

Igneous Rock Associations 9. 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 XIX^{ème} 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 serpentinitized 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 Bernoulli 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-

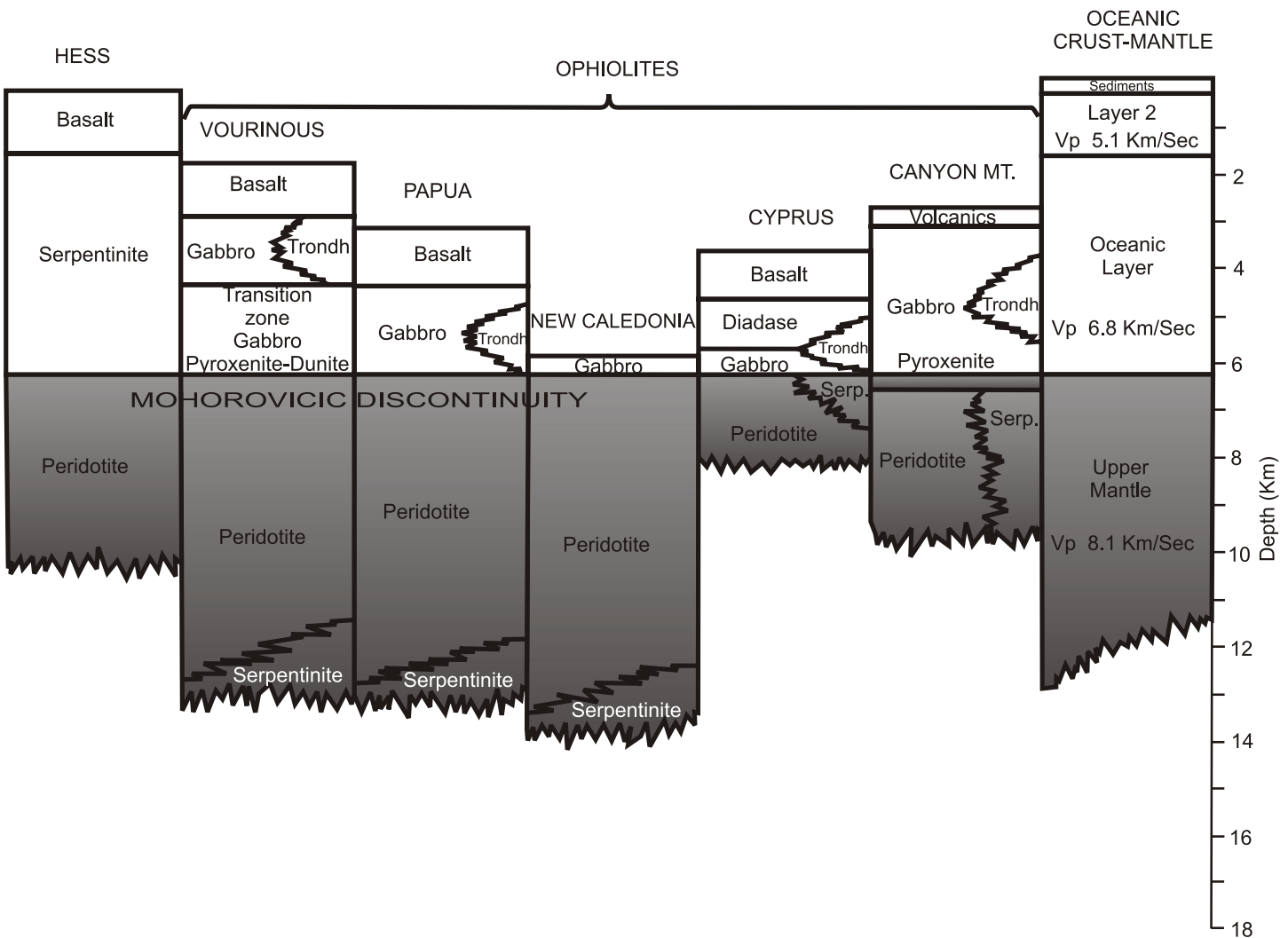


Figure 1. Comparison of the stratigraphic thickness of igneous units from various ophiolite complexes with geophysical estimates of the oceanic crustal layers. Modified after Coleman (1971). Trondh: trondhjemite; Serp: serpentinite.

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

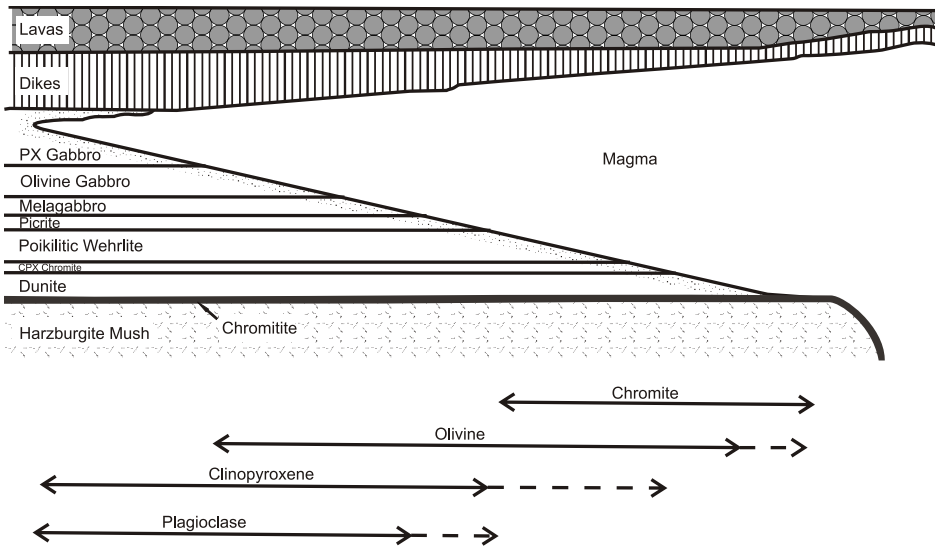


Figure 2. First magma chamber model of Greenbaum (1972). The diagram depicts a hypothetical situation existing beneath a slow spreading oceanic ridge. Modified after Coleman (1977). PX: pyroxene; CPX: clinopyroxene.

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 Vourinos 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

BACK-ARC-DERIVED OPHIOLITES

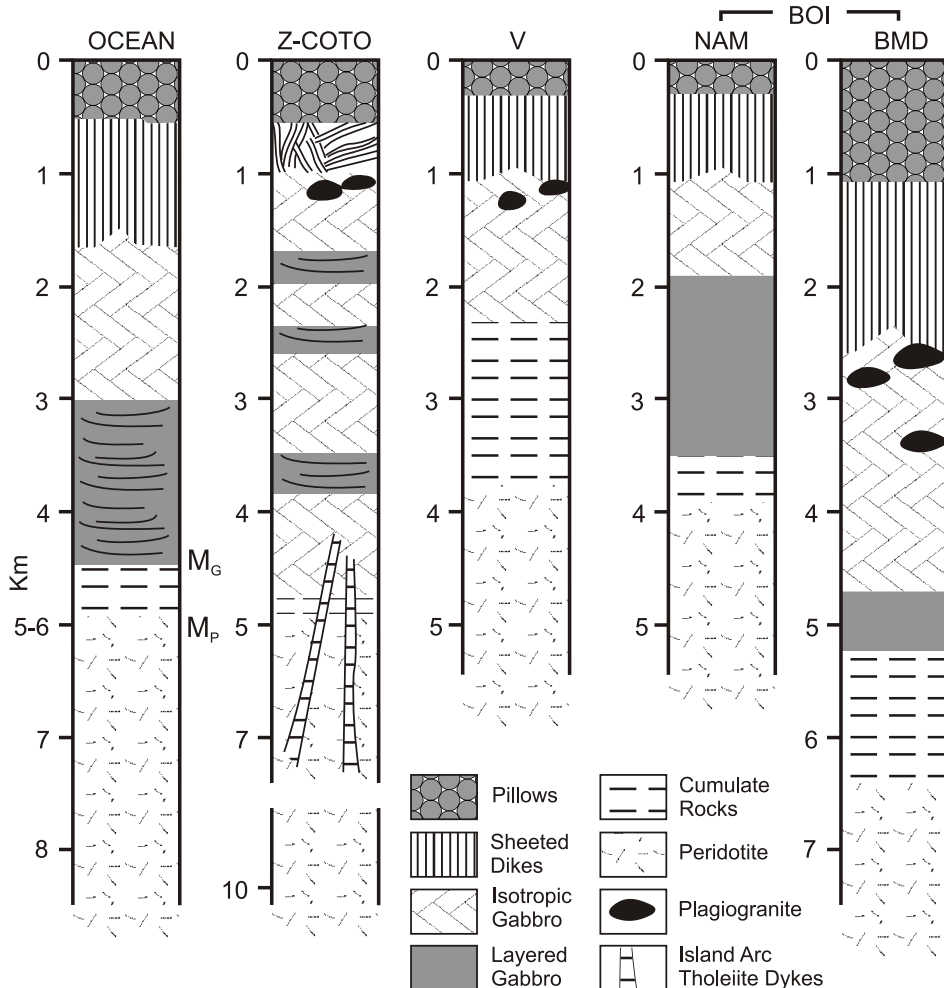


Figure 3. Back-arc derived ophiolites. Modified after Hawkins (2003). Z-Coto: Zambales-Coto; V: Vourinuous; BOI: Bay of Islands; NAM: North Arm Mountain; BMD: Blow-Me-Down Mountain; M_G: geophysical Moho; M_P: Petrological Moho.

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 Tegye (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, *Ophioliti*, 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

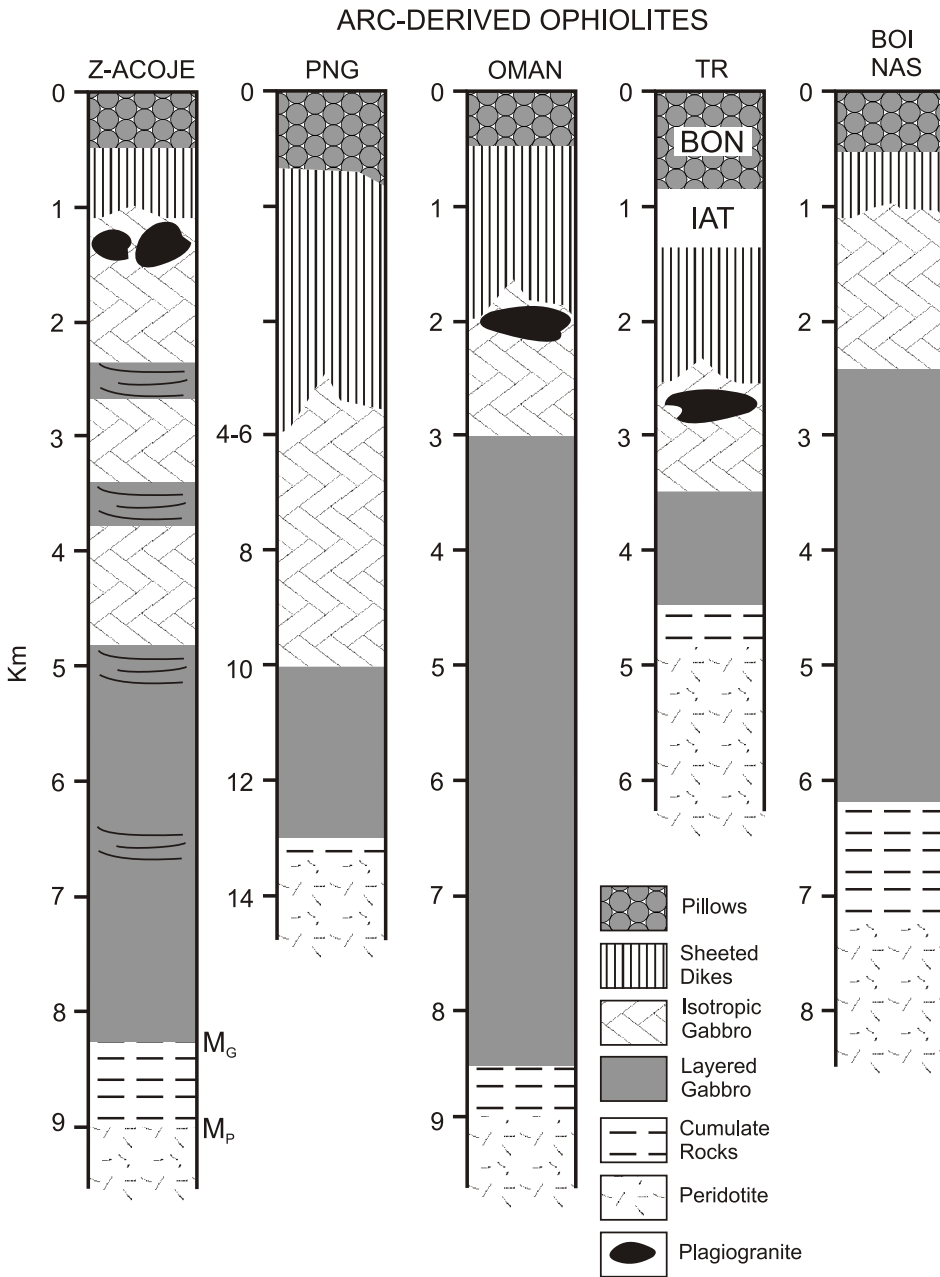


Figure 4. Arc derived ophiolites. Modified after Hawkins (2003). Z-Acoje: Zambales-Acoje; PNG: Papua New Guinea; TR: Troodos; BOI: Bay of Islands; NAS: Southern North Arm. M_G : geophysical Moho; M_P : petrological Moho.

middle of the nineteenth 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 alter-

ation of sedimentary rocks. Adams (1882) and Ells (1886, 1888, 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 serpentinitized 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 serpentinitized 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 Perderson (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

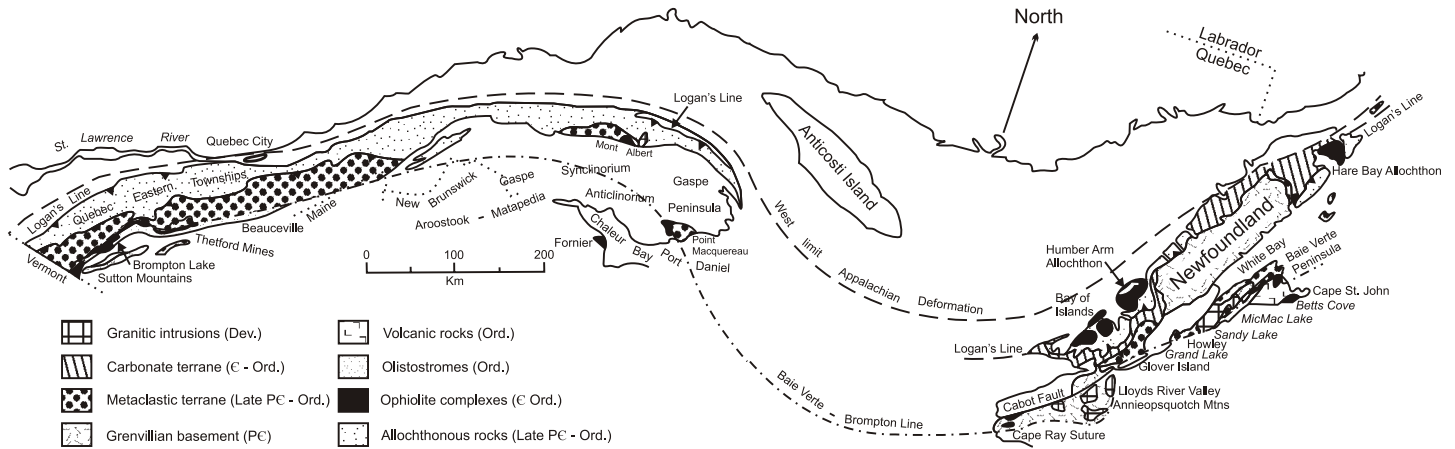


Figure 5. Simplified geologic map of the Canadian segment of the northern Appalachians in Québec and Newfoundland. Modified after Williams and St-Julien (1982). The Baie Verte-Brompton Line is indicated.

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; Trotter 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 (Moore 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).

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 Purtuniqu ophiolite, New Québec (Scott

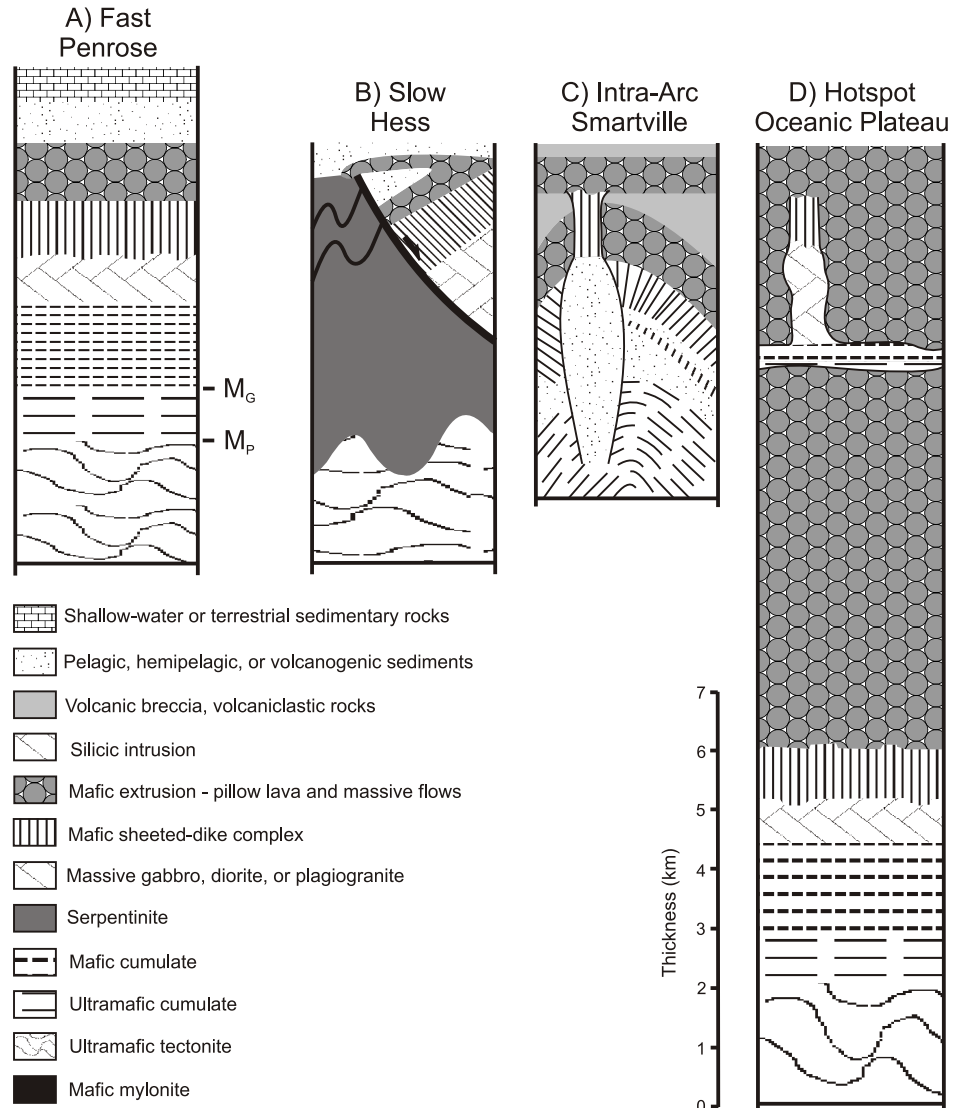


Figure 6. Schematic columnar sections of representative oceanic crust from diverse contexts and corresponding ophiolite types. A and B are for fast and slow spreading ridges. C, for an intra-arc section developed on oceanic crust, and D for a possible hotspot (oceanic plateau) section of oceanic crust.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

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), Helmstedt and Scott (1992), and Moore (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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REFERENCES

Adams, F.D., 1882, Notes sur la structure microscopique de quelques roches du Groupe de Québec: Commission géologique du Canada, Rapport des Opérations, 1880-81-82. partie A, p. 9-26.

- Aitken, J.D., 1959, Greenstones and associated ultramafic rocks of the Atlin map-area, B.C. University of California, Los Angeles, Ph.D. thesis.
- Alabaster, T., Pearce, J. and Malpas, J., 1982, Volcanic stratigraphy and petrogenesis of the Oman ophiolitic complex: Contributions to Mineralogy and Petrology, v. 81, p. 168-183.
- Amstutz, G.C., 1980, The early history of the term ophiolite and its evolution until 1945, in Proceedings International Ophiolite Symposium, Geological Survey Department, Cyprus, p. 149-152.
- Anonymous 1972, Penrose Field Conference Participants: Geotimes, v. 17, p. 24-25.
- Archibald, D.A. and Farrar, E., 1976, K-Ar ages of amphiboles from the Bay of Islands ophiolite and Little Port Complex, western Newfoundland, and their geological implications: Canadian Journal of Earth Sciences, v. 13, p. 520-529.
- Armstrong, J.E., 1949, Fort St. James Map-Area, Cassiar and Coast Districts, British Columbia: Geological Survey of Canada Memoir 232.
- Aubouin, J., 1965, Geosynclines: Elsevier Publishing Co., Amsterdam, 335 p.
- Aumento, F., 1968, Mineralogy of asbestos deposits, Jeffrey Mine, Asbestos, Québec: Geological Survey of Canada Memoir 68, part IA, p. 91.
- Aumento F., 1970, Serpentine mineralogy of ultrabasic intrusives in Canada, and on the Mid-Atlantic Ridge: Geological Survey of Canada, Communication 69-53, 51 p.
- Baragar, W.R.A., 1954, Betts Pond area, Burlington Peninsula, Newfoundland: Report to Falconbridge Nickel Mines (copy lodged with Newfoundland Department of Mines).
- Batanova, V.G., Suhr, G. and Sobolev, A.V., 1998, Origin and geochemical heterogeneities in the mantle peridotites from the Bay of Islands ophiolite, Newfoundland, Canada: Ion probe study of clinopyroxenes: Geochimica et Cosmochimica Acta, v. 62, p. 853-866.
- Bédard, J.H., 1991, Cumulate recycling and crustal evolution in the Bay of Islands ophiolite: Journal of Geology, v. 99, p. 225-249.
- Bédard, J.H., 1993, Oceanic crust as a reacting filter: Synkinematic intrusion, hybridization, and assimilation in an ophiolitic magma chamber, western Newfoundland: Geology, v. 21, p. 77-80.
- Bédard, J.H. and Constantin, M., 1991, Syn- and post-kinematic intrusions of

- troctolite, gabbro, and peridotite into layered gabbroic cumulates in the Bay of Islands ophiolite: genesis of anorthosite by partial assimilation, and troctolite by hybridization: Geological Survey of Canada, Current Research, Paper 91-1, part D, p. 79-88.
- Bédard, J.H. and Hébert, R., 1996, The lower crust of the Bay of Islands ophiolite, Canada: Petrology, mineralogy, and the importance of syntaxis in magmatic differentiation in ophiolites and at ocean ridges: *Journal of Geophysical Research*, v. 101, p. 25105-25124.
- Bédard, J.H. and Hébert, R., 1998, Formation of chromitites by assimilation of crustal pyroxenites and gabbros into peridotitic intrusions: North Arm Mountain Massif, Bay of Islands ophiolite, Newfoundland, Canada: *Journal of Geophysical Research*, v. 103, p. 5165-5184.
- Bédard, J., Lauzière, C., Tremblay, A. and Sangster, A., 1998, Evidence for forearc seafloor-spreading from the Betts Cove ophiolite, Newfoundland: oceanic crust of boninitic affinity: *Tectonophysics*, v. 284, p. 233-245.
- Benson, W.N., 1926, The Tectonic Conditions Accompanying the Intrusion of Basic and Ultrabasic Igneous Rocks. *Memoirs of the National Academy of Science*, volume XIX, Memoir 1, 90 p.
- Berclaz, A., Hébert, R. and Bédard, J.H., 1998, Predominance and significance of deformation processes in the genesis of deep oceanic crust at a slow-spreading ridge: Evidence from the Bay of Islands ophiolite, Newfoundland: Geological Association of Canada-Mineralogical Association of Canada Annual Meeting, Québec, Program with Abstracts 23: p. 15-16.
- Boudier, F. and Nicolas, A., eds., 1988, The Ophiolites of Oman: Tectonophysics (Special Issue), v. 151, p. 1-401.
- Bowen, N.L., 1927, *The Evolution of Igneous Rocks*: Princeton University Press.
- Brassard, B. and Tremblay, A., 1999, Synthèse géologique et métallogénique de la M.R.C. de l'Amiante: Rapport final préparé pour la société d'aide au développement de la collectivité de l'Amiante (SADC), échelle 1/50 000 feuillets nord et sud de la MRC de l'Amiante.
- Brongniart, A., 1813, Essai de classification minéralogique des roches mélanges: *Journal des Mines*, v. XXXIV, p. 190-199.
- Brongniart, A., 1821, Sur le gisement ou position relative des ophiolites, euphotides, jaspes, etc. dans quelques parties des Appenins: *Annales des Mines*, Paris, v. 6, p. 177-238.
- Brongniart, A., 1827, Classification et caractères minéralogiques des roches homogènes et hétérogènes: Paris, F.G. Levrault, 144 p.
- Brunn, J.H., 1959, La dorsale médio-Atlantique et les épanchements ophiolitiques: *Comptes-rendus sommaires, Société géologique de France*, p. 234-236.
- Cairnes, C.E., 1930, The serpentine belt of Coquihalla region, Yale District, British Columbia: Geological Survey of Canada Summary report for 1929, Part A, p. 144-197.
- Cameron, W.E., Nisbet, E.G. and Dietrich, V.J., 1979, Boninites, komatiites, and ophiolitic basalts: *Nature*, v. 280, p. 550-553.
- Casey, J.F. and Dewey, J., 1984, Initiation of subduction zones along transform and accreting plate boundaries, triple-junction evolution, and forearc spreading centres-implications for ophiolitic geology and obduction, in Gass, I.G., Lippard, S.J. and Shelton, A.W. eds., *Ophiolites and Oceanic Lithosphere*, Geological Society, London, Special Publications 13, p. 269-290.
- Casey, J. F., Karson, J.A., Elthon, D.L., Rosencrantz, E. and Titus, M., 1983, Reconstruction of the geometry of accretion during formation of the Bay of Islands ophiolite Complex: *Tectonics*, v. 2, p. 509-528.
- Cawood, P.A. and Suhr, G., 1992, Generation and obduction of ophiolites: constraints from the Bay of Islands Complex, western Newfoundland: *Tectonics*, v. 11, p. 884-897.
- Church, W.R., 1965, Structural evolution of northeast Newfoundland-comparison with that of the British Caledonides: *Maritime Sediments*, v. 1, p. 10-14.
- Church, W.R., 1969, Metamorphic rocks of the Burlington Peninsula and adjoining areas of Newfoundland and their bearing on continental drift, in *North Atlantic Geology and Continental Drift*. American Association of Petroleum Geologists Memoir 12, p. 212-233.
- Church, W.R., 1972, Ophiolite: its definition, origin as oceanic crust, and mode of emplacement in orogenic belts, with special reference to the Appalachians, in Irving, E. ed.: *The Ancient Oceanic Lithosphere*, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, v. 42, No.3, p. 71-85.
- Church, W.R., 1977, The ophiolites of southern Quebec: oceanic crust of Betts Cove type: *Canadian Journal of Earth Sciences*, v. 14, p. 1668-1673.
- Church, W.R., 1978, The ophiolites of southern Quebec: oceanic crust of Betts Cove type: Reply. *Canadian Journal of Earth Sciences*, v. 15, p. 1882-1883.
- Church, W.R. and Stevens, R.K., 1971, Early Paleozoic complexes of the Newfoundland Appalachians as mantle-crust sequences: *Journal of Geophysical Research*, v. 76, p. 1460-1466.
- Clague, D., Frankel, C.S. and Eaby, J.S., 1985, The age and origin of felsic intrusions in the Thetford Mines ophiolite, Quebec: *Canadian Journal of Earth Sciences*, v. 22, p. 1257-1261.
- Clague, D., Rubin, J. and Brackett, R., 1981, The age and origin of the garnet amphibolite underlying Thetford Mines ophiolite, Quebec: *Canadian Journal of Earth Sciences*, v. 18, p. 469-486.
- Coleman, R.G., 1971, Plate tectonic emplacement of upper mantle peridotites along continental edges: *Journal of Geophysical Research*, v. 76, p. 1212-1222.
- Coleman, R.G., 1977, *Ophiolites*: Springer-Verlag, Berlin-Heidelberg, 229 p.
- Coleman, R.G., 1981, Tectonic setting for ophiolite obduction in Oman: *Journal of Geophysical Research*, v. 86, p. 2497-2508.
- Colpron, M. and Nelson, J., eds., 2006, Paleozoic Evolution and Metallogeny of Pericratonic Terranes at the Ancient Pacific Margin of North America-Canadian and Alaskan Cordillera: Geological Association of Canada, Special Paper 45, 523 p.
- Condie, K.C., 1989, *Plate Tectonics and Crustal Evolution*: 3rd edition, Pergamon Press, Oxford, 476 p.
- Cooke, H.C., 1938, Régions de Thetford, de Disraéli, et de la moitié orientale de Warwick (Québec): Commission géologique du Canada, Mémoire 211, 176 p.
- Cooke, H.C., 1956, Géologie d'une partie du sud-ouest des Cantons de l'Est de la Province de Québec: Commission géologique du Canada, Mémoire 257, 173 p.
- Corcoran, P.L.L., Mueller, W.E. Kusky, T.M., 2004, Inferred ophiolites in the Archean Slave Craton, in Kusky T.M. ed., *Precambrian Ophiolites and Related rocks: Developments in Precambrian Geology* 13, Elsevier, Amsterdam, p. 363-404.
- Dallmeyer, R.D. and Williams, H., 1975, ⁴⁰Ar/³⁹Ar ages from the Bay of Islands metamorphic aureole: Their bearing on the timing of Ordovician ophiolite: *Canadian Journal of Earth Sciences*, v.

- 12, p. 1685-1690.
- David, J. and Marquis, R., 1994, Géochronologie U-Pb dans les Appalaches du Québec: application aux roches de la zone de Dunnage: *Revue Géologique du Québec* v. 1, p. 16-20.
- De Roever, W.P., 1957, Sind die alptypen Peridotitmassen vielleicht tektonisch verfrachtete Buruhstücke der Peridotschale: *Geologische Rundschau*, v. 46, p. 137-146.
- Dewey, J.F., 2001, Plate tectonics and geology, 1965 to today, in Oreskes, N., ed., *Plate Tectonics*, Westview Press, Boulder, Colorado, p. 227-242.
- Dewey, J.F. and Bird, J.M., 1969, Lithosphere plate-continental margin tectonics and the evolution of the Appalachian orogen: *Bulletin of the Geological Society of America*, v. 81, p. 1031-1060.
- Dewey, J.F. and Bird, L.M., 1970, Mountain belts and the New Global Tectonics: *Journal of Geophysical Research*, v. 75, p. 2625-2647.
- Dewey, J. F. and Bird, J.M., 1971, Origin and emplacement of the ophiolite suite: Appalachian ophiolites in Newfoundland: *Journal of Geophysical Research*, v. 76, p. 3179-3206.
- Dietz, R.S., 1963, Collapsing continental rises: an actualistic concept of geosynclines and mountain building: *Journal of Geology*, v. 71, p. 314-333.
- Dilek, Y., 2003, Ophiolite concept and its evolution, in Dilek Y. and Newcomb S., eds., *Ophiolite Concept and the Evolution of Geological Thought*: Geological Society of America Special Paper 373, p. 1-16.
- Dilek, Y. and Ahmed, Z., 2003, Proterozoic ophiolites of the Arabian Shield and their significance in Precambrian tectonics, in Dilek, Y. and Robinson, P.T. eds., *Ophiolites in Earth History*: Geological Society, London, Special Publications 218, p. 685-700.
- Dilek, Y. and Newcomb, S., 2003, Ophiolite Concept and the Evolution of Geological Thought: Geological Society of America Special Paper 373, 504 p.
- Dilek, Y. and Robinson, P.T., eds., 2003, *Ophiolites in Earth History*: Geological Society of London Special Publication 218, 717 p.
- Dilek, Y., Moores, E.M., Elthon, D., and Nicolas, A., eds., 2000, *Ophiolites and Oceanic Crust: New Insights from Field Studies and the Ocean Drilling Program*: Geological Society of America Special Paper 349, 552 p.
- Dresser, J.A., 1913, Preliminary report on the serpentine and associated rocks of southern Quebec: Geological Survey of Canada, Memoir 22, 103 p.
- Dunning G.R. and Krogh, E., 1985, Geochronology of ophiolites of the Newfoundland Appalachians: *Canadian Journal of Earth Sciences*, v. 22, p. 1659-1670.
- Dunning, G.R. and Pedersen, R.B., 1988, U/Pb ages of ophiolites and arc-related plutons of the Norwegian Caledonides: Implications for the development of Iapetus: *Contributions to Mineralogy and Petrology*, v. 98, p. 13-23.
- Edwards, S. J., 1990, Harzburgites and refractory melts in the Lewis Hills massif, Bay of Islands ophiolite complex: The base-metals and precious-metals story: *The Canadian Mineralogist*, v. 28, p. 537-552.
- Edwards, S.J., 1995, Boninitic and tholeiitic dikes in the Lewis Hills mantle section of the Bay of Islands ophiolite: Implications for magmatism adjacent to a fracture zone in a back-arc spreading environment: *Canadian Journal of Earth Sciences*, v. 32, p. 2128-2146.
- Ells, R.W., 1886, Rapport sur la géologie d'une portion des Cantons de l'Est se rattachant particulièrement aux comtés de Compton, Stanstead, Beauce, Richmond et Wolfe: Commission géologique du Canada, Rapport Annuel, volume II, partie J, 170 p.
- Ells, R.W., 1888, Deuxième rapport sur la géologie d'une partie de la Province de Québec: Commission géologique du Canada, Rapport Annuel, volume III, partie K, 139 p.
- Ells, R.W., 1889, Rapport sur les richesses minérales de la Province de Québec: Commission géologique du Canada, Rapport Annuel, volume IV, partie K, 170 p.
- Elthon, D., 1991, Geochemical evidence for formation of the Bay of Islands ophiolite above a subduction zone: *Nature*, v. 354, p. 140-143.
- Elthon, D., Casey, J.F. and Komor, S., 1982, Mineral chemistry of ultramafic cumulates from the North Arm Mountain massif of the Bay of Islands ophiolite: Evidence for high-pressure crystal fractionation of oceanic basalts: *Journal of Geophysical Research*, v. 87, p. 8717-8734.
- Feininger, T., 1981, Amphibolite associated with the Thetford Mines ophiolite complex at Belmina Ridge, Québec: *Canadian Journal of Earth Sciences*, v. 18, p. 1878-1892.
- Fouqué, F. and Michel Lévy, A., 1879, *Minéralogie Pétrographique: Mémoires et Cartes géologiques de France*, 153 p.
- Friend, C.R.L., Bennett, V.C. and Nutman, A.P., 2002, Abyssal peridotites > 3,800 Ma from southern West Greenland: field relationships, petrography, geochronology, whole-rock and mineral chemistry of dunite and harzburgite inclusions in the Itsaq Gneiss Complex: *Contributions to Mineralogy and Petrology*, v. 143, p. 71-92.
- Gabrielse, H., 1955, Petrology and structure of the McDame ultramafic belt, British Columbia: Columbia University, Ph.D thesis, New York, NY, USA.
- Gabrielse, H., 1963, McDame map-area, Cassiar District, British Columbia: Geological Survey of Canada Memoir 319.
- Gass, I. G., 1963, Is Troodos Massif of Cyprus a fragment of Mesozoic ocean floor?: *Nature (London)*, v. 220, p. 39-42.
- Gibson, I.L., Malpas, J., Robinson, P.T., and Xenophontos, C., eds., 1989, *Cyprus Crustal Study Project: Initial Report, Hole Cy-4*. Geological Survey of Canada, Paper 88-9, 393 p.
- Graham, R.P.D., 1917, Origin of massive serpentine and chrysotile of Asbestos, Black lake, Thetford Mines area, Quebec: *Economic Geology*, v. 12, p. 154-202.
- Greenbaum, D., 1972, Magmatic processes at ocean ridges, evidence from Troodos Massif, Cyprus: *Nature Physical Sciences*, v. 238, p. 18-21.
- Haggart, J.W., Enkin, R.J., and Monger, J.W.H. eds., 2006, *Paleogeography of the North American Cordillera: Evidence for and against Large-Scale Displacements*: Geological Association of Canada, Special Paper 46, 420 p.
- Harnois, L. and Morency, M., 1989, Geochemistry of Mount Orford Ophiolite complex, Northern Appalachians, Canada: *Chemical Geology*, v. 77, p.133-147.
- Hawkins, J.W. 2003, Geology of supra-subduction zones. Implications for the origin of ophiolites, in Dilek, Y. and Robinson, P.T., eds., *Ophiolites in Earth History*: Geological Society of London Special Publication 218, p. 227-268.
- Hébert, R. 1981, Conglomérats polygéniques ophiolitiques: anciens éboulis de talus de fond océaniques?: *Canadian Journal of Earth Sciences*, v. 18, p. 619-623.
- Hébert, R. and Bédard, J.H., 2000, Les ophiolites d'avant-arc et leur potential mineral: Exemple des complexes ophiolitiques du Québec: *Chronique de la Recherche Minière du BRGM*, v. 539, p. 101-117.
- Hébert, R. and Laurent, R., 1989, Mineral

- chemistry of ultramafic and mafic plutonic rocks of the Appalachian ophiolites, Québec, Canada: *Chemical Geology*, v. 77, p. 265-285.
- Helmstaedt, H. and Scott, D.J., 1992, The Proterozoic ophiolite problem, *in* Condie, K.C., *ed.*, *Proterozoic Crustal Evolution: Developments in Precambrian Geology* 10, Elsevier, Amsterdam, p. 55-95.
- Hess, H.H., 1955, Serpentinites, Orogeny, and Epiorogeny: Geological Society of America Special paper 62, p. 391-407.
- Hess, H.H., 1962, History of ocean basins, *in* Engel, A.E.J., James, H.L., and Leonard, B.F., *eds.*, *Petrologic Studies: A volume in honor of A.F. Buddington*, Geological Society of America p. 599-620.
- Hess, H. H., 1965, Mid-ocean ridges and tectonics of the sea floor, *in* *Proceedings 17th Symposium Colston Resource Society*. University of Bristol, London, Butterworths, p. 317-333.
- Huot, F., Hébert, R., and Turcotte, B., 2002, A multi-stage magmatic history for the genesis of the Orford ophiolite (Quebec, Canada): a study of the Mt Chagnon massif: *Canadian Journal of Earth Sciences*, v. 39, p. 1201-1217.
- Hunt, T.S., 1856, *Rapport de Progrès, 1853-1856: Exploration géologique du Canada*.
- International Atlas of Ophiolites, 1979, Working Group for International Geological Correlation program project 39 "Ophiolites of Continents and comparable Oceanic Rocks", Geological Society of America Maps and Charts Series MC-33.
- Irvine, T.N. and Findlay, T.C., 1972, Alpine-type peridotite with particular reference to the Bay of Islands igneous complex, *in* *The ancient oceanic lithosphere: Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa*, v. 42, No. 3, p. 97-128.
- Jamieson, R.A., 1986, P-T paths from high temperature shear zones beneath ophiolites: *Journal of Metamorphic Geology*, v. 4, p. 3-22.
- Jenner, G.A., Dunning, G.R., Malpas, J., Brown, M., and Brace, T., 1991, Bay of Islands and Little Port Complex, revisited: Age, geochemical, and isotopic evidence confirm suprasubduction zone origin: *Canadian Journal of Earth Sciences*, v. 28, p. 1635-1652.
- Juteau, T., 2003, Identification of a mantle unit in ophiolites: A major step in the evolution of the ophiolite concept, *in* Dilek, Y., and Newcomb, S. *eds.*, *Ophiolite Concept and the Evolution of Geological Thought: Boulder, Colorado*, Geological Society of America Special Paper 373, p. 31-53.
- Karson, J.A., 1984, Variations in structure and petrology in the Coastal Complex, Newfoundland: Anatomy of an oceanic fracture zone, *in* Lippard, S.J., Shelton, A.W., and Gass, I.G., *eds.*, *Ophiolites and Oceanic Lithosphere*, Geological Society of London Special Publications 13, p. 131-144.
- Karson, J.A. and Dewey, J. F., 1978, Coastal complex, western Newfoundland: An early Ordovician oceanic fracture zone. *Geological Society of America Bulletin* 89, p. 1037-1049.
- Karson, J.A., Elthon, D. and Delong, S.E., 1983, Ultramafic intrusions in the Lewis Hills Massif, Bay of Islands Ophiolite Complex, Newfoundland: Implications for the igneous processes at oceanic fracture zone: *Geological Society of America Bulletin* 94, p. 15-29.
- Kim, J. and Jacobi, R.D., 2002, Boninites: characteristics and tectonic constraints, northeastern Appalachians: *Physics and Chemistry of the Earth*, v. 27, p. 109-147.
- Komor, S. C. Elthon, D. and Casey, J.F., 1987, Petrology of leucogabbroic interval within basal layered gabbros at North Arm Mountain, Bay of Islands ophiolite: *Contributions to Mineralogy and Petrology*, v. 95, p. 278-300.
- Kontinen, A., 1987, An Early Proterozoic ophiolite-The Jormua mafic-ultramafic complex: *Precambrian Research* v. 35, p. 313-341.
- Kusky, T.M., *ed.*, 2004, *Precambrian Ophiolites and Related Rocks: Developments in Precambrian Geology* 13; Elsevier, Amsterdam, 748 p.
- Lamarque, R. Y., 1969, Evidence of Cambrian orogeny in the Disraeli area, eastern Townships: *Geological Association of Canada Annual Meeting, Montréal, Abstracts*, p. 26.
- Lamarque, R.Y., 1971, Complexe ophiolitique d'Asbestos: *Extrait de Travaux sur le terrain 1971, Ministère des Richesses Naturelles du Québec, Service géologique, rapport S-126*, p. 87-90.
- Lamarque, R.Y., 1972, Ophiolites of southern Quebec, *in* Irving, E. *ed.*, *The Ancient Oceanic Lithosphere*, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, v. 42, No. 3, p. 65-69.
- Laurent, R., 1972, The ophiolite sequences of southwestern Quebec: *Geological Society of America Penrose Conference*, 14 p.
- Laurent, R., 1973, The Thetford Mines ophiolite, Paleozoic "flake" of oceanic lithosphere in the Northern Appalachians: *Geological Society of America, Northeastern Section, Allentown*, p. 188.
- Laurent, R., 1975, Occurrences and origin of the ophiolites of southern Quebec, Northern Appalachians: *Canadian Journal of Earth Sciences*, v. 12, p. 443-455.
- Laurent, R., 1978, The ophiolites of southern Quebec: oceanic crust of Betts Cove type: Discussion: *Canadian Journal of Earth Sciences*, v. 15, p. 1880-1881.
- Laurent, R and Hébert, Y., 1977, Features of submarine volcanism in ophiolites from the Quebec Appalachians, *in* Baragar, W.R.A., Coleman, L.C., and Hall, J.M. *eds.*, *Volcanic Regimes in Canada: Geological Association of Canada Special Paper* 16, p. 91-109.
- Laurent, R. and Hébert, R., 1989, The volcanic and intrusive rocks of the Québec Appalachians ophiolites (Canada) and their island-arc setting: *Chemical Geology*, v. 77, p. 287-302.
- Leech, G.B., 1953, Geology and mineral deposits of the Shulaps Range: *British Columbia Department of Mines and Petroleum Resources, Bulletin* 32.
- Le Pichon, X., Francheteau, J., and Bonnin, J., 1976, *Plate Tectonics: Developments in Geotectonics* 6, Elsevier, Amsterdam, 311 p.
- Little, H., 1949, The ultrabasic rocks of Middle River Range, B.C: *American Journal of Science*, v. 247, p. 802-823.
- Logan, W.E., 1863, *Geology of Canada: Geological Survey of Canada, Progress Report to 1863*, 963 p.
- Malpas, J., 1979, The dynamothermal aureole of the Bay of Islands ophiolite suite: *Canadian Journal of Earth Sciences*, v. 16, p. 2086-2101.
- Malpas, J and Robinson, P.T., 2000, Oceanic lithosphere 4. The origin and evolution of oceanic lithosphere: *Magmatic processes at oceanic spreading centres: Geoscience Canada*, v. 27, p.131-146.
- Malpas, J. and Talkington, R.W., *eds.*, 1979, *Ophiolites of the Canadian Appalachians and Soviet Urals: Memorial University of Newfoundland Department of Geology Report no. 9, Contribution to IGCP Project 39*, 165 p.
- Malpas, J., Moores, E.M., Panayiotou, and Xenophontos, C., *eds.*, 1990, *Ophiolites: Oceanic crustal analogues: Proceedings of the Symposium Troodos 1987, Ministry of Agriculture and Natural Resources, Geological Survey Department, Nicosia, Cyprus*, 733 p.
- Mattinson, J.M., 1975, Early Paleozoic

- ophiolite complex of Newfoundland: isotopic ages of zircons: *Geology*, v. 3, p. 181-183.
- Mattinson, J.M., 1976, Ages of zircons from the Bay of Islands ophiolite complex, western Newfoundland: *Geology*, v. 4, p. 393-394.
- Miyashiro, A., 1973, The Troodos complex was probably formed in an island arc: *Earth and Planetary Science Letters*, v. 19, p. 218-224.
- Monger, J.W.H., 1972, Oceanic crust in the Canadian Cordillera, in Irving, E., *ed.*, *The Ancient Oceanic Lithosphere*, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, v. 42, No. 3, p. 59-69.
- Monger, J.W.H., 1977, Ophiolitic assemblages in the Canadian Cordillera, in Coleman, R.G. and Irwin, W.P. 1, *eds.* *North American Ophiolites*, Department of Geology and Mineral Industries, State of Oregon, Bulletin 95, p. 59-73.
- Moore, E.M., 1969, Petrology and structure of the Vourinos ophiolitic complex of Northern Greece: *Geological Society of America Special Paper* no. 118, 74 p.
- Moore, E.M., 1986, The Proterozoic ophiolite problem, continental emergence, and the Venus connection: *Science*, v. 234, p. 65-68.
- Moore, E.M., 2002, Pre-1 Ga (pre-Rodinian) ophiolites: their tectonic and environmental implications: *Geological Society of America Bulletin* v. 114, p. 80-95.
- Moore, E.M. and Vine, F.J., 1971, Troodos Massif, Cyprus and other ophiolites as oceanic crust: evaluation and implications: *Royal Society of London Philosophical Transactions series A*, v. 208, p. 443-466.
- Moore, E.M., Robinson, P.T., Malpas, J., and Xenophontos, C., 1984, Model for the origin of the Troodos Massif, Cyprus, and other Mideast ophiolites: *Geology*, v. 12, p. 500-503.
- Naldrett, A.J., 1972, Archean ultramafic rocks, in Irving, E., *ed.*, *The Ancient Oceanic Lithosphere*, Publications of the Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, v. 42, No. 3, p. 141-151.
- Nicolas, A., 1989, *Structures of Ophiolites and Dynamics of Oceanic Lithosphere*: Kluwer Academic Publishers, Dordrecht, 367 p.
- Oliver, J.L., Sykes, L., and Isacks, B., 1969, Seismology and the new global tectonics: *Tectonophysics*, v. 7, p. 527-541.
- Olsen, E.J., 1959, *Metamorphic differentiation during serpentinization*: Unpublished Ph.D. thesis, University of Chicago, 135 p.
- Olsen, E.J., 1961, High temperature acid rocks associated with serpentinite in eastern Quebec: *American Journal of Science*, v. 259, p. 329-347.
- Oshin, I.O. and Crocket, J.H., 1986, The geochemistry and petrogenesis of ophiolitic volcanic rocks from Lac de l'Est, Thetford Mines complex, Quebec, Canada: *Canadian Journal of Earth Sciences*, v. 23, p. 202-213.
- Panayiotou, A., *ed.*, 1980, *Ophiolites*: Proceedings International Ophiolite Symposium, Cyprus, 1979, Ministry of Agriculture and Natural Resources, Geological Survey Department, Nicosia, Cyprus, 780 p.
- Pearce, J.A., Lippard, S.J. and Roberts, S., 1984, Characteristics and tectonic significance of supra-subduction zone ophiolites, in Kokelaar, B.P. and Howells, M.F., *eds.*, *Marginal Basin Geology: Volcanic and Associated Sediments and Tectonic Processes in Modern and Ancient Marginal Basins*. Geological Society of London Special Publications 16, p. 77-94.
- Peters, T.J., Nicolas, A., Coleman, R. G. 1991, *eds.* *Ophiolite Genesis and Evolution of the Oceanic Lithosphere*, Proceedings of the Ophiolite Conference, Muscat, Oman: Kluwer Academic Publishers, Dordrecht, 903 p.
- Pinet, N. and Tremblay, A., 1995, Tectonic evolution of the Quebec-Maine Appalachians: from oceanic spreading to obduction and collision in the North Appalachians: *Journal of American Science*, v. 295, p. 173-200.
- Poitevin, E. and Graham, R.P.D., 1918, Étude sur la minéralisation de Black Lake, Québec: *Commission géologique du Canada, Bulletin du Musée*, 27, 85 p.
- Ricou, L.E., 1968, Sur la mise en place au Crétacé supérieur d'importantes nappes à radiolarites et ophiolites dans les Monts Zagros (Iran): *Comptes-rendus Académie des Sciences de Paris*, v. 267, p. 2272-2275.
- Riordon, P.H., 1954, Région de Thetford Mines-Black Lake, comtés de Frontenac, de Mégantic et de Wolfe: Ministère des Richesses Naturelles du Québec, Rapport préliminaire 295, 26 p.
- Robinson, P.T., Gibson, I.L., and Panayiotou, A., *eds.*, 1987, *Cyprus Crustal Study Project: Initial Reports*, Holes CY-2 and 2a: Geological Survey of Canada, Paper 85-29, 381 p.
- Robinson, P.T., Melson, W.G., O'Hearn, T., and Schmincke, H-U., 1983, Volcanic glass compositions of the Troodos ophiolite, Cyprus: *Geology*, v. 11, p. 400-404.
- Rodgers, J. and Neale, E.R.W., 1963, Possible "Taconic" Klippen in western Newfoundland: *American Journal of Science*, v. 261, p. 713-730.
- Rosencrantz, E., 1983, The structure of the sheeted dikes and associated rocks in the North Arm Mountain massif, Bay of Islands ophiolite complex, and the intrusive process at oceanic spreading centers: *Canadian Journal of Earth Sciences*, v. 20, p. 787-801.
- Salisbury, M.H. and Christensen, N.I., 1978, The seismic velocity structure of a traverse through the Bay of Islands ophiolite complex, Newfoundland, an exposure of oceanic crust and upper mantle: *Journal of Geophysical Research*, v. 83, p. 805-817.
- Scott, D.J., Helmstaedt, H.H. and Bickle, M.J., 1992, Portuniqu ophiolite, Cape Smith Belt, northern Quebec, Canada: A reconstructed section of Early Proterozoic oceanic crust: *Geology*, v. 20, p. 173-176.
- Scott, D.J., St-Onge, Lucas, S.B. and Helmstaedt, H., 1991, Geology and chemistry of the Early Proterozoic Portuniqu Ophiolite, Cape Smith Belt, northern Quebec, Canada, in T.J. Peters, A. Nicolas, and R.G. Coleman, *eds.*, *Ophiolite Genesis and Evolution of the Oceanic Lithosphere*: Kluwer Academic Publishers, Dordrecht, p. 817-849.
- Shanti, M. and Roobol, M.J., 1979, A late Proterozoic ophiolite complex at Jabal Ess in northern Saudi Arabia: *Nature* v. 279, p. 488-491.
- Siroky, F.X., Elthon, D.L., Casey, J. F. and Butler, J.C., 1985, Major element variations in basalts and diabases from the North Arm Mountain massif, Bay of Islands ophiolite: Implications for magma chamber processes at mid-ocean ridges: *Tectonophysics*, v. 116, p. 41-61.
- Souther, J.G., 1972, Mesozoic and Tertiary volcanism of the western Canadian Cordillera, in Irving, E., *ed.*, *The Ancient Oceanic Lithosphere*, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, v. 42, No.3, p. 55-58.
- Smith, C.H., 1958, Bay of Islands Igneous Complex, Western Newfoundland: *Geological Survey of Canada Memoir* 290, 132 p.
- Steinmann, G., 1905, *Geologische Beobachtungen in den Alpen, II. Die Schardtische Ueberfaltungstheorie und die geologische Bedeutung der Tiefseeabsätze und der ophiolithischen Massengesteine*: Ber. Naturf. Ges. Freiburg (im breisgau), 16.
- Steinmann, G., 1927, *Die ophiolithischen*

- Zonen in den mediterranen Kettengebirgen: *Compte-rendu XIVe Congrès géologique international 1926 Madrid, Graficas Reunidas*, v. 2, p. 637-667.
- Steinmann, G., 2003, Die ophiolitischen Zonen in den mediterranen Kettengebirgen (The ophiolitic zones in the Mediterranean mountain chains), Bernouilli, D. and Friedman, G.M., translators, *in* Dilek, Y. and Newcomb, S., eds., *Ophiolite Concept and the Evolution of Geological Thoughts*: Boulder, Colorado, Geological Society of America Special Paper 373, p. 77-91.
- Stern, R.J. and Bloomer, S.H., 1992, Subduction zone infancy: examples from the Eocene Izu-Bonin-Mariana and Jurassic California Arcs: *Geological Society of America Bulletin*, v. 104, p. 151-170.
- Stevens, R.K., 1970, Cambro-Ordovician Flysch sedimentation and tectonics in west Newfoundland and their possible bearing on a proto-Atlantic Ocean: *Geological Association of Canada Special Paper* v. 7, p. 165-177.
- St-Julien, P., 1968, Les « argiles-à-blocs » du sud-ouest des Appalaches du Québec: *Le Naturaliste Canadien*, v. 95, p. 1345-1356.
- St-Julien, P., 1970, Géologie de la région de Disraëli (moitié est): Ministère des Richesses Naturelles du Québec, Rapport préliminaire 587, p.
- St-Julien, P., Hubert, C., Skidmore, B., and Béland, J., 1972, Stratigraphie et structure des Appalaches du Québec: *Livret-guide des excursions A56-C56, XXIVième Congrès International*, Montréal, 105 p.
- St-Onge, M.R., Lucas, S.B., Scott, D.J., Bégin, N.J., 1989, Evidence for the development of oceanic crust and for continental rifting in tectonostratigraphy of the early Proterozoic Cape Smith Belt: *Geoscience Canada*, v. 16, p.119-122.
- Suhr, G. and Cawood, P.A., 2002, South-eastern Lewis Hills (Bay of Islands ophiolite): *Geology of a deeply eroded, inside-corner, ridge-transform intersection*. Geological Society of America Bulletin v. 113, p. 1025-1038.
- Suhr, G. and Edwards, S.J., 2000, Contrasting mantle sequences exposed in the Lewis Hills massif: Evidence for the early, arc-related history of the Bay of Islands ophiolite, *in* Dilek, Y., Moores, E.M., Elthon, D. and Nicolas, A., eds., *Ophiolites and Oceanic Crust, New insights From Field Studies and the Ocean Drilling program*: Geological Society of America Memoir 349, p. 433-442.
- Suhr, G. and Robinson, P.T., 1994, Origin of mineral chemical stratification in the mantle section of the Table Mountain massif (Bay of Islands ophiolite): *Lithos*, v. 31, p. 81-102.
- Sun, S-S, and Nesbitt, R.W., 1978, Geochemical regularities and genetic significance of ophiolitic basalts: *Geology*, v. 6, p. 689-693.
- Swinden, H.S., Jenner, G.A., and Szybinski, Z.A., 1997, Magmatic and tectonic evolution of the Cambrian-Ordovician Laurentian margin of Iapetus: Geochemical and isotopic constraints from the Notre Dame subzone, Newfoundland, *in* Sinha, A.K., Whalen, J.B., and Hogan, J.O., eds., *The nature of magmatism in the Appalachian Orogen*: Geological Society of America Memoir 191, p. 337-365.
- Tegvey, M., 1990, Ophiolite and Metamorphic Rocks of the Oman Mountains: A Petrographic Atlas: Ministry of Petroleum and Minerals, Sultanate of Oman Muscat, 140 p.
- Thayer, T.P., 1969, Peridotite-gabbro complexes as keys to petrology of mid-oceanic ridges: *Geological Society of America Bulletin* v. 80, p. 1515-1522.
- Thy, P. and Dilek, Y., 2003, Development of ophiolitic perspectives on models of oceanic magma chambers beneath active spreading centers, *in* Dilek, Y. and Newcomb, S., eds., *Ophiolite Concept and the Evolution of Geological Thought*: Boulder, Colorado, Geological Society of America Special Paper 373, p. 187-226.
- Tremblay, A., Bédard, J.H. and Lauzière, C., 1997, Taconian obduction and Silurian exhumation of the Betts Cove ophiolite, *Canadian Appalachians: Journal of Geology*, v. 105, p. 701-716.
- Trottier, J., 1982, Géochimie et pétrologie du complexe ophiolitique de Thetford Mines: Ph.D., dissertation, Université du Québec à Montréal, 168 p..
- Varfalvy, V., Hébert, R., and Bédard, J.H., 1996, Melt-upper mantle interactions in the North Arm Mountain massif, Bay of Islands ophiolite, Newfoundland: Implications for the genesis of boninitic magmas: *Chemical Geology*, v. 129, p. 71-90.
- Varfalvy, V., Hébert, R., Bédard, J.H. and Lafleche, M.R., 1997, Petrology and geochemistry of pyroxenite dikes in upper mantle peridotites of the North Arm Massif, Bay of Islands ophiolite, Newfoundland: Implications for the genesis of boninitic and related magmas: *The Canadian Mineralogist*, v. 35, p. 543-570.
- Vissers, R.L.M and Nicolas, A., eds., 1995, *Mantle and Lower Crust Exposed in Oceanic Ridges and in Ophiolites*: Kluwer Academic Publishers, Dordrecht, 214 p.
- Vuagnat, M., 1963, Remarques sur la trilogie serpentinites-gabbros-diabases dans le bassin de la Méditerranée occidentale: *Geologische Rundschau*, v. 53, p. 336-357.
- Vuagnat, M., 1968, Quelques réflexions sur le complexe basique-ultrabasique de la zone d'Ivrée et les ultramafites alpinotypes: *Schweizerische Mineralogische und Petrographische Mitteilungen*, v. 49, p. 157-164.
- Whitehead, J., Dunning, G.R. and Spray, J.G., 2000, U-Pb geochronology and origin of granitoid rocks in the Thetford Mines ophiolite, *Canadian Appalachians: Geological Society of America Bulletin*, v. 112, p. 915-928.
- Whitehead, J., Reynolds, P.H. and Spray, J.G., 1995, The sub-ophiolitic metamorphic rocks of the Québec Appalachians: *Journal of Geodynamics*, v. 19, p. 325-350.
- Williams, H., 1971, Mafic-ultramafic complexes in western Newfoundland Appalachians and the evidence for their transportation: A review and interim report: *Geological Association of Canada Proceedings* 24, p. 9-25.
- Williams, H., 1979, Appalachian orogen in Canada: *Canadian Journal of Earth Sciences* v. 16, p. 792-807.
- Williams, H., Kennedy, M.J. and Neale, E.R.W., 1974, The Northeastern Termination of the Appalachian Orogen, *in* Nairn, A.E.M. and Stehli, F.G. eds., *The Ocean Basins and Margins*: Plenum Publishing Corporation, New York, p. 79-123.
- Williams, H. and Malpas, J., 1972, Sheeted dikes and brecciated dike rocks within transported igneous complexes, Bay of Islands, Western Newfoundland: *Canadian Journal of Earth Sciences*, v. 9, p. 1216-1229.
- Williams, H. and Smyth, R., 1973, Metamorphic aureoles beneath ophiolite suites and Alpine peridotites: tectonic implications with west Newfoundland examples: *American Journal of Science*, v. 273, p. 594-621.
- Williams, H. and St-Julien, P., 1982, The Baie Verte-Brompton Line: Early Paleozoic continent-ocean interface in the Canadian Appalachians, *in* St-Julien, P. and Béland, J., eds., *Major Structural Zones and Faults of the Northern Appalachians: Geological Association of Canada, Special Papers* 24, p. 177-207.
- Wilson, J.T., 1966, Did the Atlantic close and then re-open?: *Nature*, v. 211, p. 676-681.

Wilson, R.A.M., 1959, The geology of the Xeros-Troodos area: Ministry of Agriculture and Natural Resources, Geological Survey Department, Cyprus, Memoir 1, 184 p.

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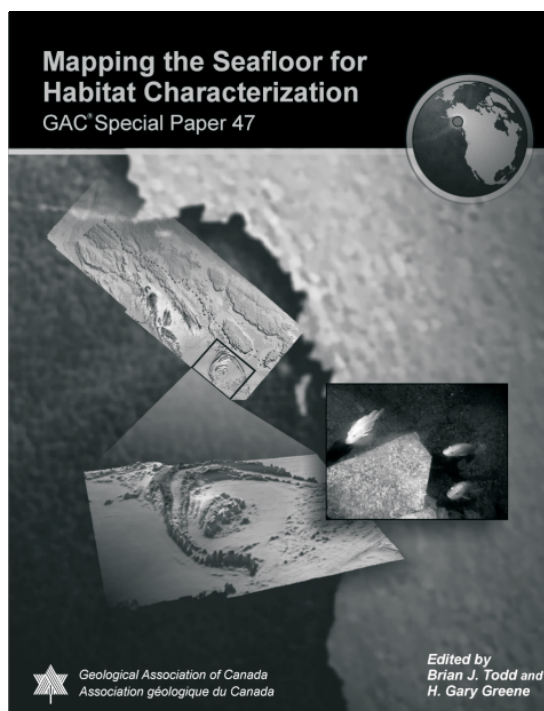
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