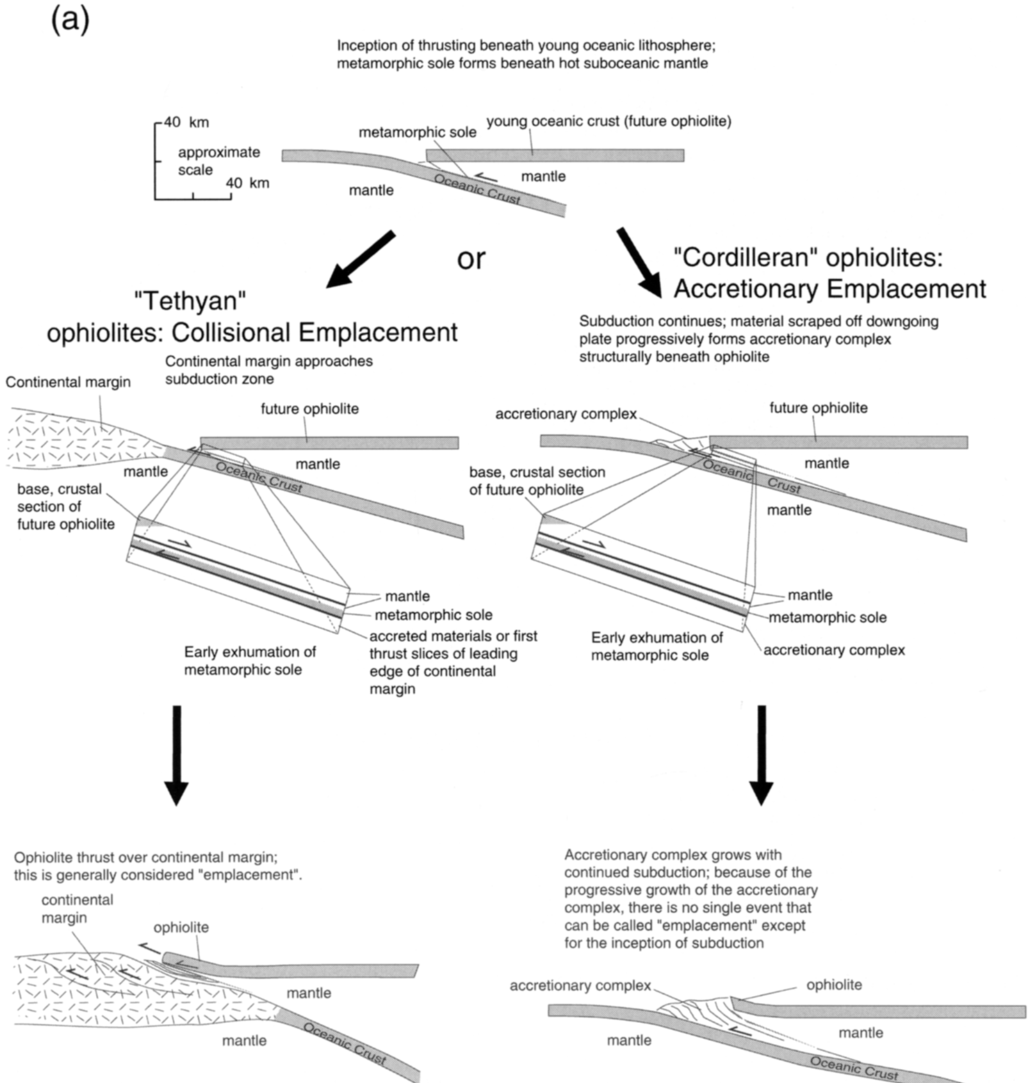

Fig. 4. Emplacement of Tethyan and Cordilleran ophiolites (**a**) and ridge–trench ophiolites (**b**). It should be noted that if a continental margin is attached to the plate subducting beneath a Cordilleran ophiolite, such an ophiolite may eventually be thrust over a continental margin, 'converting' it to a Tethyan-type ophiolite. Similarly, if subduction continues after ridge–trench ophiolite emplacement, a subduction complex may develop structurally beneath such an ophiolite and it would effectively become a Cordilleran ophiolite, although rocks structurally above the ophiolite would exhibit higher-grade metamorphism than those associated with a typical Cordilleran ophiolite. Ridge–trench emplacement may also be followed by collision, converting the ophiolite into a Tethyan ophiolite; rocks structurally above the ophiolite would show a higher grade of metamorphism than a typical Tethyan ophiolite setting.

zone dips beneath the recently emplaced ophiolite. In such a scenario, emplacement of the ophiolite is facilitated by the previous subduction zone dipping away from the continental margin. Such subduction polarity flips have occurred in the SW Pacific, including the continuing subduction polarity flip in eastern New Guinea (Cooper & Taylor 1987), and the *c.* 10–5 Ma polarity flip in northern Sulawesi (Hall 1996). Because the collision of a buoyant microcontinent or arc with a subduction zone results in the arresting of subduction, similar to the collision of a continent in the downgoing

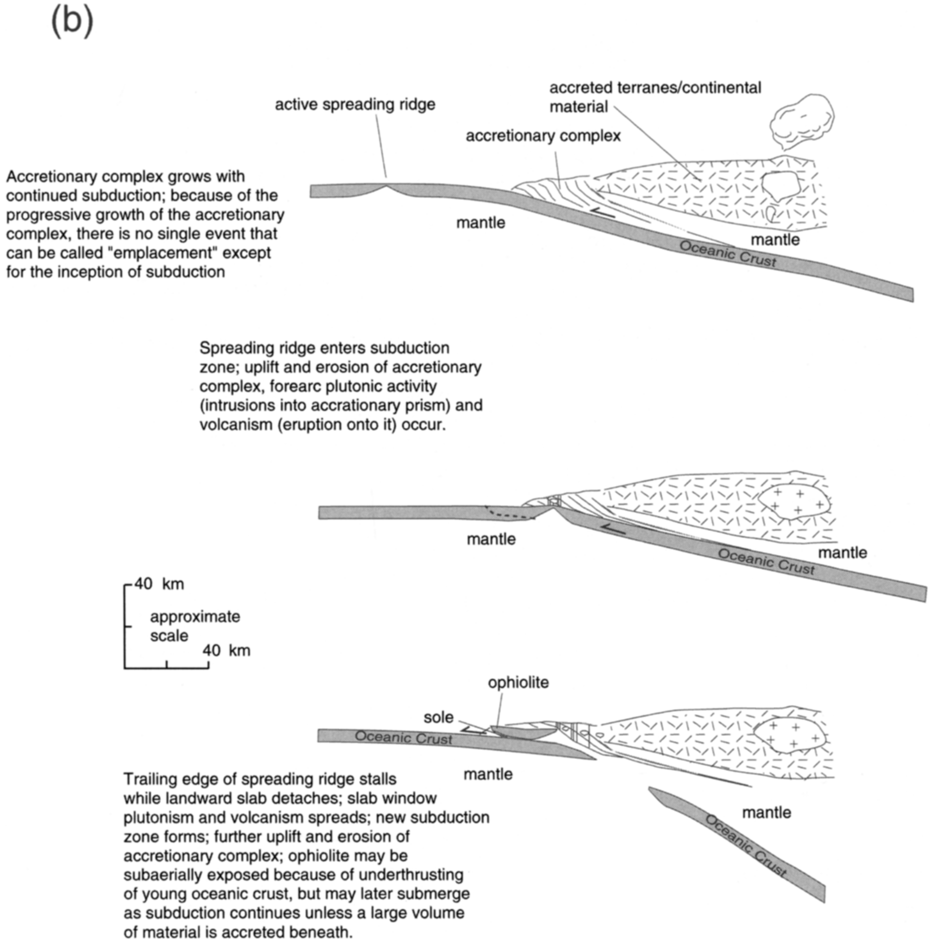

Fig. 4. (*continued*)

plate with a trench (e.g. Cloos 1993), ophiolites that are thrust over microcontinents or island arcs (e.g. Hall 1996) are also considered as Tethyan-type ophiolites in this treatment. We define this mechanism of emplacement as 'collisional'.

The emplacement of collisional Tethyan-type ophiolites includes the following events from oldest to youngest: (1) initiation of intra-oceanic subduction and formation of metamorphic sole; (2) exhumation of metamorphic sole relative to the ophiolite; (3) thrusting of the ophiolite over continental margin via collision; (4) subaerial exposure of the ophiolite. Ages of metamorphic soles are commonly similar to or slightly younger (<2 Ma) than the igneous ages of crustal rocks in many Tethyan ophiolites, and most Tethyan ophiolites were emplaced onto continental crust within 10 Ma of their formation (Dewey 1976; Dilek *et al.* 1999). A notable exception is the Cretaceous Troodos ophiolite, whose thrusting over the Eratosthenes Seamount was facilitated by the collision of this seamount with the Cyprus trench (and a north-dipping subduction zone) starting in the Pliocene (Robertson 1998).

Oman ophiolite. The Tethyan-type Oman ophiolite, considered by many as the best-exposed and most complete ophiolite in the world, has been the subject of debate over its emplacement mechanism(s). Some researchers believe that the Oman ophiolite was emplaced over a single subduction zone directed away from the Arabian continental margin (e.g. Dewey 1976; Hacker *et al.* 1996; Searle & Cox 1999; Searle *et al.* 2003). Other workers have concluded that an earlier episode of subduction, dipping beneath the continent, was followed by gravitational collapse and possible formation of a new subduction zone dipping away from the continent (Gregory *et al.* 1998; Gray *et al.* 2000; Gray & Gregory 2003). In this model, ophiolite emplacement is inferred to have been associated with the latter two events. The controversy involves different interpretations of the structures and, in particular, the geochronology of the high-*P* metamorphic rocks, including blueschists and eclogites, which occur structurally beneath the ophiolite. One research group interprets the metamorphic ages as reflecting a high-*P*, subduction-related metamorphic event that preceded ophiolite generation (Miller *et al.* 1999; Gray *et al.* 2000; Gray & Gregory 2003). Other researchers (e.g. Hacker *et al.* 1996; Searle *et al.* 2003) have concluded that Ar/Ar metamorphic ages from eclogites that exceed the ophiolite in age are a consequence of excess Ar that results in ages significantly older than the actual crystallization age of the metamorphic rocks. If the interpretation of older eclogites is correct, the Oman ophiolite may differ markedly in tectonic setting from all other ophiolites. This is because high-*P* metamorphic rocks are universally younger than the ophiolites that structurally overlie them (Wakabayashi & Dilek 2000).

Accretionary emplacement of Cordilleran-type ophiolites

Similar to the emplacement of Tethyan ophiolites, the emplacement of Cordilleran ophiolites begins with the inception of subduction beneath the future ophiolite and the formation of a metamorphic sole. The ophiolite is not thrust over a passive continental margin as in collisional Tethyan ophiolites; instead, materials are added to subduction–accretion complex beneath the ophiolite by progressive tectonic accretion (Fig. 4). The history of subduction may also involve removal of previously accreted materials, known as subduction erosion (e.g. von Huene 1986). The subduction–accretion complexes beneath Cordilleran ophiolites include trench sediments, as well as the upper parts of seamounts, oceanic plateaux and aseismic ridges, and other topographic highs from the downgoing oceanic plate (e.g. Cloos 1993). The emplacement process of a Cordilleran ophiolite is gradual or cumulative, in contrast to the punctuated process of Tethyan ophiolite emplacement.

The following events are common to all Cordilleran ophiolites: (1) initiation of subduction and formation of metamorphic sole; (2) exhumation of metamorphic sole relative to ophiolite; (3) progressive underthrusting of oceanic material beneath the ophiolite following inception of subduction; (4) subaerial exposure of the ophiolite.

Coast Range ophiolite. The emplacement history of the Coast Range ophiolite in California illustrates the stages of emplacement of a Cordilleran ophiolite (Fig. 5). The Coast Range ophiolite forms scattered exposures over a distance of 900 km in western California, a distance that extends to 1300 km when slip on the dextral San Andreas fault system is restored (Bailey *et al.* 1970; Hopson *et al.* 1981). The crustal sections of the ophiolite are 4 km thick or less, and the exposures range from sheared ultramafic rocks with lenses of gabbro and mafic volcanic rocks, to nearly 'complete' Penrose-type sequences that include ultramafic rocks, cumulate and isotropic gabbros, sheeted intrusive rocks, and mafic and intermediate volcanic rocks (e.g. Point Sal ophiolite, Hopson *et al.* 1981). The Coast Range ophiolite structurally overlies the Franciscan subduction complex (e.g. Bailey *et al.* 1970) and is depositionally overlain by the forearc basin strata of the Great Valley Group (Dickinson 1970).

The Coast Range ophiolite was formed at about 165–170 Ma (Mattinson & Hopson 1992; Hopson *et al.* 1996), possibly in a back-arc or nascent arc setting (e.g. Moores 1970; Schweickert & Cowan 1975; Dickinson *et al.* 1996; Ingersoll 2000; Wakabayashi & Dilek 2000) (Fig. 5). Alternatively, the ophiolite may have been formed in a forearc (Shervais 1990; Saleeby 1996) or a mid-ocean ridge setting (Hopson *et al.* 1981, 1996). Any of the proposed settings of ophiolite genesis is broadly compatible with the emplacement events described below (starting with the inception of subduction beneath the ophiolite); the tectonic setting of ophiolite genesis places no constraint on the mechanisms of emplacement.

The Coast Range ophiolite was placed in the upper plate of the east-dipping Franciscan subduction zone at 165–160 Ma, based on interpreted age of metamorphic sole formation of 159–163 Ma (Wakabayashi & Dilek 2000). Continued subduction resulted in overprinting of the sole with high-*P*–low-*T* (HP–LT) metamorphic minerals (Wakabayashi 1990) (Fig. 6), and continued deformation broke up the metamorphic sole. Remnants of the sole currently occur mostly as blocks in Franciscan mélanges, commonly referred to as 'high-grade' blocks (Wakabayashi 1990; Wakabayashi & Dilek 2000).

Some of the pieces of the metamorphic sole and some of the structurally highest (and oldest) blueschist-facies rocks of the structurally underlying Franciscan Complex may have been exhumed by Tithonian time (151–144 Ma; Gradstein *et al.* 1995) based on the following observations:

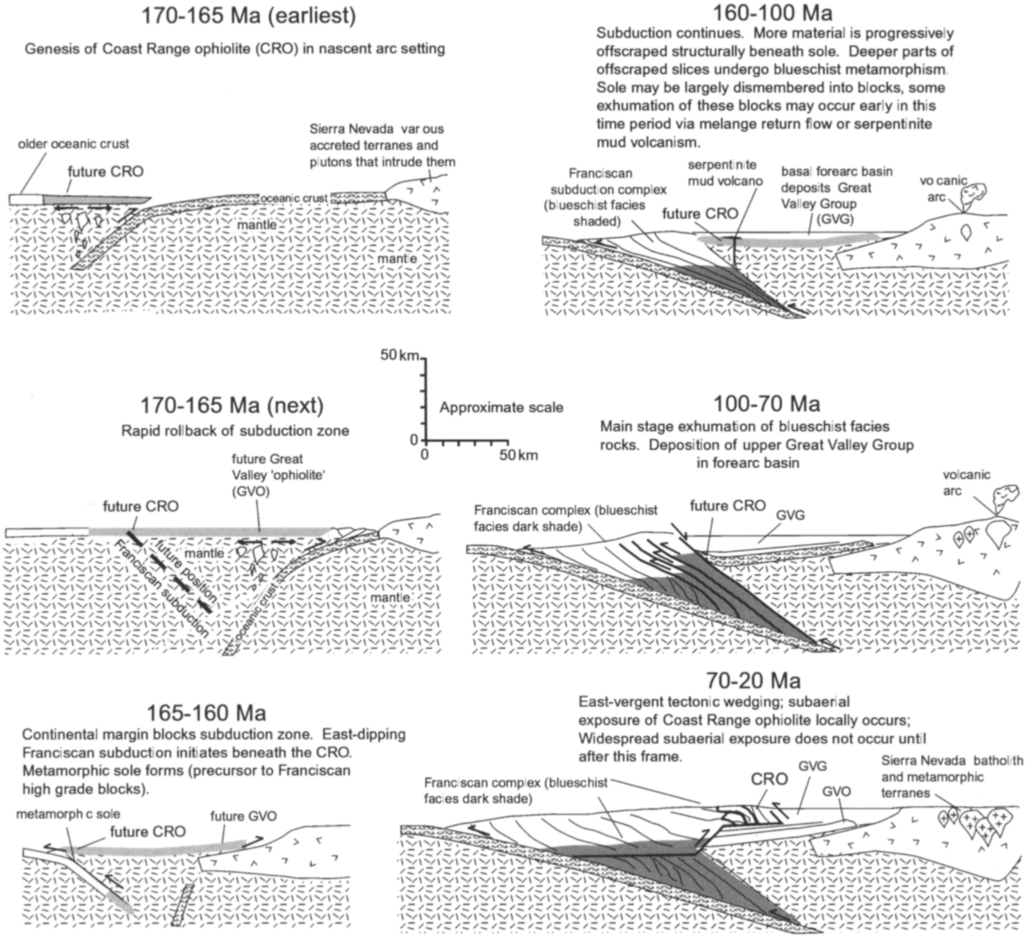

Fig. 5. Tectonic history of the Coast Range ophiolite. The ophiolite is illustrated as being generated in a nascent arc setting, although other tectonic settings are compatible with the tectonics of emplacement. It should be noted that the width of the metamorphic sole is greatly exaggerated so that it shows on the diagram. The entire forearc region is submerged until the final frame (70–20 Ma). The last three frames are modified from Wakabayashi & Unruh (1995) and Wakabayashi (1999).

(1) high-grade blocks are present in basal (Tithonian and Valanginian) Great Valley Group (Carlson 1981; Phipps 1984); (2) a Tithonian–Valanginian Franciscan sandstone (Moore 1984) contains block(s) of high-grade rock(s); (3) blueschist cobbles including rutile (in Franciscan metamorphic rocks found only in the high-grade blocks) are present in some Tithonian to Valanginian age Franciscan conglomerates (Moore & Liou 1980); (4) intergrown lawsonite and white mica (a texture limited to Franciscan high-grade blocks) are detrital clasts in some Tithonian–Valanginian Franciscan sandstones (Crawford 1975; Brothers & Grapes 1989). Older blueschist belts in the Sierra Nevada to the east (east of the forearc basin) lack the mineral assemblages or textures listed above. These observations collectively suggest that parts of the blueschist-overprinted metamorphic sole were exhumed prior to Tithonian–Valanginian redeposition into the trench and forearc basin. Much of the early exhumation of the sole may have occurred as blocks in a shear zone rather than as a coherent sheet, because many of the blocks have actinolite- and chlorite-bearing rinds suggesting reaction with surrounding ultramafic rocks at reasonably elevated temperatures (Coleman & Lanphere 1971). The high-grade blocks may have been exhumed as blocks in serpentinite diapirs, a setting similar to the occurrence of blueschist blocks in serpentinite

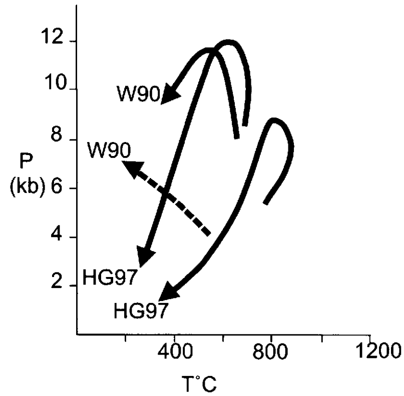

Fig. 6. Comparing two representative *P–T* paths from the high-grade blocks of the Franciscan Complex [*P–T* paths labelled W90 from Wakabayashi (1990)] with two representative *P–T* paths from the metamorphic sole of the Oman ophiolite (Hacker & Gnos 1997; labelled HG97).

mud volcanoes in the Marianas forearc (Fryer *et al.* 2000) (Fig. 5).

Franciscan subduction continued unabated for over 140 Ma, resulting in progressive accretion of units scraped off the downgoing plate (Wakabayashi 1992). At least 25% of the exposed Franciscan complex was metamorphosed under HP–LT, blueschist-facies conditions. Deposition of clastic sediments in the forearc basin on the future Coast Range ophiolite took place while the Franciscan subduction complex was forming structurally beneath the ophiolite (Fig. 5). The burial of the ophiolite beneath forearc strata did not result in significant burial metamorphism of the ophiolite.

Subaerial exposure of the Coast Range ophiolite and some of the underlying accretionary complex may have locally occurred in the Eocene (Nilsen & McKee 1979), while subduction was still active, and was widespread by the Miocene, when a transform plate boundary replaced the subduction zone (Cole & Armentrout 1979). As illustrated in this Coast Range ophiolite example, emplacement of a Cordilleran ophiolite is gradual, with only the inception of subduction standing out as a well-defined event in the history of the ophiolite.

Emplacement of RTI ophiolites

Ridge–trench intersection ophiolites are emplaced as a consequence of the subduction of an oceanic spreading ridge (Forsythe & Nelson 1985; van den Beukel & Wortel 1992). Published models suggest that the emplacement process occurs by stranding a piece of the oceanic plate from the landward side of the spreading centre (e.g. van den Beukel & Wortel 1992). It is difficult to envision why the oceanic flake would form from the landward side of the spreading centre because such a piece is attached to the downgoing plate, and because the strength of the oceanic plate should be lowest at the spreading centre (e.g. Mueller & Phillips 1991) (Fig. 4). It seems more plausible that the ophiolitic slice is derived from the seaward side of the spreading centre (Fig. 4) where the oceanic lithosphere, of zero age and buoyant, is separated from the downgoing oceanic slab and thus from slab pull forces by the spreading centre itself. If this scenario is correct, then this piece of young oceanic lithosphere stalls and does not subduct. A new subduction zone then forms outboard of the stalled piece of oceanic lithosphere (Fig. 4). Near-trench intrusions and volcanism occur as a result of thermal activity related to the slab-free window (e.g. Thorkelson 1996) and the initiation of new subduction (Fig. 4). Elevated geothermal gradients from the slab-free window result in low-*P*–high-*T* metamorphism (e.g. Sisson & Pavlis 1993; Brown 1998). An exhumed accretionary wedge with such high-temperature metamorphism and plutons may resemble an exhumed magmatic arc (Brown 1998).

Ridge–trench intersections are common geological phenomena and this process has been suggested as a common ophiolite emplacement mechanism (van den Beukel & Wortel 1992). However, only two examples of this type of ophiolite have been identified thus far. This may be because the ophiolite subsides beneath sea level after subduction resumes (e.g. Collot *et al.* 1995; see discussion below). If a significant volume of accretionary wedge material were accreted structurally beneath the ophiolite as a consequence of continued subduction, then the ridge–trench intersection ophiolite would become a Cordilleran-type ophiolite.

Emplacement of the Macquarie Island ophiolite

Interpretations of the emplacement of the Macquarie Island ophiolite include emplacement over a subduction complex (Dewey & Bird 1971) and emplacement antithetic to subduction (Coleman 1971). More recent studies have suggested that the Macquarie Island ophiolite has been thrust over oceanic crust as a consequence of transpression along a diffuse transpressional plate boundary (Varne *et al.* 2000; Goscombe & Everard 2001). In contrast, Frohlich *et al.* (1997) and Dazcko *et al.* (2002) suggested that there is no evidence for underthrusting of oceanic crust beneath Macquarie Island.

The Macquarie Island ophiolite differs from all other known ophiolites in that no lower-density material structurally underlies the ophiolite. The ophiolite structurally overlies either oceanic crust or suboceanic mantle. If the ophiolite overlies suboceanic mantle instead of underthrust oceanic crust, a good argument could be made that the Macquarie Island ophiolite is not emplaced at this time. Subduction may be initiating along segments of the transform plate boundary both north and south of Macquarie Island (Ruff *et al.* 1989; Collot *et al.* 1995; Frohlich *et al.* 1997). If subduction begins and then progresses beneath the ophiolite, the upper plate of the subduction zone may subside, leading to submergence of the ophiolite. Submergence of islands on the upper plate of the subduction zone has occurred along the northern part of the plate boundary, where subduction has only recently initiated (Collot *et al.* 1995). If the Macquarie Island ophiolite should experience such submergence in the future, it is likely that re-emergence of the ophiolite would occur only with significant underplating of a subduction complex beneath the ophiolite (converting the ophiolite to a Cordilleran-type) or collision of a passive continental margin (i.e. the western edge of the Campbell Plateau) with the subduction zone beneath the ophiolite (converting the ophiolite to a Tethyan-type).

Potential impact of complex plate interactions along irregular continental margins

The discussion of different types of ophiolite emplacement mechanisms has focused on 2D, cross-sectional views of emplacement processes. Such cross-sectional views assume regular continental margins and a uniformity of processes along the strike of a subduction zone; these features do not reflect the actual complexity of interactions observed along modern convergent plate margins (e.g. Hall 1996). Synchronous ophiolite emplacement and new oceanic crust generation may occur at some convergent plate boundaries, where the collision of an irregular continental margin with a trench may result in ophiolite emplacement at promontories whereas in slab-rollback, forearc magmatism and young ocean crust formation within embayments. Actualistic examples exist along the collision zone between the Indo-Australia plate and the Sunda arc–trench system, where the Australian continental margin is colliding with a segment of the trench south of Timor, whereas subduction of the Indian Ocean floor is proceeding along the Sunda Trench farther west (Harris 2003). As a consequence, emplacement of a single ophiolite may vary along-strike from collisional to accretionary. In addition to changes along the strike of a subduction zone, strike-slip faulting may play an important role in the juxtaposition of ophiolites with adjacent terranes (e.g. Hopson *et al.* 1996) and/or in lateral translation of ophiolites and 'suspect terranes' for long distances along-strike of an orogenic belt (e.g. Cowan *et al.* 1997).

Discussion: how should we define ophiolite emplacement?

Existing definitions of ophiolite emplacement in the literature, developed mainly for Tethyan ophiolites, clearly cannot be applied to other ophiolite types. Two geological events are common to all types of ophiolites despite their differing tectonic histories: (1) initiation of subduction beneath the ophiolite; (2) subaerial exposure of ophiolite. An emplacement definition that would apply to all ophiolites, with the possible exception of the Macquarie Island ophiolite, would be the inception of subduction beneath the ophiolite. However, using the inception of subduction as the definition of emplacement may create confusion because it would contradict decades of published emplacement definitions for Tethyan ophiolites.

Given that ophiolites are defined as 'on-land fossil oceanic crust', an argument could be made that subaerial exposure of an ophiolite characterizes its emplacement. To date, there are no submerged units of oceanic rocks that are called ophiolites (unless they are physically connected to a subaerial exposure). The only named ophiolite in the world that does not have a surface exposure is the 'Great Valley ophiolite' of California (Godfrey & Klemperer 1998; Coleman 2000; Godfrey & Dilek 2000), which is buried beneath several kilometres of sedimentary rocks of the Great Valley basin. Some may argue, however, that the Great Valley ophiolite does not truly fit the definition of an ophiolite because it is not exposed. Subaerial exposure of an ophiolite is generally fairly easy to define in the geological record, but it is not commonly associated with an important tectonic event in its history. Consequently, defining subaerial exposure as emplacement may not be as useful as the inception of subduction for the purposes of discussing ophiolite tectonic history. In addition, existing ophiolites can be submerged as a result of eustatic sea-level changes, subsidence, or tectonically induced burial by sediment and rock avalanches, leading to a potential for future 'unemplacement' of an ophiolite.

Another alternative is to consider emplacement as the entire process between subduction initiation and subaerial exposure of the ophiolite. Thus, geological events such as inception of subduction, thrusting over a continental margin (if applicable), and subaerial exposure become individual stages in the emplacement of an ophiolite.

A viable alternative would be to classify the emplacement mechanism according to the four prototypes discussed in this paper. Classifying the emplacement mechanisms using these four prototypes would require little modification of existing definitions, but complications still exist. For example, the potential for along-strike changes from accretionary to collisional emplacement can potentially complicate the use of a single emplacement classification for an ophiolite. In addition, closure of wide ocean basins following a protracted subduction history may result in the thrusting of an ophiolite and underlying accretionary wedge over a continental margin. In essence, this may 'convert' an emplacement mechanism from an 'accretionary' to a 'collisional' one in time. Another drawback of classifying emplacement mechanisms according to the four prototypes is the potential confusion resulting from our mechanistic rather than geographical use of the terms 'Cordilleran' and 'Tethyan'.

No single definition of emplacement is free of drawbacks in terms of the potential confusion that it may cause for readers of the ophiolite literature. Perhaps the best recommendation is for researchers to clearly specify what they mean by emplacement when they use the term, with the awareness that inception of subduction beneath an ophiolite is probably the only definition that would apply to all ophiolites.

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