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Ophiolites 1: From the Beginning to Modern Times

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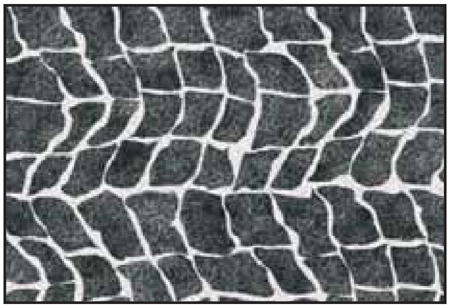
Article abstract

This paper on ophiolites is the first of four that will appear in Geoscience Canada; it reviews a fascinating history dating back to the very first, glorious days of field mapping in the western Alps in the 1800s. Originally used to describe serpentinites, the term ophiolite progressively evolved to designate a field association (rock clan) of peridotites, gabbros, and radiolarites. Early on, the deep ocean origin of this association was recognized. Recognition of the ophiolitic rock clan in North America was late, due to conflicts among field geologists, experimental petrologists, and marine geologists. The advent of plate tectonic theory helped put the ophiolitic rock clan in the right geodynamic context with respect to mountain belts. Also, the clan was expanded to include pillow lavas, sheeted dikes, abyssal sedimentary rocks, and other metamorphic units. Starting in 1957, it was clear that the basal peridotites were partly derived from the upper mantle and some others derived by crystal fractionation processes, as defined by Bowen. This basal peridotite and the rest of the rock clan constituted the so-called Penrose-type stratigraphy as defined in 1972. Since then, countless studies have shown that ophiolites are transported sheets, a concept fitting plate tectonic theory and the Wilson cycle. Still debated is the geodynamic significance of ophiolites. Are they produced in large ocean basins at mid-ocean ridges or in more confined settings like forearcs, arcs or back-arc basins close to continental margins? Decades of research have shown that Penrose-type ophiolitic sequences can be produced in a variety of geodynamic settings and with complex geochemical attributes. This new approach led to the possibility that ophiolites could be present throughout the geological column and particularly in Precambrian terrains. Originally thought to begin in Neoproterozoic time, ophiolite sequences are now thought to be found in the Archean but those older than 1 Ga have different stratigraphy and geo-chemical compositions. However, these differences are currently matters of debate. The new concept of Precambrian ophiolites might shed light on the early mechanisms controlling the mobile parts of the Earth.

SERIES



Igneous Rock Associations 9. Ophiolites 1: From the Beginning to Modern Times

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SUMMARY

This paper on ophiolites is the first of four that will appear in Geoscience Canada; it reviews a fascinating history dating back to the very first, glorious days of field mapping in the western Alps in the 1800s. Originally used to describe serpentinites, the term ophiolite progressively evolved to designate a field association (rock clan) of peridotites, gabbros, and radiolarites. Early on, the deep ocean origin of this association was recognized. Recognition of the ophiolitic rock clan in North America was late, due to conflicts among field geologists, experimental petrologists, and marine geologists. The advent of plate tectonic theory helped put the ophiolitic rock clan in the right geodynamic context with respect to mountain belts. Also, the clan was expanded to include pillow lavas, sheeted dikes, abyssal sedimentary rocks, and other metamorphic units. Starting in 1957, it was clear that the basal peridotites were partly derived from the upper mantle and some others derived by crystal fractionation processes, as defined by Bowen. This basal peridotite and the rest of the rock clan constituted the so-called Penrose-type stratigraphy as defined in 1972. Since then, countless studies have shown that ophiolites are transported sheets, a concept fitting plate tectonic theory and the Wilson cycle. Still debated is the geodynamic significance of ophiolites. Are they produced in large ocean basins at mid-ocean ridges or in more confined settings like forearcs, arcs or back-arc basins close to continental margins? Decades of research have shown that Penrose-type ophiolitic sequences can be produced in a variety of geodynamic settings and with complex geochemical attributes. This new approach led to the possibility that ophiolites could be present throughout the geological column and particularly in Precambrian terrains. Originally thought to begin in Neoproterozoic time, ophiolite sequences are now thought to be found in the Archean but those older than 1 Ga have different stratigraphy and geochemical compositions. However, these differences are currently matters of debate. The new concept of Precambrian ophiolites might shed light on the early mechanisms controlling the mobile parts of the Earth.

SOMMAIRE

Dans ce premier article de quatre des « Igneous Rock Associations 9 »de Geoscience Canada sur les ophiolites on découvre une histoire fascinante qui remonte aux temps glorieux des premiers levés géologiques dans les Alpes occidentales au XIXème siècle. D'abord utilisé pour décrire principalement les serpentinites, le terme ophiolite a progressivement évolué pour désigner une association géologique de terrain comprenant des péridotites, des gabbros et des radiolarites dont on a perçu très tôt leur origine marine profonde. Le terme ophiolite a mis beaucoup de temps avant d'être introduit dans la littérature nord-américaine pour cause de mésentente idéologique entre les géologues de terrain, les expérimentalistes et les géologues marins. La croissance rapide des données marines qui ont conduit à l'énoncé de la théorie des plaques a permis de replacer géodynamiquement cet ensemble lithologique auquel on a associé depuis les laves en coussins, les complexes filoniens, les sédiments abyssaux et autres lithologies métamorphiques dérivées. Il devenait clair à partir de 1957 que les péridotites basales originaient du manteau. La partie crustale supérieure des ophiolites équivalait à une séquence se formant selon les règles de la cristallisation fractionnée énoncées par Bowen et surmontée de laves sous-marines elles-mêmes coiffées de sédiments abyssaux. C'est la stratigraphie de type Penrose définie en 1972. Depuis, les nombreux travaux de recherche sur les ophiolites ont montré que ces séquences étaient transportées appuyant du même coup la théorie de la tectonique des plaques et le fameux cycle de Wilson. Les ophiolites sont toujours sujettes à controverses quant à leur signification géodynamique. Proviennent-elles de grands bassins océaniques et formées en contexte de dorsales en expansion ou bien, de bassins plus restreints en marge des continents où des dispositifs en expansion comme les avant-arcs, les arcs et les bassins arrière-arcs peuvent générer une stratigraphie de type Penrose et expliquer leur complexe composition géochimique? Cette vision plus large de la formation des ophiolites a permis que les ophiolites soient reconnues dans des ensembles lithologiques de plus en plus anciens du Protérozoïque supérieur puis progressivement jusqu'à l'Archéen. Les séquences plus anciennes que 1 Ga sont distinctes en ce qui a trait à leur stratigraphie interne et leur composition géochimique. La signification de ces différences fait l'objet d'un débat contemporain. Les séries ophiolitiques précambriennes pourraient nous en apprendre beaucoup sur les mécanismes et le fonctionnement des premières parties mobiles terrestres.

INTRODUCTION

Ophiolites are tectonically transported assemblages of peridotite and other ultramafic rocks, gabbro, diabase, and mafic pillow lavas, commonly capped by chert or other pelagic sedimentary rocks. They occur in linear zones in many mountain belts of the world. Ophiolites are generally interpreted as fragments of oceanic crust and mantle that have been thrust ("obducted") onto the adjacent continental margin. They commonly have a metamorphic sole and are thrust over complex mélanges of sedimentary and volcanic rocks. They attest to the presence of ancient oceans and allow interpretations of seabed geology, specifically the workings of magmatic, hydrothermal, and metamorphic processes that occurred in the oceanic environment.

Ophiolites have always occupied a very strategic place on the podium of scientific investigations of mountain belts and have had a profound impact on our understanding of the evolution of ocean basins. Even though ophiolites have been investigated for a long time, a formal definition of an ophiolite was not internationally adopted until the early 1970s, i.e. an ophiolite is a distinctive association of plutonic ultramafic and mafic rocks, hypabyssal and volcanic mafic rocks and deep-sea sediments (Anonymous, 1972; Fig. 1). More than 180 years after the introduction of the term ophiolite by Brongniart (1813), a tremendous amount of geologic information has been accumulated, and it is time to summarize what has been learned so far, from a Canadian perspective, and to discuss the most important issues remaining to be deciphered.

This paper is the first of four that are planned for publication in Geoscience Canada under the Igneous Rock Associations Series. This one focuses on the evolution of the concepts that have given ophiolites their star status in the Earth Sciences and Geodynamics. Some of these concepts were developed here in Canada, and it is important to sort out the impact of these particular findings on the ophiolitic and oceanographic communities for the historical record. The second paper will discuss the architecture, petrography, and petrology of ophiolites, and their variability in time and space, with special attention to geodynamic consequences and possible modern analogues. The third paper will synthesize a large geochemical database for ophiolites, and summarize petrogenetic implications and controversies. The fourth paper will focus on future developments in ophiolite studies, and try to encourage Canadian contributions to this fascinating field of science.

HISTORICAL DEVELOPMENT OF OPHIOLITE CONCEPTS

Pre-1960

The first use of the word, ophiolite, is attributed to Brongniart (1813, 1821, and 1827). The term is derived from the Greek root "ophi", meaning snake, probably reflecting the green colour, structure and texture of ultramafic rocks, and "lithos" meaning rock. The term was used initially to designate serpentinite and later on, a suite of mafic and ultramafic intrusive rocks (ultramafic rocks, gabbro, and diabase) and volcanic extrusive rocks (Brongniart 1821). Subsequently, Fouqué and Michel Lévy (1879) used a derivative term "ophite" to describe diabase or dolerite. The term "alpine peridotite" was used by Benson (1926) to designate the deformed and serpentinized peridotites found in ophiolites. The reader is referred to Amstutz (1980), for a detailed history on the early use of the term ophiolite.

The modern sense of the term, ophiolite, is attributed to Gustav Steinmann (1905, 1927). His benchmark paper in 1927, which had been presented at the XIV International Geological Congress in Madrid in 1926, described the field relationships among a series of rocks comprising serpentinite, diabase, and radiolarite. In this paper, he proposed to use the term ophiolite to name this rock association. The English version of this paper entitled: "Ophiolite concept and the evolution of geological thought", translated by Bernouilli and Friedman in 2003, was published in Geological Society of America Special Paper 373 (see Steinmann 2003). In this remarkable paper, Steinmann clearly attributed a deep ocean floor origin for the ophiolitic association and established the petrogenetic relationship between ultramafic and mafic rocks, which were believed to have intruded the oceanic sedimentary rocks during a major mountain-building (orogenic) event. The association of serpentinite, diabase, and radiolarite led to the term "Steinmann's trinity", which then spread through the literature.

De Roever (1957) was the very first to propose a mantle origin for the peridotite unit, the tectonic emplacement of ophiolite, and the consanguinity of mafic and some ultramafic units. Later, Brunn (1959) noted the resemblance between rocks of the Mid-Atlantic Ridge and ophiolite sequences.

The 1960s and 1970s

A series of classical papers in the 1960s interpreted the origin of ophiolites within the framework of plate tectonics that was being developed at that time (Oliver et al. 1969; Coleman 1971; Dewey and Bird 1971; Moores and Vine 1971). The key papers are those by Gass (1963), Dietz (1963), Hess (1962, 1965), Vuagnat (1968), Ricou (1968), Moores (1969), and Thayer (1969). Geophysical evidence suggested that the layering of oceanic crust reflected the internal rock succession found on land in ophiolite complexes (Salisbury and Christensen 1978, and references therein). As early as 1963, Thayer (1969) proposed that a magma chamber was required to generate the cumulate pile over the basal peridotites. Vuagnat (1968) then suggested that the term ophiolite should be restricted to ultramafic and mafic sequences, com-

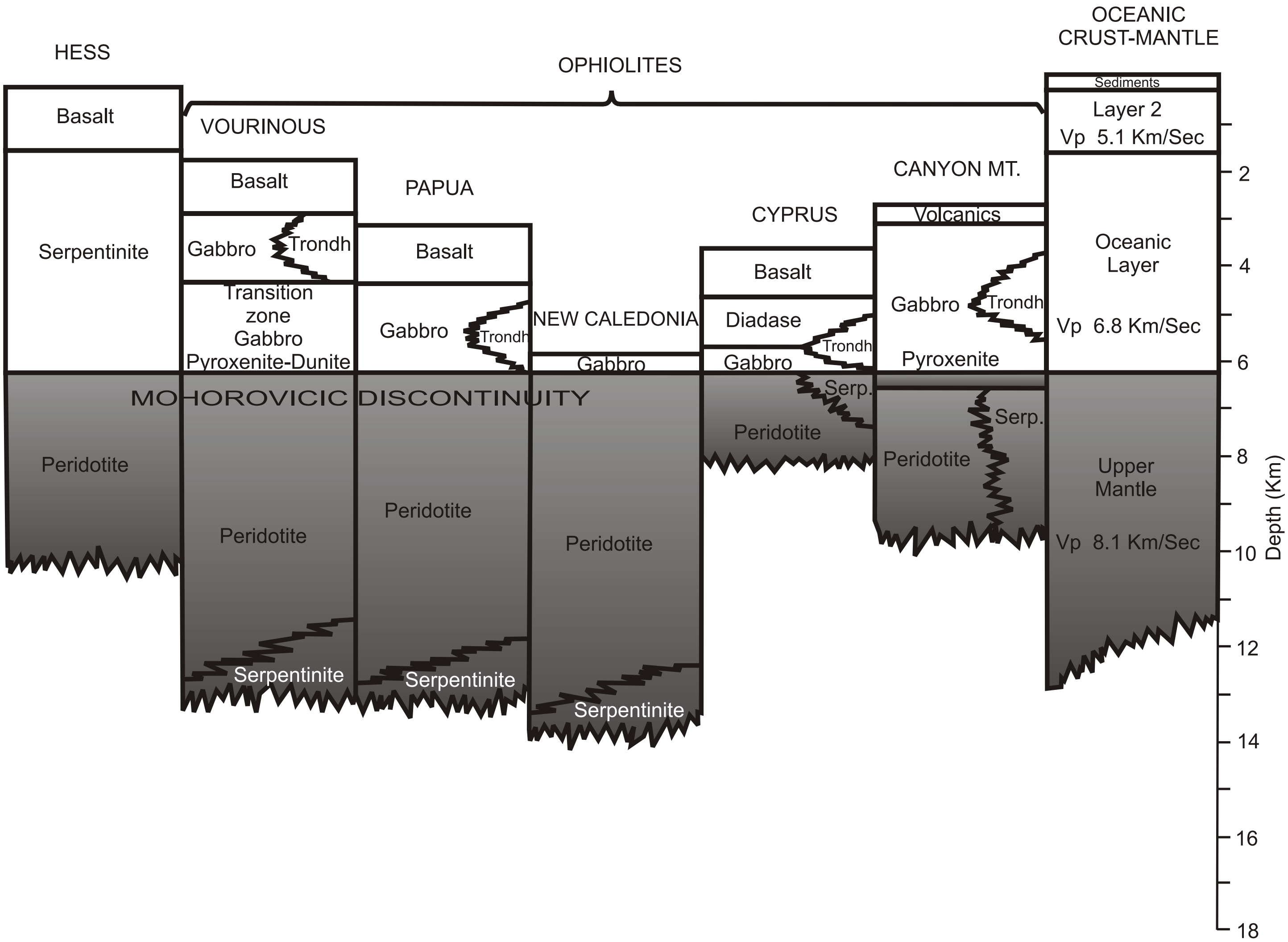

Figure 1. Comparison of the stratigraphic thickness of igneous units from various ophiolite complexes with geophysical estimates of the oceanic crustal layers. Modified after Coleman (1971). Trondh: trondhjemite; Serp: serpentinite.

parable in structure to the Mesozoic layered intrusive–extrusive rock associations of the Mediterranean Alpine system. However, a debate still continued concerning how ophiolites are generated. Most geologists agreed that ophiolites had to develop deep within ocean basins because of their close association with radiolarites, flysch, and deep-sea clays.

Two major schools evolved, one following the work of Steinmann (1927), Brunn (1959), and Aubouin (1965), and the other following Hess (1955) and Dietz (1963). Hess (1955) advocated that ophiolites represented ocean floor emplaced during an orogenic phase in an island-arc setting; this connection also would be made later by Miyashiro (1973) on geochemical grounds. The Hess and Dietz models formed the basis for the later plate tectonic model, first comprehensively assembled by Le Pichon et al. (1976). In contrast, Aubouin (1965) proposed that ophiolites were generated through differentiation of gigantic deep extrusions on the seafloor, in the frame of the geosyncline concept, an idea already proposed by Brunn (1959). However, the geosyncline concept would not last long due to the emergence of the new plate tectonic theory (see illustration in Juteau 2003, p. 37). Even before the advent of plate tectonics, Vuagnat (1963) criticized the Brunn-Aubouin model on the basis of the mismatch between the thickness of the peridotites and the mafic rocks. He pointed out many elements of dissimilitude between ophiolites and layered mafic igneous complexes, such as Skaergaard, including the scarcity of plagioclase in the ophiolitic peridotites, their relatively uniform mineral composition, the high-temperature deformation of peridotites, the occurrence of deformed chromite deposits and the paucity of hypabyssal rocks of various compositions. Finally, Vuagnat (1963) questioned the nature of the so-called concordant basal contact with deep-sea sedimentary rocks.

Investigations of ophiolites in the eastern Mediterranean played a pivotal role in the interpretation of ophiolite sequences, Wilson (1959) was among the first to accurately map and provide excellent illustrations of macroscopic and microscopic features of ophiolites in Cyprus. Others followed including Gass (1963), Moores and Vine (1971), Miyashiro (1973), Panayiotou (1980), Robinson et al. (1987), and Malpas et al. (1990). As a result, the Troodos igneous complex

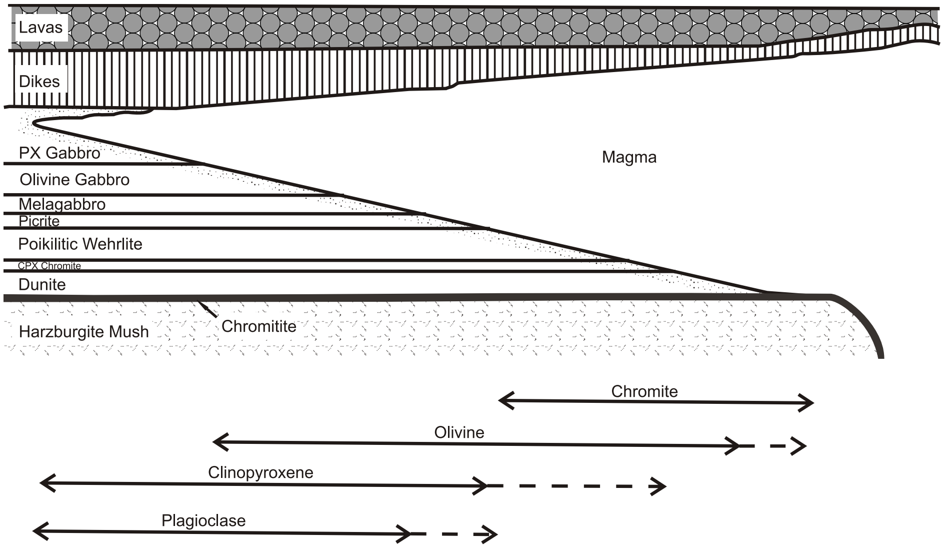

Figure 2. First magma chamber model of Greenbaum (1972). The diagram depicts a hypothetical situation existing beneath a slow spreading oceanic ridge. Modified after Coleman (1977). PX: pyroxene; CPX: clinopyroxene.

would become one of the best known ophiolites anywhere in the world. Among many notable discoveries was the sheeted dike complex, which had a profound impact on magma chamber models and led to the spreading centre origin for ophiolites. In Greece, regional studies by Brunn (1959) and Aubouin (1965) were followed by the detailed work of Moores (1969) on the Vourinous ophiolite.

It took a long time for ophiolites to be accepted in North America, due mainly to the influence of Bowen's (1927) work on crystal fractionation. Hess was an advocate of the existence of ultramafic magma, a notion Bowen never accepted, and Hess found it difficult to reconcile field evidence with Bowen's experimental evidence. Neither Bowen nor Hess was in agreement with European geologists, who had already recognized the allochthonous nature of ophiolites. North American geologists felt that the consanguineous relationship between peridotites and associated mafic rocks made it necessary to reconsider the European views on ophiolites as allochthonous sheets. Coleman (1971) published a very important paper which was a discussion of the tectonic emplacement of ophiolites on continental margins at consuming plate boundaries. This mechanism has since become known as obduction, in contrast to subduction.

A Penrose conference held in September 1972 (Anonymous, 1972), provided the first internationally accepted definition of ophiolites and reduced the knowledge gap between European and North American geologists. Ophiolites were equated with oceanic lithosphere that was created at mid-ocean ridges. A growing volume of seismic data from the ocean floor made it tempting to compare the so-called "well preserved stratigraphy" of ophiolites, later to be called "Penrose stratigraphy", with the geophysical stratigraphy of modern oceanic lithosphere (Fig. 1). In this spirit, Greenbaum (1972) published one of the very first magma chamber models (Fig. 2), which would later be revised to account for new discoveries from the ocean floor and land field studies. The reader is referred to Malpas and Robinson (2000) and Thy and Dilek (2003) for a detailed review of this subject.

The years following 1972 were a booming period for publications on ophiolites, covering discoveries concomitantly made on the ocean floor and on land. Mapping and application of geochemical discrimination tools led to recognition of the diversity among ophiolites and the realization that ophiolites could be generated in different geodynamic environments, not only at mid-ocean ridges, but also in island arcs (Miyashiro 1973). Sun and Nesbitt (1978) discussed the origin of low-Ti basalts (later referred to as boninites by Cameron et al. 1979) and made the connection between ophiolites and subduction zones. This led to the concept that ophiolites could form at spreading centres above subduction zones, i.e. the supra-subduction zone model of Alabaster et al. (1982). This concept was reinforced by Pearce et al. (1984) who demonstrated the foresight of Miyashiro's (1973) hypothesis. The discovery of fresh glass of boninitic affinity in Troodos volcanic rocks (Robinson et al. 1983) and the recognition of forearc and back-arc settings as modern analogs for ophiolites (Moores et al. 1984) marked a turning point in our understanding of ophiolite provenance. Subsequently Stern and Bloomer (1992) established a link between initiation of subduction, boninite production and ophiolite formation. The 1960s and 1970s represent the period when the gap amongst the marine, field, and geochemical communities was bridged.

The 1980s to Present

In 1978, after successful drilling in Iceland, an international consortium of scientists from Canada, Denmark, the United Kingdom, Iceland, the United States and West Germany, joined to form the International Crustal Research Drilling Group (ICRDG). The ICRDG proposed to drill several sites on the Troodos ophiolite to make comparisons with cores from the ongoing Deep Sea Drilling Project. Field work was conducted in conjunction with the drilling program from 1980 to 1985. At the end of the drilling operations, more than 4563 m from five holes at three sites had been cored with a 95% core recovery. Scientific results are summarized in Geological Survey of Canada of Paper 85-29 (Robinson et al. 1987) and Paper 88-9 (Gibson et al. 1989).

Since 1979, four landmark meetings have contributed to the evolution of concepts about ophiolite. One of them was held in Cyprus in 1979 (Panayiotou, 1980), another in 1987 (Malpas et al. 1990), a third in Oman in 1990 (Peters et al. 1991) and the fourth in 1998 was a Penrose Conference (Dilek et al. 2000). The first three meetings were attended by several hundred specialists and each was

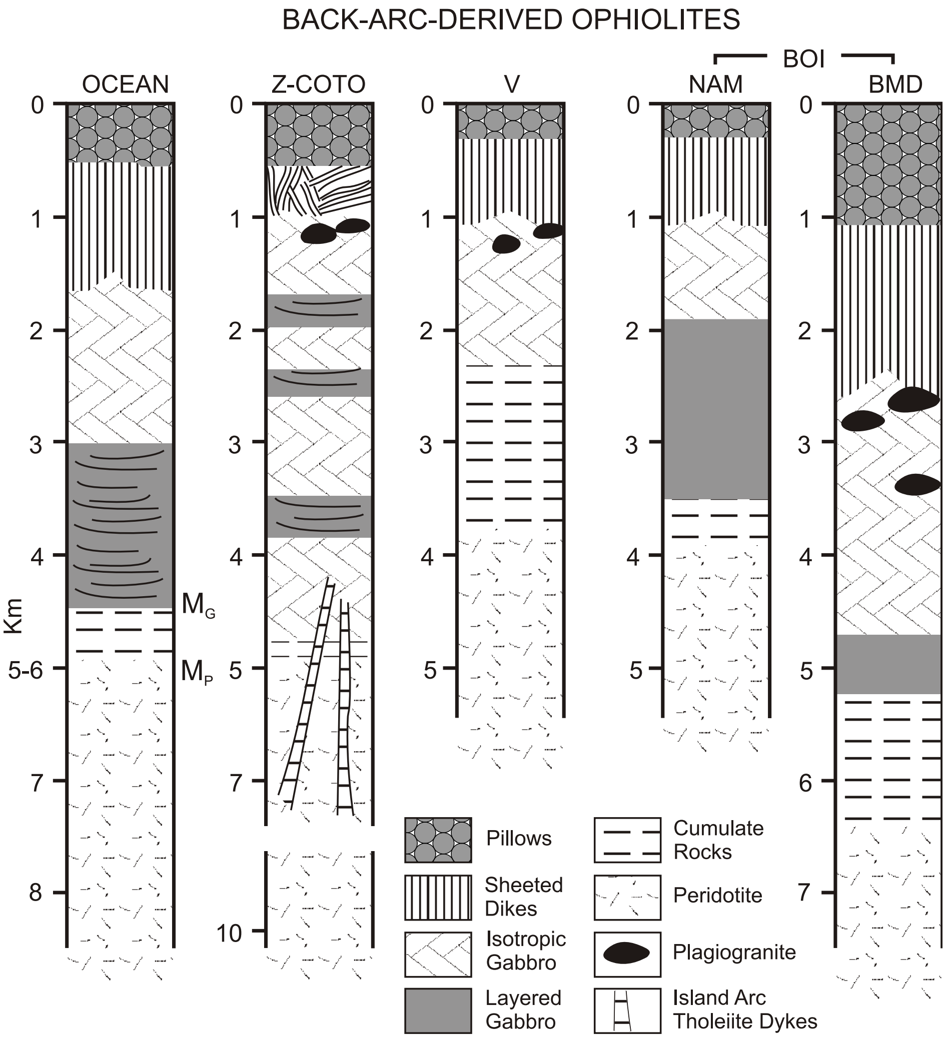

Figure 3. Back-arc derived ophiolites. Modified after Hawkins (2003). Z-Coto: Zambales-Coto; V: Vourinous; BOI: Bay of Islands; NAM: North Arm Mountain; BMD: Blow-Me-Down Mountain; M_G: geophysical Moho; M_P: Petrological Moho.

complemented by field trips. They were intended to synthesize the voluminous information available on ophiolites around the world. Debates were centred on the origin of ophiolites, their significance, and diversity. No clear consensus emanated from the discussions. At the Oman meeting, a superb petrographic atlas was released by Tegyey (1990) and contributors. The Penrose Conference, the second on ophiolites, was held with the objective of rejuvenating discussion about ophiolites in light of DSDP and ODP results. At this meeting, it was shown that modern oceanic lithosphere is very heterogeneous and that stratigraphic successions at slow-spreading ridges are neither simple nor uniform. In addition, many structural features found in ophiolites are inherited from the pre-obduction period, i.e. are not related to orogenic events.

A series of publications, including special issues of journals, disseminated information to the ophiolite community and beyond. For instance, a thematic journal, *Ofioliti*, was launched two years after the establishment of the Working Group for Mediterranean Ophiolites, in April 1976. The US work on ophiolites appeared in the Jackson Volume published by the *American Journal of Science* in 1980 (v. 280A, p. 171-388); in 1981 a special issue of *The Journal of Geophysical Research* (v. 86 (B4), p. 2497-2782) was devoted to the Oman ophiolites, making available the results of scientific investigations initiated in the 1970s by British and American groups (Coleman 1981). A special issue of *Tectonophysics* (v. 151, nos.1-4), edited by Boudier and Nicolas (1988) reported on the results of seven years of investigations on the Oman ophiolites by the French universities of Nantes and Strasbourg as well as the Bureau de Recherches Géologiques et Minières.

Twelve years after the publication of the classic book on ophiolites by Coleman (1977), Nicolas (1989) published a more extensive book on the structure of ophiolites, with a perspective on the dynamics of oceanic lithosphere. This book comprehensively summarized the immense progress made on the understanding of the petrogenesis, structural evolution, obduction and reworking of ophiolites, and oceanic lithosphere. Nicolas (1989) introduced harzburgite-type and lherzolite-type ophiolites.

More recent publications challenge some of the accepted concepts about ophiolites. The book, *Mantle and Lower Crust Exposed in Oceanic Ridges and in Ophiolites*, edited by Vissers and Nicolas (1995), ties together some of the findings based upon both marine and field geology. The Geological Society of London Special Publication 218, edited by Dilek and Robinson (2003), is a review of ophiolite studies that were orally presented at special sessions of the Annual Meeting of the Geological Society of America (Boston) and the Fall Meeting of the American Geophysical Union (San Francisco) in 2001. Geological Society of America Special Paper 373, edited by Dilek and Newcomb (2003), and Special Paper 349, edited by Dilek et al. (2000), review the evolution of ophiolite concepts. For example, we now recognize ophiolitic complexes in back-arc and arc environments (Figs. 3, 4, respectively). We are perhaps witnessing a re-evaluation of accepted concepts that were proposed nearly 25 years ago. Regardless, I recommend these Special Papers to all "fresh" scientists plunging for the first time into the voluminous literature about ophiolites.

OPHIOLITES IN CANADA

First Occurrences Discovered in Québec and Newfoundland

Field mapping in the Québec Appalachians started as early as the

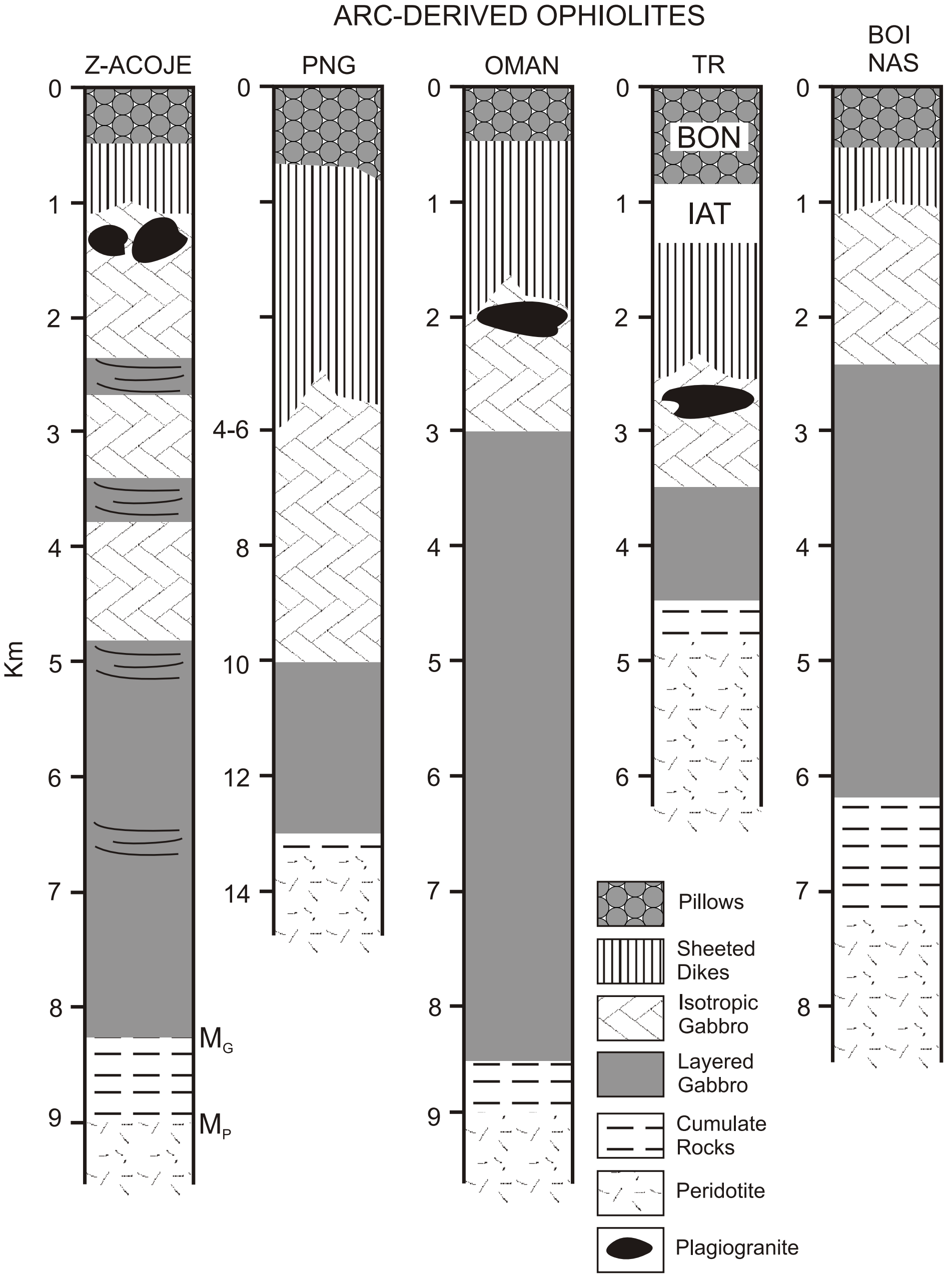

Figure 4. Arc derived ophiolites. Modified after Hawkins (2003). Z-Acoje: Zambales-Acoje; PNG: Papua New Guinea; TR: Troodos; BOI: Bay of Islands; NAS: Southern North Arm. M_G: geophysical Moho; M_P: petrological Moho.

middle of the nineteen century and the occurrence of serpentinite, pyroxenite, and volcanic rocks was reported by Logan (1863), based on field operations in 1847. However, T. Sterry Hunt was the first Canadian geologist to use the term ophiolite in the literature (Hunt, 1856). He compared the Eastern Townships occurrences to locations in Europe, such as Montgenèvre, the Lizard Peninsula, and others in Italy. At that time, the serpentinites were thought to be derived from alteration of sedimentary rocks. Adams (1882) and Ells (1886, 1988, 1889) revisited the geology of the Eastern Townships, and defined a "Serpentinite Band" associated with diorite and volcanic rocks. Dresser (1913) defined the "Serpentinite Zone" throughout southern Québec, passing through Orford-Asbestos-Thetford Mines, which would later become the "Ophiolite Belt" in the early 1970s (Fig. 5). Near Asbestos, he recognized that the peridotite, chromite-bearing dunite, pyroxenite, gabbro, diabase, porphyrite, hornblende granite, and aplite are all parts of a thick sill. The base of the sill was described as highly serpentinized and contains the chrysotile ore-bodies. Graham (1917) and Poitevin and Graham (1918) proposed that the rocks of the Serpentinite Zone were comagmatic, and described several gradual contacts between pyroxenite and gabbro at the Mill Hill section in the Asbestos igneous complex. Riordon (1954) was convinced that several intrusive sequences occur in the Thetford and Asbestos igneous complexes, and that the pyroxenite and gabbro were not cogenetic.

In the middle of the 20th century, significant mapping progress was made in Québec (Cooke, 1938, 1956) and Newfoundland (Smith 1958). Baragar (1954) was among the first (probably in the world!) to describe, in detail, a sheeted dike complex within an igneous assemblage in Newfoundland, which would later on be designated as the Betts Cove Ophiolite Complex. This topic was addressed later by Williams and Malpas (1972). He recognized that emplacement of such dikes required repeated injections in openings intermittently active in a rift system. In Québec, the basal peridotites were first recognized as alpine-type by Olsen (1959, 1961). He postulated that the upper mafic part of the section is the result of differentiation by crystal fractionation. The first articles referring to western Newfoundland igneous rocks as ophiolites were released by Church (1965, 1969) and Williams (1971).

Canadian Ophiolites and Plate Tectonics

The application of plate tectonic concepts to Appalachian ophiolites had a profound impact on understanding the geodynamic significance of ophiolites in mountain chains around the world. It took several years for it to become generally accepted that the ophiolites of Québec and Newfoundland were both oceanic crust and allochthonous. Lamarche (1969, 1971) adopted the Brunn-Aubouin model and even gave a talk at the 1972 International Geological Congress held in Montréal on the role of liquid immiscibility in forming the gigantic igneous submarine sequence. A collection of papers from a Geodynamics Project Working Group meeting held in Ottawa in October 1970 were published in a Geological Survey of Canada volume in 1972. One paper in this volume still referred to the Bay of Islands Igneous Complex as an alpine-type peridotite (see Smith 1958), but other papers by Lamarche (1972) and Church (1972) used the word ophiolite in their title. In their paper, Irvine and Findlay (1972) made clear that the peridotites had a residual composition. Earlier, mineralogical studies of Aumento (1968, 1970) showed the resemblance of the Asbestos peridotite to serpentinized peridotites dredged from the Mid-Atlantic Ridge. In Newfoundland, Stevens (1970) and Dewey and Bird (1969, 1970, 1971) recognized that the Ordovician ophiolite complexes, already documented by Hess (1955) and Dietz (1963), were fragments of oceanic crust and mantle and this interpretation was subsequently applied to the Québec ophiolites (St-Julien et al. 1972; Laurent 1972, 1973, 1975).

Regional studies by Rodgers and Neale (1963) in the Newfoundland Appalachians and by St-Julien (1968, 1970), Lamarche (1969, 1971), Church and Stevens (1971), and Dewey and Bird (1971), established the allochthonous character of the ophiolite sequences. The allochthonous character of the Newfoundland ophiolites was first demonstrated by Church (1965, 1969) and Williams (1971) and later work (Williams and Smyth 1973; Williams et al. 1974) documented the presence of a metamorphic sole. Once the allochthonous, oceanic-crust origin of ophiolites was accepted, the position of these rocks within the tectonic framework of the Northern Appalachians could be established, with the recognition of continental and oceanic terranes extending from Newfoundland to Québec (Williams 1979; Williams and St-Julien 1982). Stevens (1970) proposed an Ordovician age of emplacement, which was echoed by St-Julien et al. (1972) and Laurent (1972, 1973, 1975) for ophiolites found farther south in the Appalachians.

The international importance of the Newfoundland ophiolites arose from a series of papers by Dewey and Bird (1969, 1970, 1971), which applied new plate tectonics theories to the understanding of mountain belts. As noted decades later (Dewey 2001), Tuzo Wilson's 1966 paper entitled: *"Did the Atlantic close and then reopen?"* had a big influence on the thinking of Dewey and Bird. The extensive zone of serpentinites and volcanic rocks within the northern Appalachians was the key to recognizing the presence of former oceanic crust. The paper by Dewey and Bird (1971), on the Appalachian ophiolites of Newfoundland, was reprinted by the *Journal of Geophysical Research* as one of 31 seminal papers on plate tectonics, which were published in that journal. By the early 1970s, Newfoundland was world famous for its ophiolites and for the information that they provided about orogenesis and the internal structure of oceanic lithosphere.

IGCP Project 39 funded the publication entitled "*Ophiolites of the Canadian Appalachians and Soviet Urals,*" edited by Malpas and Talkington (1979). This publication is a collection of papers on Paleozoic ophiolites, which synthesize knowledge about Appalachian and Uralian massifs at that time. These papers clearly demonstrated the allochthonous character of ophiolites and emphasized their diversity along the same orogenic belt. The same year, the GAC-MAC Annual meeting in Québec City had a special session on ophiolites with related field trips. This session was held allowing participants to share their field experience in order to better constrain the similarities and differences between Newfoundland and Québec ophiolite occurrences.

Age and Geodynamic Context of Appalachian Ophiolites

The tectonostratigraphic framework of the Northern Appalachians was established by Williams (1979) and Williams and St-Julien (1982). Continental and oceanic terranes were defined and correlated in Québec and Newfoundland (Fig. 5). Ophiolites mark the interface between continental and oceanic derived rock assemblages and the timing of juxtaposition depends upon the age of the basal metamorphic sole to the ophiolite. For the St. Anthony complex, the basal metamorphic sole was described by Williams and Smyth (1973), Malpas (1979), and Jamieson (1986) and dated earlier by Archibald and Farrar (1976) and Dallmeyer and Williams (1975) at 469–463 Ma. In Québec, the metamorphic sole to the Thetford Mines ophiolite was investigated by Clague et al. (1981) and Feininger (1981) and dated at 491 Ma. However, the age was reassessed by Whitehead et al. (1995), who reported an age of 480 Ma. Originally, the age of Bay of Islands ophiolite was reported to be 508–504 Ma (Mattinson 1975, 1976) but is now known to be 486 Ma (Dunning and Krogh 1985). Later on, Dunning and Perdersen (1988), published an U-Pb age on zircon extracted from a trondhjemite of 479 Ma. The age of the Asbestos ophiolite was determined as 472 Ma (see Hébert and Bédard 2000 for a review). These results show that the ophiolite complexes were short-lived and rapidly obducted onto continental crust. These ophiolites were probably generated in basins that adjoined the continental margin in the Early Ordovician.

Modern analogues for Newfoundland ophiolites have been proposed. Karson and Dewey (1978) and Karson (1984) interpreted the Little Port Complex as an oceanic fracture zone. This complex, dated at 508 Ma by Archibald and Farrar (1976), has since been reinterpreted as a subduction complex (Jenner et al. 1991). The oceanic provenance of the breccia found at the top of the Little Port Complex was recognized by Hébert (1981) for a similar unit found on top of Asbestos Ophiolite Complex in Québec. The Bay of Islands ophiolite is attributed to subduction processes because of the composition and high pressure origin of some of the cumulates (Elthon et al. 1982; Komor et al. 1987; Elthon 1991). Rosencrantz (1983) studied the architecture of the sheeted dikes in the North Arm Mountain massif and made reference to processes at mid-ocean ridges. Karson et al. (1983) investigated ultramafic intrusions at Lewis Hills in the context of a fracture zone setting and Casey et al. (1983), Casey and Dewey (1984), and Siroky et al. (1985) speculated on the geometry of accretion of the Bay of Islands ophiolite in a mid-oceanic spreading environment. Dunning and

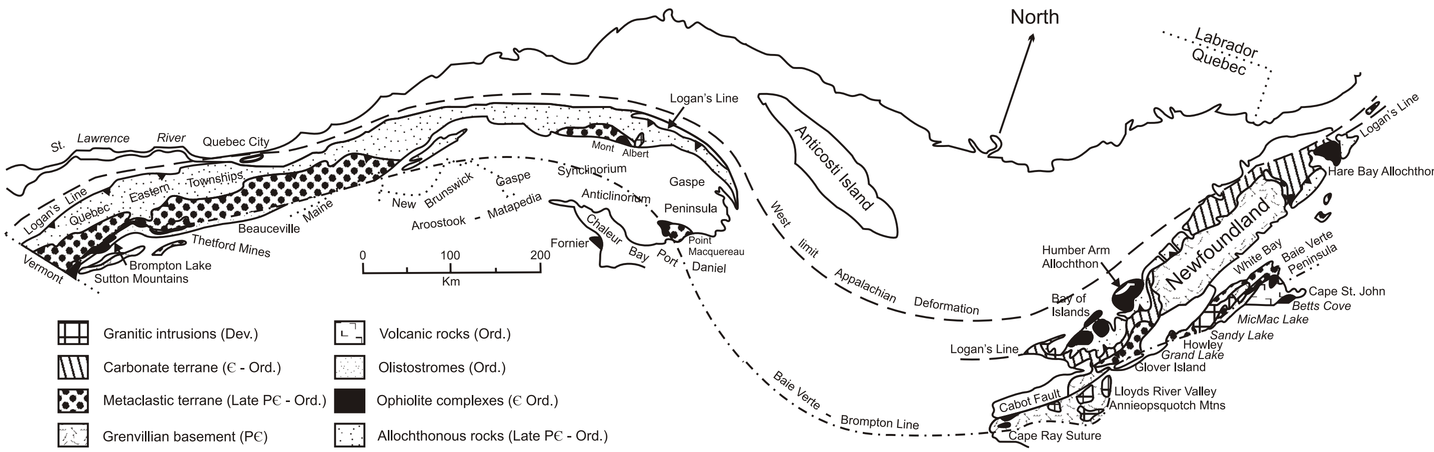

Figure 5. Simplified geologic map of the Canadian segment of the northern Appalachians in Québec and Newfoundland. Modified after Williams and St-Julien (1982). The Baie Verte-Brompton Line is indicated.

Krogh (1985) proposed a crystallization age of 488 Ma for the Bay of Islands ophiolite.

Meanwhile in Québec, the stratigraphy and geochemistry of ophiolitic volcanic rocks was still being defined (Laurent and Hébert 1977; Trottier 1982). A controversy among Church (1977, 1978), Laurent (1978), and Oshin and Crocket (1986) concerning the geodynamic significance of the Thetford Mines ophiolites mirrored the debate in the international community concerning the oceanic ridge versus arc settings of ophiolites. Subsequently, geochronological studies were performed on felsic intrusions (Clague et al. 1985; Whitehead et al. 2000) and on the metamorphic sole (Whitehead et al. 1995); ultimately the age of the Orford complex was established at 504 Ma by David and Marquis (1994). The mineralogy and geochemistry of the ophiolite was revisited by Laurent and Hébert (1989), Hébert and Laurent (1989), Harnois and Morency (1989), and Huot et al. (2002), who showed that these rocks were generated through polycyclic magmatic, tectonic, metamorphic, and sedimentary processes that are typical of a supra-subduction setting. Pinet and Tremblay (1995) proposed that emplacement of the Québec ophiolites was caused by the collision of an island arc with the North American continent during the Ordovician. A new map of part of the Thetford Mines ophiolite was published by Brassard and Tremblay (1999). For post-2000 literature, a review is proposed in paper Ophiolites 2 of Igneous Rock Associations 9.

In Newfoundland, the mineralogy of upper mantle rocks was reinvestigated by Batanova et al. (1998). The Lewis Hills massif was studied by Edwards (1990, 1995) and Suhr and Edwards (2000 and references therein) and Table Mountain by Suhr and Robinson (1994). Suhr and Cawood (2002) interpreted the southeastern part of the Lewis Hills massif to be derived from the inside-corner of a ridge-transform intersection. The Betts Cove ophiolite was remapped and reinterpreted as a forearc sequence of mostly boninitic affinity (Tremblay et al. 1997; Bédard et al. 1998; Kim and Jacobi 2002).

The 1988 GAC-MAC-CSPG Meeting in St John's, Newfoundland convened participants at a special session on ophiolites followed by a field trip to the Bay of Islands complex. This field trip was the starting point of a five-year collaborative project between the Geological Survey of Canada in Québec City and Université Laval devoted to a reassessment of the North Arm Mountain massif. This investigation on the most "complete" section in the Bay of Islands ophiolite has led to the new idea that the mantle is affected by cryptic melts. The formation of oceanic crust was thought to largely result from the injection of boninitic sills that followed ductile deformation corridors (Bédard 1991, 1993; Bédard and Constantin 1991; Bédard and Hébert 1996, 1998; Berclaz et al. 1998; Varfalvy et al. 1996, 1997). Cawood and Suhr (1992) proposed a new model for emplacement of the Bay of Islands ophiolite, which involved the interactions of ridges, transform faults and subduction in a complex marginal system. Some 30 years after initially recognizing the plate tectonic significance of Appalachian ophiolites, their geodynamic settings are now much better understood (Swinden et al. 1997).

British Columbia

On the Pacific coast of Canada, occurrences of ultramafic rocks have been known since the pioneering work of Cairnes (1930), Armstrong (1949), Little (1949), Leech (1953), Aitken (1959), and Gabrielse (1955, 1963). Souther (1972) stated that island arc volcanic edifices are partly preserved in the Cordillera but ophiolite suites have not been identified. However, in the same volume, Monger (1972) pointed out that upper Paleozoic basalt, alpine-type ultramafic rock, and chert in the Cordillera could correspond to what was regarded as a characteristic deep-ocean basin association. He also suggested that more work was needed to document the presence of "classical ophiolites" in the Cordillera, and especially in the Cassiar–Omineca–Columbia Mountains. Rock associations typical of the ophiolite suite of Aubouin (1965) had already been described by Leech (1953). Monger (1977) summarized the occurrences of ophiolites in the Cordillera. Since then, several papers have been published on Cordilleran ophiolites, but their degree of preservation and size mean that they have had little impact internationally on the understanding of ophiolite genesis. Regionally, they are important in unravelling the plate tectonic history of the Cordillera. The reader is referred to Geological Association of Canada Special Papers 45 (Colpron and Nelson, 2006) and 46 (Haggart et al. 2006) for further information concerning this region.

PRECAMBRIAN OPHIOLITES

Some highly tectonized Precambrian volcanic and plutonic suites resemble ophiolites, but Penrose-type stratigraphy is lacking in pre-1 Ga sequences (Moores 2002). For a recent complete review of the subject of Precambrian ophiolites, the reader is referred to the book edited by Kusky (2004) on Precambrian ophiolites and related rocks. Many Neoproterozoic occurrences show Penrose-type stratigraphy, including a basal ultramafic unit derived from the upper mantle (e.g. Shanti and Roobol 1979, and Dilek and Ahmed 2003, for Arabic massifs; and Kontinen 1987, for the Jormua suite in northern Finland). However, older occurrences are reported to date back to the early Proterozoic and even the Archean. Precambrian ophiolites do not include all of the Penrose-type units, i.e. mantle peridotites, sheeted dikes and deep ocean sedimentary rocks are rarely found, and they have geochemical attributes that contrast with Proterozoic and Phanerozoic occurrences (Condie 1989; Fig. 6). One notable exception is the Archean (3.8 Ga) upper mantle peridotite that is found in southwest Greenland (Friend et al. 2002).

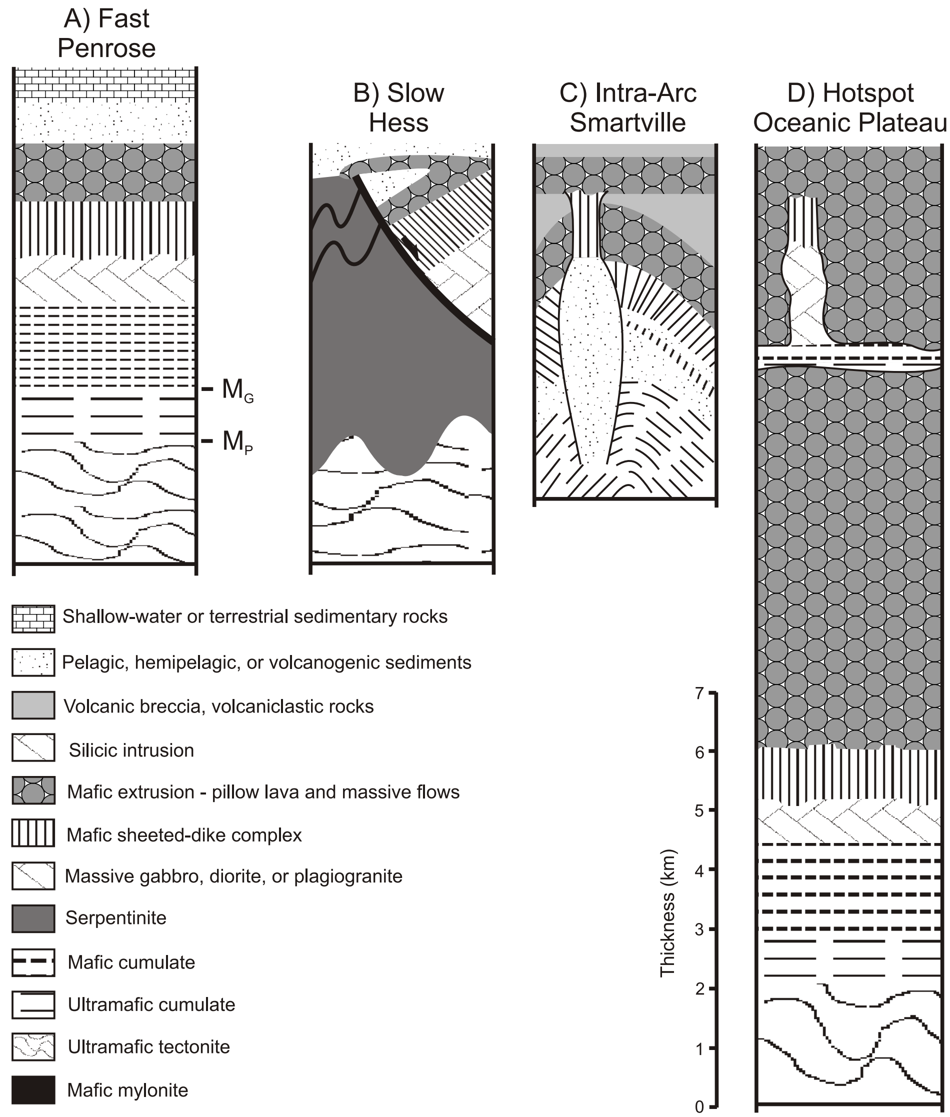

Figure 6. Schematic columnar sections of representative oceanic crust from diverse contexts and corresponding ophiolite types. A and B are for fast and slow spreading ridges. C, for an intra-arc section developed on oceanic crust, and D for a possible hotspot (oceanic plateau) section of oceanic crust. Modified after Moores (2002).

Canadian Cratons

Naldrett (1972) rejected the possibility of having Precambrian ophiolites (transported mafic–ultramafic sequences) in Canadian cratons. He pointed out that no alpine-type ultramafic rocks have ever been reported, that the ultramafic–mafic–chert association does not exist, and that most sections consist of intruded differentiated complexes and extruded ultramafic lavas (komatiites). Since then very few papers have been published on the subject of Canadian Precambrian ophiolites. The occurrence of the 2.0 Ga Purtuniq ophiolite, New Québec (Scott et al. 1991, 1992) and the Archean Slave Craton (Corcoran et al. 2004) are notable exceptions. The authors described rock units such as deep-sea sedimentary rocks, pillow basalts, dike complexes and ultramafic cumulate rocks. However it is not clear how these units are related to each other because of poor exposure and lack of detailed geochronologic data.

Precambrian ophiolites: wish or myth?

The interpretation of highly tectonized, Precambrian volcanic and plutonic suites as ophiolites raises some fundamental questions:

- Do Precambrian ophiolites exist?
- Why is Penrose-type stratigraphy (and especially the upper mantle unit) missing in pre-1 Ga sequences?
- Did Neoproterozoic tectonics and mobile blocks show a different behaviour compared with older Precambrian occurrences?
- Was the Wilson Cycle valid in the Precambrian?
- Were "true ophiolites" really formed in the early Precambrian?

St-Onge et al. (1989), Helmsteadt and Scott (1992), and Moores (2002) addressed some of these questions. Thermal models suggest that Precambrian oceanic crust of pre-

Rodinian age was much thicker than its post-1 Ga counterpart (see Moores 2002 and references therein), reaching to 25 to 50 km in Archean times. These models are invoked to explain the lack of mantle peridotites and dynamothermal aureoles at the base of the Precambrian sequences. Moores (1986) proposed that the transition from thick oceanic crust to thin crust occurred rapidly around 1 Ga, after which a Penrose-type ophiolitic stratigraphy developed (Dilek and Ahmed 2003). On geochemical grounds, these igneous sequences were formed in a wide range of geodynamic environments (Moores 2002).

Clearly, the dismemberment of the Rodinian supercontinent initiated multiple convergent and divergent systems, where complex interactions with transform faults and hot spots resulted in the production of the first "modern type" thin crust. The reconstruction of the pre-Rodinian period is still debated so one should be very cautious in equating modern and Neoproterozoic ophiolites with more ancient igneous complexes, because the stratigraphy, geochemistry, and petrogenetic processes could have been very different. In addition, complex structural and metamorphic features are superimposed, making it hazardous to decipher the parentage of strongly deformed igneous sequences. At the present time, it is suggested that a different class of "ophiolite-like" sequence should be considered, to prevent any confusion with ophiolites from the well documented post-1 Ga mobile period of Earth history. Moores (2002) suggested a revised definition of ophiolite to include Precambrian occurrences, but this definition is not very satisfactory. Perhaps a third Penrose Conference focusing on Precambrian ophiolites is needed.

CONCLUSION

This paper summarizes the evolution of concepts about ophiolites from first reference to the name in 1813 to the present day. The European-born ophiolitic sequence was late in making its way to North America, due to apparent conflicts between field, marine, and laboratory observations. From the very beginning, ophiolites were recognized as rock successions formed in the deep ocean. However, much debate occurred to reconcile the evidence from marine geology with descriptions of ophiolites from the continents. The allochthonous nature of ophiolitic sequences was recognized in the late 1950s, as was the upper mantle origin of basal peridotites. The elaboration of plate tectonic theory set the basis for equating ophiolites with oceanic lithosphere. In the mid-1970s, an additional vigorous debate was engaged between proponents of ridge- and arc-generated ophiolites. The extrapolation of the mid-ocean ridge geodynamic setting, as the unique locus to create ophiolites, to other settings opened the door to the possibility of Precambrian ophiolites. Although Neoproterozoic ophiolites have a Penrose-type stratigraphy, the pre-1 Ga occurrences do not. Several questions are raised, vis-à-vis, the existence of Precambrian ophiolites. For example, what are the implications for crustal mobility of the Earth through time? Rarely in the Earth Sciences has a research topic created such passionate and sustained debate as has the topic of ophiolites. Since conflicting ideas and observations still persist after nearly 200 years, the need for an ophiolite forum is obviously alive and well.

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