CLASSIFICATION AND DISTRIBUTION OF OPHIOLITE

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ABSTRACT

Ophiolites, and discussions on their origin, classification and distribution as well as their significance in the earth’s history, have been instrumental in the formulation and establishment of the hypotheses and theories in earth sciences. However, here, I present a review of the distribution and the classification of ophiolite, incorporating the diversity in their structural architecture and geochemical signatures that result from variations in petrological, geochemical and tectonic processes during their formation in different geodynamic settings. I define ophiolite as pieces of oceanic plate that have been obducted onto the edge of continental plates or uplifted by accretionary uplift. Ophiolite was first described in the Alps in the early 20th century and was later discovered from almost every orogenic belt on the Earth. They are characterized by a classic sequence of rocks. This sequence is well exposed at the Semail ophiolite in Oman and Coast Range ophiolite of California. Subduction-related ophiolites which include supra-subduction -zone ophiolites developed during the closure of ocean basins and their evolution is governed by slab dehydration and accompanying metasomatism of the mantle, melting of the subducting sediments, and repeated episodes of partial melting of metasomatized peridotites. Subduction-unrelated ophiolites which include mid-ocean ridge type evolved during rift drift and seafloor spreading.
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Chapter one

1.0 INTRODUCTION TO OPHIOLITE

An ophiolite is a section of the earth’s oceanic crust and the underlying upper mantle that has been uplifted and exposed above sea level and often emplaced unto continental crustal rocks. Ophio is Greek for “snake”, lite means “stone” from the Greek lithos after the often green coloured rocks (spilites and serpentinites) that make up many ophiolites.

The term ophiolite was originally used by Alexandre Brongniart for an assemblage of green rocks (serpentinite, diabase) in the Alps; Steinmann later modified its use to include serpentinite, pillow lava and chert. This is known as steinmann’s trinity and is again based on occurrences in the Alps. The term was little used in other areas until the late 1950s to early 1960s, with the recognition that this assemblage provided an analog for oceanic crust and the process of seafloor spreading. This recognition was tied to two events

1. The observation of magmatic anomaly stripes on the seafloor, parallel to oceanic ridge systems, interpreted by Frederick Vine and Drummond Mathews to represent the formation of new crust at the oceanic ridge and its subsequent symmetric spreading away from that ridge.

2. The observation of a sheeted dike complex within the troodos ophiolite (Cyprus) by Lan Graham Gass and co-workers which must have formed by repetitive extension of crust and intrusion of magma resulting in a formation consisting of 100% dikes with no older wall rocks preserved within the complex.

Moores and Vine concluded that the sheeted dike complex at troodos could only form by a process similar to the seafloor spreading proposed by Vine and Mathews. Thus, it became widely accepted that ophiolites represent oceanic crust that has been emplaced on land.

1.1 OCCURRENCE AND DISTRIBUTION OF OPHIOLITE
Ophiolite was first described from the Alps in the early 20th century, and was later discovered from almost every orogenic belt on the earth. Semail ophiolite in Oman (Mesozoic), Troodos ophiolite in the Troodos Mountains of Cyprus (Mesozoic), Papua ophiolite in Papua-New Guinea (Mesozoic), and bay of islands ophiolite in Newfoundland (Paleozoic) are the best known. Yakuno (Paleozoic), Horokanai (Mesozoic) and Poroshiri (Mesozoic) are the three full-membered ophiolites in Japan, which also has many dismembered ophiolites such as Oeyama (Paleozoic), Miyamori (Paleozoic), Mikabu (Mesozoic) and Setegawa-mineoka (Cenozoic).

In collisional orogenic belts, ophiolites generally lie on older continental basement. In circum-pacific orogenic belts, however, ophiolites generally lie on younger accretionary complexes. For example, Jurassic Tamba accretionary complexes are overlain by the late Paleozoic Yakuno ophiolite, which is in turn overridden by the early Oeyama ophiolite. The younger Mikabu and Setegawa-Mineoka ophiolite underlies the Jurassic accretionary complexes in the Pacific coastal areas.

Most ophiolites can be divided into two groups: Tethyan and Cordilleran. Tethyan ophiolites are characteristic of those that occur in the eastern Mediterranean Sea area, e.g., Troodos in Cyprus and Semail in Oman, which consists of relatively complete rock series corresponding to classic ophiolite assemblage which have been emplaced onto a passive continental more or less intact. Cordilleran ophiolites are characteristic of those that occur in the mountain belts of western North America. These ophiolites sit on subduction zone accretionary complexes (subduction complexes) and have no association with passive continental margin. These include the Coast Range ophiolite of California, the Josephine ophiolite of Klamath Mountains (California, Orogen), and ophiolites in the southern Andes of South America. Despite their differences in mode of emplacement, both types of ophiolites are exclusively Supra-Subduction Zone (SSZ) in origin.

Ophiolites are found in all the major mountain belts of the world whether collisional (e.g. Himalayas) or not (e.g. Andes). The occurrence of ophiolites
throughout Earth history is not constant but rather they were formed and emplaced at specific intervals. These intervals correspond closely to times of super-continent break-up and dispersal, not because they form at the ridges that separate the drifting continents but because the large ocean basin that must coexist with any super-continent must subduct along new subduction zones as rifting processes.

1.2 OPHIOLITE PULSES

Reported formation ages of ophiolites show three distinct peaks at about 750, 450 and 150 Ma, respectively. These are called ophiolite pulses. Each pulse corresponds to the period of worldwide magmatic event as represented by voluminous granite intrusions.

Production rate of oceanic crust was distinctly high during the 80 and 120 Ma interval of Cretaceous time, as evidenced by wide area of the ocean floor formed in this interval. Magnetic reversals of the earth, which take place every million years, were unreasonably absent during this interval. These facts lead Larson (1991) to a hypothesis of super plume, a big plume of hot mantle rock which ascended from core/mantle boundary and erupted beneath the South Pacific Ocean during this interval, causing worldwide magmatic event. This interval corresponds to the later half of the Mesozoic ophiolite pulse.
1.3 OPHIOLITE BELTS ON THE EARTH

Ophiolites issued by each pulse tend to form a particular ophiolite belt. Late Proterozoic (750 Ma) ophiolite are distributed in the Pan-African orogenic belt, early Paleozoic (450 Ma) ophiolite appear in the Appalachian-Caledonian-Uralian belt, and Mesozoic (150 Ma) ophiolite dominate the Alpine-Himalayan belt. However, the circum-Pacific orogenic belts bear ophiolites of widely varying ages, including at least two pulses (early Paleozoic and Mesozoic). This may be due to continuous, subduction-induced, accretionary orogeny that have taken place in the circum-Pacific areas from early Paleozoic to the present, showing contract to the episodic, short-lived, collisional orogeny in the continental areas. Circum-Pacific ophiolites may be the best witnesses of the history of super plumes.
1.4 OPHIOLITES IN THE CIRCUM-PACIFIC OROGENIC BELTS

Ophiolites in the circum-pacific orogenic belts generally occur intercalated among the accretionary complexes and show multiple tectonic superpositions as exemplified by the Klamath Mountains in western USA as shown in the diagram below.

The oldest early Paleozoic ophiolite occupies structurally uppermost position, and younger ones take lower seats. Such “Confucian” ophiolite belts are also present in Japan and northeastern Russia, and forms “circum-Pacific Paleozoic multiple belts”. This structure may be formed by underplating of the accreted oceanic material and trench-fill sediments beneath the overlying SSZ lithosphere (ophiolite) and subsequent underplating of the younger SSZ-trench system.
The circum-Pacific ophiolite belts are also characterized by extreme petrologic diversity. Juxtaposition of depleted, clinopyroxene-free harzburgite and fertile lherzolite is common, though such a case is rare in the collisional orogenic belts.
Diagram of a simplified structure of an ophiolite suite:

1- Axial magma chamber
2- Pelagic sediments
3- Pillow basalts
4- Sheeted basaltic dykes
5- Intrusive, layered gabbro
6- Dunite/peridotite cumulates

The stratigraphic sequence observed in ophiolites corresponds to the lithosphere-forming processes at mid oceanic ridges:
Sediments: mud (black shales) and cherts deposited since the crust formed.

Extrusive sequence: basaltic pillow lavas show magma/seawater contact.

Sheeted dykes: vertical and parallel dykes which fed lavas above.

High level intrusive: isotropic gabbro indicative of fractionated magma chamber.

Layered gabbro, resulting from settling out of minerals from a magma chamber.

Cumulate peridotite: dunite-rich layers of minerals that settled out of magma chamber.

Tectonized peridotite: harzburgite/lherzolite rich mantle rocks

An international conference on ophiolite in 1972 redefined the term ophiolite to include only the igneous rocks listed above, excluding the sediments formed independently of the crust they sit on. This definition has been challenged recently because new studies of oceanic crust by the Integrated Ocean Drilling Program and other research cruises have shown that in situ ocean crust can be quite variable, especially in places where volcanic rocks sit directly on peridotite tectonite, with no intervening gabbros.

Scientists have only drilled about 1.5km into the 6-7km thick of the oceanic crust, so the understanding of oceanic crust largely comes from comparing ophiolite structure to seismic sounding of in situ oceanic crust. Oceanic crust has a layered velocity structure that implies a layered series similar to that listed above. In detail there are problems, with many ophiolites exhibiting thinner accumulations of igneous rock than are inferred for oceanic crust. Another problem relating oceanic crust and ophiolites is that the thick gabbro layer of ophiolites calls for large magma chambers beneath mid-ocean ridges. Seismic sounding has only revealed a few magma chambers and these are quite thin. A few deep drill holes into oceanic crust have intercepted gabbro, but are not layered like ophiolite gabbro.

The circulation of hydrothermal fluid through young oceanic crust causes serpentinization, alteration of the peridotites and alteration of minerals in the
gabbros and basalts to lower temperature assemblages. For example, plagioclase, pyroxenes and olivine in the sheeted dikes and lavas will alter to albite, chlorite and serpentine respectively. Often, ore bodies such as iron-rich sulfide deposits are found above highly altered epidosites (epidote-quartz rocks) that are evidence of (the now relict) black smokers which continue to operate within the seafloor spreading centers of ocean ridges today.

Thus, there is a reason to believe that ophiolites are indeed oceanic mantle and crust; however, certain problems arise when looking closer. Compositional differences regarding silica (SiO2) and titania (TiO2) contents, for example place ophiolite basalts in the domain of subduction zones (55% silica and <1% titania), whereas mid-ocean ridge basalt typically have 50% silica and 1.5-2.5% titania. These chemical differences extend to a range of trace elements as well. In particular, trace elements associated with subduction zone (island arc) volcanic tend to be high in ophiolites and trace elements that are high in ocean ridge but low in subduction zone volcanics are also low in ophiolites.

The crystallization order of feldspar and pyroxene in the gabbros is unexpectedly reversed, and ophiolites also appear to have a multi-phase magmatic complexity on par with subduction zones. Indeed, there is increasing evidence that most ophiolites are generated when subduction begins and thus represents fragments of fore-arc lithosphere. This lead to the introduction of the term “supra-subduction zone (SSZ)” ophiolite in the 1980’s to acknowledge that some ophiolites are more closely related to island arcs than ocean ridges. Ironically, some of the classic ophiolite occurrences used to relate ophiolites to seafloor spreading (e.g. Troodos in Cyprus and Semail in Oman) were found to be “SSZ” ophiolites formed by rapid expansion of fore-arc crust during subduction initiation.

A fore-arc setting for most ophiolites also solves the otherwise perplexing problem of how oceanic lithosphere can be emplaced on top of continental crust. It appears that continental crust, if carried by the down going plate into a subduction zone, will jam it up and cause subduction to cease, resulting in the rebound of the continental crust with fore-arc lithosphere (ophiolite) on top of it.
Ophiolites with composition comparable to hotspot-type eruptive settings or normal mid-oceanic ridge basalt are rare, and their examples are generally strongly dismembered in subduction zone accretionary complexes.

2.1 OPHIOLITE AND THE OCEANIC LITHOSPHERE

Ophiolite is interpreted to be thrust sheet of ancient oceanic lithosphere which has been obducted over the continental crust in the course of orogeny. The ophiolite succession can be correlated with the seismologic layering of the oceanic lithosphere as shown in the figure below.

![Ophiolite succession and seismic layers of oceanic crust](image)

The sedimentary cover corresponds to Layer 1, basaltic pillow lava matches Layer 2, sheeted dikes and gabbro with occasional plagiogranite intrusions are correlated to Layer 3, and ultramafic cumulates and residual mantle peridotite represent Layer 4 (mantle).
Chapter three

3.0 PETROLOGIC CLASSIFICATION OF OPHIOLITES

Ophiolites are classified into two types based on place of formation. Ophiolites may have formed either at divergent plate boundaries (mid-oceanic ridges) and are called mid-oceanic ridge “MOR” ophiolite, or it may be formed at convergent plate boundaries (supra-subduction zones; i.e. island arcs and marginal basins) and these are called supra-subduction zone “SSZ” ophiolites.

These types are identified by chemical composition of the rocks and minerals in comparison with those from various tectonic settings on the earth at present. Ophiolitic mantle peridotite is the refractory residue after extraction of basaltic melt through partial melting processes in the mantle. Although primary melting peridotite may be Iherzolite with abundant clinopyroxene, it changes into clinopyroxene-poor (or free) harzburgite as the degree of melting increases as shown in the figure below.
The mantle peridotite samples dredged from the mid-oceanic ridges are mostly lherzolite, while those dredged from supra-subduction zones (trench walls) are mostly harzburgite.

Ophiolitic igneous cumulates shows systematic variation in the crystallization sequence of minerals corresponding to the petrologic diversity of the underlying peridotite mantle. The mineral crystallizing next to olivine varies from plagioclase through clinopyroxene to orthopyroxene as the degree of melting in the underlying mantle increases. The characteristic cumulate rocks correspondingly vary from troctolite through wehrlite to harzburgite.

In general, Ophiolitic basalt also varies from alkali basalt to high-alumina basalt (like mid-ocean ridge basalt (MORB)) through low alumina-basalt (like island arc
tholeiite (IAT)) to boninite (high-magnesian andesite) in correspondence with the petrologic variation of the underlying members.

A recent review of ophiolites proposed a classification of ophiolites into seven different types:

1. Ligurian-type ophiolites formed during the early opening of an ocean basin like today’s Red Sea.
2. Mediterranean-type ophiolites formed during the interaction of two oceanic plates like today’s Izu-Bonin forearc.
3. Sierra-type ophiolites which represent complex histories of island-arc subduction like today’s Philippines.
4. Chilean-type ophiolites formed in a back-arc spreading zone like today’s Andaman Sea.
5. Macquarie-type ophiolites formed in the classic mid-ocean setting like today’s Macquarie Island in the Southern ocean.
6. Caribbean-type ophiolites which represent the subduction of oceanic plateaus or Large Igneous Provinces.
7. Franciscan-type ophiolites which are accreted pieces of oceanic crust scraped off the subducted plate onto the upper plate, as in Japan today.

3.1 SUPRA-SUBDUCTION OPHIOLITES;

THE LIFE CYCLE OF SUPRA-SUBDUCTION ZONE OPHIOLITES

The supra-subduction zone (SSZ) ophiolites display a consistent sequence of events during their formation and evolution that suggests that they form in response to processes that are common to all such ophiolites. This sequence includes the following:

1. Birth, which entails the formation of the ophiolite above a nascent or reconfigured subduction zone; this stage is typically characterized by the eruption of arc tholeiite lavas and the formation of layered gabbros and sheeted dike complex.
2. Youth, during which continued melting of refractory asthenosphere (depleted during birth) occurs in response to fluid flux from the subducting slab, with extensional deformation of the older plutonic suite, eruption of refractory lavas, and the intrusion of wehrlite-pyroxenite.

3. Maturity, with the onset of semistable arc volcanism, typically calc-alkaline, as the subduction zone matures and stabilizes, and the intrusion of quartz diorite and eruption of silicic lavas.

4. Death, which is the sudden demise of active spreading and ophiolite-related volcanism, which in many cases is linked to collision with an active spreading center and the onset of shallow underthrusting of the buoyant spreading axis; expressed as dikes and lavas with oceanic basalt compositions that crosscut or overlie rocks of the older suites.

5. Resurrection, which is emplacement by obduction unto a passive margin or accretionary uplift with continued subduction.

The early stages (1-3) may be diachronous, and each stage may overlap in both time and space. The existence of consistent progression implies that ophiolite formation is not a stochastic event but is a natural consequence of the SSZ tectonic setting.

These events generally progress in an orderly fashion from birth through death and resurrection, but not all ophiolite display all stages of this proposed life cycle. In particular, some SSZ ophiolites never reach maturity but skip directly to death and resurrection. In others, death and resurrection are coincident, with no evident for a prolonged interval between these events. The birth and youth stages seem to be common to all SSZ ophiolites and are in fact the most characteristic phases of ophiolite growth in a SSZ setting. The structural aspects of resurrection are also characteristic of all SSZ ophiolites and reflect their original formation in the upper plate of a subduction zone. In all cases, the relative progression of events is consistent from ophiolite to ophiolite, so that events occur in the same relative order even if evidence for some stages of development is missing.
Detailed studies of well-exposed ophiolites over the last 20 years have shown that many formed in the supra-subduction zone (SSZ) settings; that is, in the upper plate at a convergent plate boundary, and not at mid-ocean ridge spreading centers. The supra-subduction zone setting encompasses the early evolution of nascent or reorganized subduction zones, prior to the onset or renewal of emergent arc volcanism and plutonism, and includes processes that lead to arc rifting and the formation of fore-arc and intra-arc basins.

Subduction zone ophiolites have many features in common that indicate a consistent sequence of events during their formation and evolution. In this contribution, I review the sequence of plutonic and volcanic units that are common to most supra-subduction zone ophiolites, their petrologic and geochemical characteristics, and their inferred origins within the supra-subduction zone environment. I will also examine events that may lead to the death of these ophiolites, and their subsequent resurrection as they are emplaced at structural levels in the crust that expose them for our study.

Supra-subduction zone ophiolites sensu lato include both those formed in back arc basins (e.g., the Josephine ophiolite of northern California and southern Oregon) and those that contain rocks typically associated with fore arc extension (e.g., Troodos, Oman, and the Coast Range ophiolite of California). Back arc ophiolite are characterized by lithologic associations and geochemical systematic grossly similar to mid-ocean ridge basalts (MORB); Ophiolites formed in this setting are for the most part indistinguishable from MORB geochemically and can only be associated with a back arc origin by careful study of the regional geologic setting. I will focus here on those ophiolites thought to be associated with fore arc rifting. These constitute most of the major ophiolite occurrences of the world, including those that are commonly used as structural analogues for oceanic crust.

One of the most robust models for SSZ ophiolite formation is that of Stern and Bloomer (1992), which builds on earlier work by Hawkins et al. (1984), Casey and Dewey (1984), Leitch (1984), and others. This model proposes that ophiolites generally form during subduction zone initiation, when old, relatively dense, oceanic lithosphere begins to sink into the asthenosphere. Lithosphere in the
upper plate adjacent to the sinking lithosphere sinks. Crustal formation is fed by melts from hot asthenosphere that must flow upward into the region above the sinking plate margin, even as the sinking plate displaces the asthenosphere below itself (Stern and Bloomer, 1992). Melting of the hot asthenosphere that flows into the gap created by the sinking plate margin is enhanced by a massive fluid flux from the sinking lithosphere. This combination of rapid decompression melting with fluid enhanced by lowering of solidus leads to extensive melting of the shallow asthenospheric wedge, creating refractory lavas such as boninites and high-Mg andesites and leaving an even more refractory residue of harzburgite tectonite (Stern and Bloomer, 1992). A similar progression could also form during major reorganizations of plate boundaries.

3.2 PETROLOGIC AND GEOCHEMICAL SIGNATURES OF SUPRA-SUBDUCTION ZONE OPHIOLITES

The supra-subduction zone ophiolites have been reviewed by many investigators including Miyashiro (1973), Wood (1980), Pearce (1982), Shervais (1982), Pearce et al. (1984), Harris et al. (1986), and Pearce and Parkinson (1993).

These geochemical signatures result from processes or conditions that are unique to subduction zones or that are enhanced within the subduction zone environment. As a result, likely candidates for formation within a supra-subduction setting are ophiolites that are characterized by the geochemical and isotropic signatures listed below:

1. Enrichment in large ion lithophile element (LILE: K, Rb, Cs, Th) and the light rare earth elements (LREE) relative to normal MORB (NMORB) in response to aqueous fluids or melts expelled from the subducting slab. (e.g., Pearce, 1982; Wood, 1980). These elements correspond in general to the low field strength elements of Saunders et al. (1980). Some LILE (e.g., K, Rb, and Ba) tend to be soluble in aqueous solutions or melts during slab dewatering reactions; others (Th, LREE) are relatively immobile during alteration.
2. Depletion in the high field strength elements (HFSE: Ti, Nb, Ta, Hf) relative to NMORB, which may be caused by larger fractures of partial melting, also in response to aqueous fluids or melts expelled from the subducting slab (e.g., Pearce, 1982; Pearce and Norry, 1979; Shervais, 1982; Wood, 1980).

3. The common occurrence of refractory, second stage melts with high MgO (more olivine in source), and high LILE (slab component added with aqueous fluid or melt expelled from the subducting slab) [Crawford et al., 1988; Juteau et al. 1988; Malpas, 1990; Robinson and Malpas, 1990].

4. Higher oxygen fugacities than NMORB, as reflected by low Ti/V ratios in arc volcanic and in supra-subduction zone ophiolites, and by the occurrence of calc-alkaline fractionation trends in some arc volcanic suites.

5. The typical occurrence of clinopyroxene before plagioclase during crystallization, resulting in the crystallization sequence olivine-clinopyroxene-plagioclase instead of the typical MORB crystallization sequence olivine-plagioclase-clinopyroxene [Cameron et al., 1980; Herbert and Laurent, 1990].

6. The common occurrence of highly calcic plagioclase and/or orthopyroxene in some cumulate plutonic rocks caused by changes on the phase equilibria during hydrous melting and crystallization [e.g., Beard, 1986; Herbert and Laurent, 1990].

7. The association with refractory lithosphere comprising harzburgite tectonites and dunite in contrast to the more fertile abyssal Iherzolite commonly found with oceanic crust [e.g., Dick, 1989; Dick and Bullen, 1984].

8. Mineral compositions in the lavas and mantle tectonites that are refractory compared to those found in oceanic basalts and abyssal peridotites, e.g., Cr spinels with high Cr/Al ratios and low Mg/Fe ratios [Cameron, 1985; Crawford et al., 1989; Dick, 1989; Dick and Bullen, 1984; Umino et al., 1990].

9. Enrichment in the radiogenic isotopes of Sr and Pb, resulting in higher 87Sr/86Sr, 206Pb/204Pb ratios, and depletion in radiogenic Nd, resulting
in lower 143Nd/144Nd ratios, in the volcanic rocks relative to MORB [e.g., Cohen and O’Nions, 1982; Hanan and Schilling, 1989; Noiret et al., 1981; Sun, 1980].

3.3 MID-OCEAN RIDGE BASALT (MORB) OPHIOLITES WITH ARC SIGNATURES

There are few circumstances in which oceanic igneous rocks with these signatures (listed above for supra-subduction zone ophiolites) are erupted in mid ocean spreading ridge settings. One is when a subduction zone flips polarity, leaving relict back arc crust and its subduction–enriched lithosphere and asthenosphere in front of the new crust is formed at a spreading center in this location (which is likely if back arc spreading was active prior to the polarity flip), this crust will carry the memory of its former position in the upper plate of a subduction zone. The classic example of this process is the Woodlark Basin in the SW pacific, which was a back arc basin to the Solomon islands arc prior to its collision with the Ontong Java plateau [Perfit et al., 1987; Staudigel et al., 1987; Taylor and Exon, 1987].

The other special circumstance is found where subduction of an active spreading center occurs at high angles to the subduction zone. In this case, a “slap window” opens inside the subduction zone in response to the extinction of the spreading center when it enters the trench. Active spreading in front of the subduction zone continues to form new oceanic crust, leaving a wedge-shaped opening or “window” in the subducting slap. This window allows subduction- enriched asthenosphere to rise through the slap into the region of active spreading; in the same manner that plume-enriched mantle flows outward along a sublithospheric conduit beneath active spreading centers [e.g., Hanan and Schilling, 1989]. The best example of this process is where the south Chile Rise is subducted beneath South America slap [Karsten et al., 1995; Sherman et al., 1997; Klein and Karsten, 1995; Sturm et al., 1999].

These observations show that it is possible to create oceanic crust at mid-ocean ridge spreading centers that resemble arc tholeiites and many explain the origin of SSZ ophiolites that are structurally associated with the lower plate in the
subduction. However, these settings do not explain the occurrence of the later magma suites in SSZ ophiolites, nor do they solve the problem of how large intact sheets of ocean crust are transferred to the upper plate and obducted onto passive continental margins.

Nonetheless, these examples show that it is not possible to establish the origin of any particular ophiolite on the basis of geochemical discriminants alone. Each ophiolite must be evaluated based on its structural setting, its associated sedimentation, and its relationship to adjacent terranes, in addition to any geochemical fingerprinting.

3.4 CLASSIFICATION OF MOR OPHIOLITE

The MOR-type ophiolites can be classified further into two:

1. Those formed in slow-spreading environments
2. Those formed in fast-spreading environments

Slow-spreading or continental rift settings are thought to give rise to ophiolites with Iherzolitic mantle sections corresponding to low degrees of melt depletion. Slow-spreading ridges have incomplete, highly faulted sections, with surface exposure of serpentinite and gabbro, similar to ophiolites in the western Mediterranean (Alps and Apennines).

Fast-spreading settings are thought to give rise to ophiolites with harzburgitic mantle sections formed by high degrees of melt depletion. Fast-spreading ridges exhibit a complete ophiolite sequence with minimal crustal attenuation, similar to that of Semail complex.

There are also intermediate MOR ophiolites which resemble sections of the Ordovician ophiolite of Norway. The obvious inference is that the Semail complex, the Norwegian ophiolites and the western Mediterranean ophiolites formed at fast, intermediate and slow spreading ridges respectively.
3.5 DIFFERENCES BETWEEN SUPRA-SUBDUCTION ZONE (SSZ) OPHIOLITES AND MID-OCEAN RIDGE (MOR) OPHIOLITES.

The supra-subduction zone ophiolites (SSZ) differ from mid-oceanic ridge (MOR) ophiolites not only in their geochemistry but also in the more depleted nature of their mantle sequences, the more common presence of podiform chromite deposits, and the crystallization of clinopyroxene before plagioclase which is reflected in the high abundance of wehrlite relative to troctolite in their cumulate sequences. This occurrence of clinopyroxene before plagioclase during crystallization results in the crystallization sequence of olivine-clinopyroxene-plagioclase in SSZ instead of the typical MORB crystallization sequence of olivine-plagioclase-clinopyroxene. The association with refractory lithosphere in SSZ comprising harzburgite tectonites and dunite in contract to the more fertile abyssal lherzolites commonly found with mid-oceanic ridge. SSZ ophiolites have higher oxygen fugacities than the MOR ophiolites, as reflected by low Ti/V ratios in arc volcanic and in supra-subduction zone ophiolites, and by the occurrence of calc-alkaline fractionation trends in some arc volcanic suites.
Chapter four

4.0 SIGNIFICANCE OF OPHIOLITE OCCURRENCE

1. The great significance of ophiolites relates to their occurrence within mountain belts such as the Alps and Himalayas where they document the existence of former ocean basins that have now been consumed by subduction. This insight was one of the founding pillars of plate tectonics and ophiolites have always played a central role in the plate tectonic theory and the interpretation of ancient mountain belts.
2. The structure of well preserved ophiolite complexes can be used as an indicator of past spreading rates and would become a powerful tectonic tool.
3. Ophiolites have been of particular importance in the reconstruction of ancient plate boundaries ever since their recognition as on-land fragments of oceanic lithosphere. Thus ophiolites complements significantly our knowledge of the architecture and generation of oceanic crust that is derived mainly from seismic images and drill holes at Mid Oceanic Ridge (MOR).
4. Knowledge on ophiolite complexes and their locations provide valuable information about the origin, occurrence and distribution of certain economically important mineral deposits like sulphides of copper, zinc and iron.
5. Ophiolites mark the interface between continental and oceanic derived rock assemblage and the timing of juxtaposition depend upon the age of the basal metamorphic sole to the ophiolite.
6. The oldest oceanic crust is dated at approximately 200 million years so dating of ophiolite which is significantly older than the oldest oceanic crust provides evidence for longtime operation of plate tectonic mechanism and seafloor spreading.
7. Using data from the studies of ophiolite complexes, geologists are able to determine the scenario for ocean crust formation according to material composition.

The magma up-welled from spreading centers or rift zones originate from partially melted peridotite in the asthenosphere. Because of its molten state, it is less dense than surrounding solid rocks causing the magma to move upward from its initial source (35km below the seafloor) to a portion very near the ridge crest. The upward migration causes the ocean floor to open (pushed and pulled at different point) allowing the magma to erupt to the surface. The initial flow is fluid causing it to spread broadly and thinly at spreading centers. New layers of lava overlay former ones later. Magma stored in the nearer source tends to cool.
and thicken over time and forms into pillow lava upon flow. Pillow lava can grow as high as mountains and will eventually be detached from the magma source, leaving it to be carried away by the spreading seafloor. The magma material that is not upwelled crystallizes at depth creating what are known as gabbros. As the oceanic crust is pushed and pulled in either sides, the materials are also displaced and mantled by other materials, mostly deep sea sediments.

This process explained above simultaneously explains the spreading of the seafloor and the generation of the structure of the oceanic crust which is thought to be equivalent to the entire sequence of the ophiolite suite. In addition to exposing ocean crust, ophiolites also often expose a section of the underlying mantle. Since scientists have never drilled deep enough into the earth to observe the mantle, ophiolite are important because they are places where geologists can observe large sections of mantle rocks directly.
5.0 CASE STUDY: COAST RANGE OPHIOLITE OF CALIFORNIA

The Coast Range ophiolite of California is a typical Cordilleran ophiolite of Moore. It differs from Tethyan ophiolites like Troodos and Semail largely in its mode of emplacement, or rather, its lack of emplacement. Unlike typical Tethyan ophiolites, which are obducted onto passive continental margins, the Coast Range ophiolite (CRO) of California have been emplaced by accretionary uplift: the underplating of material in the accretionary prism, which gradually lifts the overlying ophiolite until collapse of the accretionary wedge preserves the ophiolite along low angle normal faults. New and revised U/Pb zircon dates for evolved rocks in the CRO show that it is somewhat older than recognized previously, with most dates falling in the range of 172 to 165 Ma, although younger dates of about 145 Ma are still found in the Del Puerto Canyon ophiolite remnant. This corresponds to the middle Jurassic shortly after the initiation of spreading in the North Atlantic and during a time of plate reorganization along the Cordilleran margin.

5.0.1. STAGE 1 (BIRTH) IN THE COAST RANGE OPHIOLITE

Stage 1 in the Coast Range ophiolite of California is represented in most locales by layered gabbros and dunites of the plutonic complex, much of the sheeted dike/sill complex, and by plagioclase-clinopyroxene phryic arc tholeiite lavas that form the so-called “lower volcanic series”. The layered gabbro often display solid-state deformation fabrics, including foliation, deformed layering, and high temperature normal-faults. The dunites and layered gabbros are typically crosscut by later stage 2 intrusions or form xenoliths within the later stage 2 intrusions. Calculated parent magmas of the layered gabbros are light rare earth element (LREE) depleted arc tholeiite magmas similar to the plagioclase-clinopyroxene phryic lower volcanic series.

Initiation of stage 1 subduction probably occurred in response to an increase in convergence rate in the middle Jurassic that was associated with opening of
the central North Atlantic circa 175 Ma and collapse of a fringing arc against the western margin of North America.

5.0.2. STAGE 2 (YOUTH) OF COAST RANGE OPHIOLITE

Stage 2 in the Coast Range ophiolite is represented by an ultramafic intrusive complex and by an upper volcanic series of which include olivine-clinopyroxene phryic basalts, high-Mg andesites, and boninites. The ultramafic intrusive complex includes wehrlites, clinopyroxenites, harzburgites, primitive pegmatoidal gabbros, and some isotropic gabbros and diorites. These rocks crosscut layering and foliation in the older layered gabbro. They commonly form sill-like complexes at the base of the layered gabbro as well as stocks which intrude to higher levels in the ophiolite; these high level intrusions may form igneous megabreccias as they subsume the older layered gabbros. The stage 2 volcanic rocks include olivine-pyroxene basalts and basaltic andesites, often with Cr rich spinel microphenocrysts. Rocks with boninitic affinities (high Si, Mg, Cr, and Ni) occur at several Coast Range ophiolite localities, including Cuesta Ridge and Del Puerto Canyon.

5.0.3 STAGE 3 (MATURITY) OF COAST RANGE OPHIOLITE

Stage 3 in the Coast Range ophiolite is clearly expressed in localities east of the San Andreas Fault (Sacramento Valley, Diablo Range) by extensive plutons and sills of diorite, quartz diorite, and hornblende quartz diorites, and by lavas and tuffs of andesite, dacite, and rhyolite. The intrusive rocks include sills of quartz keratophyre (andesite) up to 30m thick, as well as tuffs and sill-like plutons of hornblende diorite and hornblende quartz diorite up to 1 km thick and several kilometers long. The late intrusive commonly form igneous breccias (agmatites) in which xenoliths of dike complex, volcanic rock, older isotropic gabbro, and layered gabbro are submerged in a matrix of diorite or quartz diorite. Stage 3 volcanic rocks include pillows, flows, and volcaniclastic breccias of basaltic andesite, andesite, dacite, rhyolite, and extensive tuffs of dacitic to
rhyolitic compositions. These volcanic rocks form horizons up to 1.2 km thick on top of the older volcanic rocks. In places (e.g., the “Crowfoot Point Breccia” at the Elder Creek ophiolite) these volcanic flows and breccias were reworked to form sedimentary breccias that unconformably overlie the ophiolite igneous complex but that are conformable with the overlying Great Valley Series. These sedimentary breccias record tectonic disruption of the ophiolite shortly after its formation and prior to deposition of sediments in the forearc basin beginning in the late Tithonian.

In the West of the San Andreas and Sur Nacimiento faults, stage 3 is represented by less extensive intrusions of plagiogranite in the upper plutonic complex, by sill complexes of keratophyre, quartz gabbro, hornblende diorite, and quartz diorite, and by volcanic ash-rich radiolarian cherts that overlie the upper volcanic series.

5.0.4 STAGE 4 (DEATH) OF COAST RANGE OPHIOLITE

Death came to Coast Range ophiolite in the northern Coast Ranges with subduction of an active spreading ridge in the earliest late Jurassic. Evidence for a ridge subduction event is found throughout the Sacramento Valley and Diablo Range; this evidence includes the following:

1. Late dikes with MORB geochemistry that crosscut plutonic and volcanic rocks of the earlier (stage 1 through stage 3) igneous cycles at Elder Creek, Del Puerto Canyon, Mount Diablo, Sierra Azul and Cuesta Ridge.
2. Pillow lavas with MORB geochemistry that are intercalated with sedimentary breccias above the Elder Creek ophiolite.
3. Pillow lavas that compose the upper part of the ophiolite sequence at the Black Mountain and Mount Diablo.
4. The Stonyford Volcanic complex, a seamount that preserves fresh volcanic glass with ocean island basalt (OIB), alkali basalt, and high-Al basalt intercalated with radiolarian cherts similar to those that cap the Coast Range ophiolite elsewhere.
5. Globules of immiscible MORB-composition basaltic glass within the Leona rhyolite. This event has been dated at 163 Ma in the northern Coast Ranges, based on 39Ar/40Ar dates of volcanic glass from the Stonyford Volcanic Complex, but may be younger in the Diablo Range, where stage 3 volcanism persisted until 150 Ma.

5.0.5. STAGE 5 (RESURRECTION) OF COAST RANGE OPHIOLITE

Resurrection of Coast Range ophiolite did not occur by obduction, since the western margin of North America has not collided with a passive continental margin since the CRO formed. It was emplaced instead by the process of accretionary uplift. Accretionary uplift is the process through which uplift of the ophiolite occurs in response to progressive underplating of the ophiolite by the accretionary prism in the subduction zone. As material is accreted in the subduction zone beneath the ophiolite, the ophiolite is progressively elevated, until gravitational collapse of the accretionary complex begins to exhume rocks subjected to high-pressure metamorphism, while the overlying ophiolite is preserved in the upper plate of the detachment fault. During its life overlying the accretionary complex, the ophiolite may undergo several cycles of uplift and detachment faulting. Changes in relative plate motions and convergence directions can even lead to the onset of compressional tectonics and the juxtapositioning of units along thrust faults; these changes are characteristics of CRO tectonics during the Neogene.
CHAPTER SIX

6.0 CONCLUSION

It is clear from the preceding discussion that ophiolites represent a section of the crust and the underlying upper mantle that has been obducted or subducted onto the continental margin. Ophiolites will only be preserved where the “ophiolite-forming” process is arrested during its early stages of development (“death”) and where later tectonic events lead to exposure through obduction or accretionary uplift (“resurrection”). These conditions are typically found in collisional environments, which are thus the most common setting for preservation of ophiolites. Ophiolites are classified into two namely Mid-oceanic ridge ophiolites (MOR) and Supra-subduction ophiolites (SSZ) based on place of formation. MOR ophiolites are those that formed at divergent plate boundaries while SSZ are those that formed at convergent plate boundaries. Ophiolite was first described from the Alps in the early 20th century, and was later discovered from almost every orogenic belt on the earth. Ophiolites are found in all the major mountain belts of the world whether collisional (e.g. Himalayas) or not (e.g. Andes).
REFERENCES


