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Application of the modern ophiolite concept with special reference to Precambrian ophiolites

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Much has been learned in the past 40 years about the great diversity of the internal structure and geochemical compositions of Phanerozoic ophiolites, indicating that these on-land fragments of ancient oceanic lithosphere formed in distinctly different tectonic settings during their igneous evolution. Recent studies in Archean and Proterozoic greenstone belts have shown that the Precambrian rock record may also include exposures of a diverse suite of ophiolite complexes as part of craton development in the early history of the Earth. We review the salient features of the Precambrian ophiolite record to highlight what has been learned about Precambrian oceanic spreading systems since the original Penrose definition of ophiolites in 1972. Some of the diagnostic, characteristic, typical, and rare aspects of ophiolites of all ages are presented in a table in order to help determine if tectonically deformed and metamophosed sequences in Precambrian shield areas may be considered as ophiolites. The results of this comparative study are important in that they enable researchers to more realistically characterize allochthonous mafic/ultramafic rock sequences as ophiolitic or non-ophiolitic. This approach is more deterministic in contrast to some other arbitrary classification schemes requiring three or four of the Penrose-style ophiolitic units to be present in the Precambrian record for a specific rock sequence to be considered ophiolitic. Once these tectonic fragments are recognized as remnants of ancient oceanic lithosphere, great progress shall be made in understanding early Earth history. We discuss the significance and implications of the Precambrian ophiolite record to constrain the mode and nature of the plate tectonics that operated in deep time.

ophiolite, Precambrian, craton, greenstone belt

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Understanding the early history of the Earth and how the planet developed from a planetary nebula to its present, life-sustaining state is one of the most fundamental problems in Earth sciences and one that has occupied the thoughts of scholars for centuries. To approach these questions it is necessary to synergize data from a variety of sources to estimate how plate tectonics, which is presently the surface expression of planetary heat loss, has evolved from a period of higher heat flow from the early Earth to its present state [1]. This knowledge leads to a better understanding of how the surface and interior of the planet have evolved with time and how previous interactions of the lithosphere, atmosphere, hydrosphere, and biosphere have been driven by the fundamental heat loss from the interior

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of the Earth. These broad geodynamic goals require the integration of data from many different fields, including structural geology and tectonics, geophysics, petrology and geochemistry, geochronology, sedimentology, and biology. It also involves several different scales of observation, from global geophysical data sets, to regional syntheses, through the outcrop scale, to the microscopic and lattice levels, which yield clues about the boundary conditions of formation and deformation. Understanding the early history of the Earth is thus a multi-disciplinary, multi-scale problem.

To make headway in understanding how the early Earth operated and how it may have differed or been similar to today's Earth, it is necessary to compare studies of important Precambrian geological provinces with possible modern analogs. In this contribution we review modern advances in understanding ophiolites and then describe some examples of rock sequences from Precambrian shield areas, mostly in greenstone belts, that have been suggested to contain ophiolitic components. We evaluate whether these suggestions are plausible or not, then compare these possible Precambrian ophiolites with their younger counterparts. We use an unashamedly uniformitarianist approach to the problem [2] and rely mostly on the field relationships and general rock types present, following the original definition of ophiolite [3].

1 General characteristics of ophiolites

Ophiolites are a distinctive association of rocks interpreted to have formed in a variety of plate tectonic settings, including oceanic spreading centers, back-arc basins, forearcs, arcs, and other extensional magmatic settings [4–17]. A classic Penrose-type ophiolite [3] is typically 5–15 km thick, and if complete, consists of the following sequence from base to top (Figure 1), with a fault marking the base of the ophiolite. The base of most ophiolites consists of harzburgite, consisting of olivine + orthopyroxene (± chromite), often forming strongly deformed or transposed compositional layering, forming harzburgite tectonite. The lowest unit in some ophiolites is lherzolite, consisting of olivine + clinopyroxene + orthopyroxene, generally interpreted to be fertile, undepleted mantle. In some ophiolites, harzburgite overlies lherzolite. The harzburgite is generally interpreted to be the depleted residual mantle from which overlying mafic rocks were derived, and the deformation is related to the overlying lithospheric sequence flowing away from the ridge along a shear zone within the harzburgite. The harzburgite sequence may be more than 10 km thick in some ophiolites, such as the Semail ophiolite in Oman, and the Bay of Island ophiolite in Newfoundland (Canada).

Resting above the upper mantle peridotites is a group of rocks that were crystallized from magma derived by partial melting of the harzburgite. The lowest unit of these crustal rocks includes crystal cumulates of pyroxene and olivine, forming distinctive layers of pyroxenite, dunite, and other olivine + clinopyroxene + orthopyroxene peridotites including wherlite, websterite, and pods of chromite + olivine. The boundary between these rocks (derived by partial melting and crystal fractionation) and those below from which melts were extracted is one of the most fundamental boundaries in oceanic lithosphere and defines the petrological Moho, or base of the crust. In this case, the Moho is a chemical boundary, without a sharp seismic discontinuity, and the seismic boundrary is at the top of the dunites. In many ophiolites, such as Semail, this boundary is invaded by gabbroic sill intrusions that make up magma lenses at the crust-mantle transition zone. A seismic discontinuity occurs about half a kilometer higher than the chemical Moho in most complete ophiolites, between the ultramafic cumulates (dunites) and gabbroic section of the ophiolite [18].

The layered ultramafic cumulates grade upwards into a zone of interlayered pyroxenite and plagioclase-rich cumulates, then into a variable but typically up to 1-km-thick unit of layered gabbro. Individual layers within this thin unit may include gabbro, pyroxenite, and rarely, anorthosite. The layered gabbro is succeeded upward by several to 5 km of isotropic gabbro, which is generally massive but may have a faint layering. The layers within the isotropic gabbro in some ophiolites define a curving trajectory, interpreted to represent crystallization along the walls of a paleo-magma chamber. The upper part of the gabbro may contain many xenoliths of basalt, pods of trondhjemite (plagioclase plus quartz plus hornblende), and may be cut by dolerite dikes.

The next highest unit in a complete Penrose-model ophiolite is typically a sheeted dike complex, consisting of a 0.5–2-km-thick complex of doleritic, gabbroic, to silicic dikes that show mutually intrusive relationships with the underlying gabbro. In ideal cases, each dolerite dike intrudes into the center of the previously intruded dike, forming a sequence of dikes that have chilled margins developed only on one side, though in many ophiolites (e.g., Cyprus) most dikes have two-sided chill margins. In some ophiolites that are not severely deformed or metamorphosed, examples of one way chilling may be found, but statistically the one-way chilling may only show directional preference in 50%–60% of cases. Sheeted dike complexes are absent in many ophiolites and are only preserved in about 10% of ophiolite fragments world-wide [19], replaced instead by a sill or dike/sill complex. In strongly deformed or metamorphosed ophiolites it is commonly difficult to impossible to positively identify the sheeted dike complex, because the delicate chill margins on the dikes are easily recrystallized, typically being preserved only as a layered amphibolite unit.

The sheeted dikes represent magma conduits that fed lava flows on the seafloor. These flows are typically pillowed or massive, with lobes and tubes of basalt forming bulbous shapes distinctive of underwater basaltic volcanism.

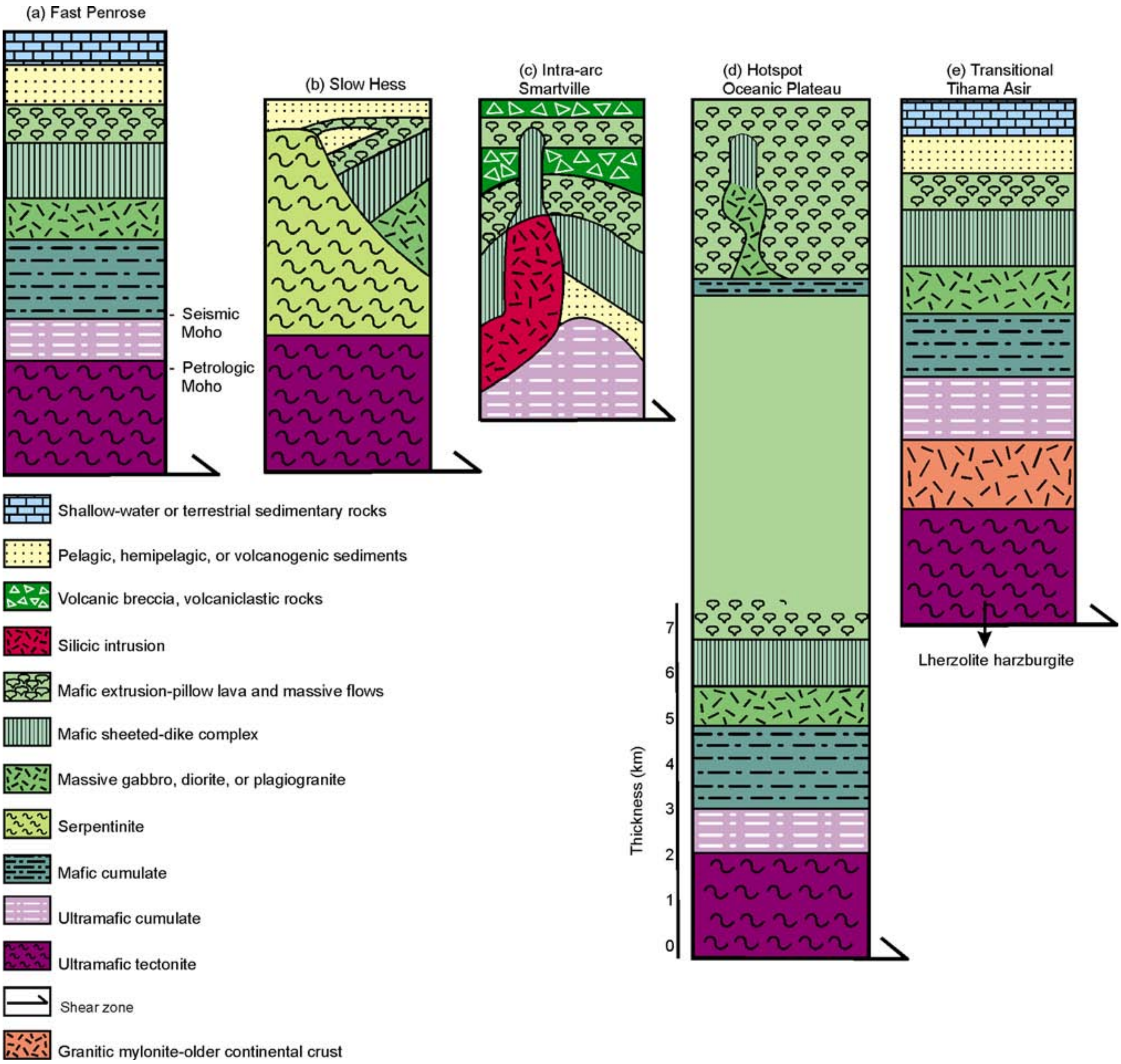

Figure 1 Simplifed magmato-stratigraphic sections of different types of ophiolites recognized from the extant plate tectonic plate mosaic.

The extrusive section is typically 0.5–1 km thick. Interstices between the pillows may be filled with chert, jasper or pelagic limestone, and sulfide minerals are common. In some cases, massive sulfide deposits are preserved, some with convincing examples of fossil black-smoker chimneys [20–23].

Many ophiolites are overlain by deep-sea sediments, including chert, red clay, or in some cases carbonates, clastic sedimentary rocks, pyroclastics, or sulfide layers. Many variations are possible, depending on tectonic setting (e.g., conglomerates and clastic sediments may form in some settings), water depth and CCD, water temperatures, and age (e.g., siliceous biogenic oozes and limestones would not form in Archean ophiolites, before the life forms that contribute their bodies developed on Earth). In the 1960s and 1970s much research was aimed at defining a type ophiolite succession, which became known as the Penrose-type of ophiolite [3]. More recent research has revealed that the variations between individual ophiolites are as significant as any broad similarities between them [3, 7, 11, 15–18, 24–28].

2 Variations between ophiolites and oceanic crust formed under different conditions

Research in ophiolite studies and *in-situ* oceanic crust since the Penrose definition of ophiolite in the 1970's [3, 29, 30] has revealed a much greater diversity in the abundance and sequence of rock types present (Figure 1) than originally known when the Penrose-definition was published [7, 15, 16, 24, 25, 27]. For instance, it has been suggested that Penrose-style ophiolites form at fast spreading ridges such as the East Pacific Rise, whereas slow-spreading ridges like the Atlantic may have massive serpentinite or basalt overlying harzburgite tectonite, in turn faulted against pillow lavas, dikes and gabbros [31]. However, other ophiolites are interpreted to form in suprasubduction zone settings where the factors determining magma supply are completely different from those in operation at mid-ocean ridges, leading to different sequences of rocks in the ophiolite pseudostratigraphy (Figure 1). In some of these slow-spreading systems, tectonic extension is proceeding faster than magma can upwell to keep pace with the seafloor spreading rates [32], resulting in highly faulted and attenuated oceanic crust, and detachment faulting at these oceanic spreading centers can juxtapose the pillow lava section adjacent to the mantle peridotites [33]. Ophiolites produced in arc environments, either the main arc, forearc, or back arc, typically have thick mafic cumulate sections, interstratified volcaniclastic, pelagic, or hemipelagic sediments, and thick lava sequences, some with boninitic and picritic compositions. Some arc-type ophiolites are intruded by plutons with mafic to silicic compositions that fed upper parts of the arc sequence with differences in ages between the sequences typically being tens of millions of years.

Oceanic crust produced at or near hot spots (Figure 1), such as the mid-Atlantic ridge near Iceland, has particular relevance to the Archean, since some models for the Archean suggest that the mantle may have been slightly hotter (at least locally) in earlier times, and possibly analogous to hot spots. However, hot spots are not much hotter than surrounding mantle, but simply produce greater amounts of magma than surrounding mantle. Places like Iceland, where a hot spot is superimposed on a mid-ocean ridge may be particularly analogous to Precambrian oceanic spreading environments where both upwelling and enhanced melting processes are occurring. Oceanic plateaus, with thick crustal sections, may have been the norm for oceanic crust in the Archean, with a possible candidate for an oceanic plateau preserved in the circa 2.7 Ga Belingwe greenstone belt, Zimbabwe [34–36]. Hence it is difficult, when assessing oceanic crust formed in early times, to differentiate between so-called normal oceanic crust and plateau-type crust. Oceanic plateaus have crustal sections that may reach or exceed 10–15 km in thickness. It may be best, during our present early stages of studies of ancient oceanic crust, to use the standard of the present when describing Archean sequences. In this way any similarities or differences between the present and Precambrian can be better-assessed than approaches that use a moving target of reference such as the "alternative Earth" model of Hamilton [37], or the ad-hoc models of Bickle et al. [38].

Several Precambrian ophiolites in the Slave Province and the Scandanavian Shield appear to have formed within the transition from rifted continental margins to ocean spreading centers during early stages of ocean opening [39, 40], then to have been structurally detached and/or deformed and incorporated into convergent margins during ocean closure. These ophiolites are distinctive from classical Penrose-style ophiolites (Figure 1) and others formed in forearc and back arc environments [41] and have been named "continental margin ophiolites" [41] or "transitional ophiolites" [17]. During early stages of ocean formation, continental crust and lherzolite of the subcontinental mantle are extended forming a graben structure on the surface and ductile mylonites at depth, reminiscent of continental metamorphic core complexes. Sedimentary basins may form in the graben, and as the extension continues magmatism locally affects the rifted margin, either forming volcanic rifted margins or migrating to a spreading center forming an oceanic spreading center. New asthenospheric mantle upwells along the new ridge and may intrude beneath the extended continental crust. In some cases, wedges of extended mid- to lower continental crust overlying mylonitic lherzolitic sub-continental mantle become intruded by numerous dikes and magmas from this new asthenospheric mantle. These dikes then feed a crustal gabbroic magma chamber closer to the surface which, in turn, may feed a dike complex and basaltic pillow/massive lava section. If preserved, this unusual sequence grades down from subaquatic sediments, to pillow lavas, dikes, sheeted dikes, layered gabbro, dunite and pyroxenite cumulates, then remarkably into stretched, typically mylonitic granitic mylonites, underlain by lherzolite. The lherzolite tectonite may be underlain by harzburgite tectonite or harzburgite.

Examples of this type of transitional ophiolite are found in the Proterozoic Jourma complex, and in some of the Slave Province ophiolites [39, 40]. Modern analogs for such transitional ophiolites are found around the Red Sea, including at Tihama Asir, Saudi Arabia, where a 5–10 Ma old transitional ophiolite has a dike complex overlying layered gabbro, which in turn overlies continental crust [26, 42]. Also, on Egypt's Zabargad Island, oceanic mantle is exposed, and it is likely that the crustal structure near this region preserves transitional ophiolites as well [43].

The main lesson from post-1972 ophiolite studies is that ophiolites may form in many tectonic settings, from extended continental crust, to mid ocean ridges, to forearcs, arcs, back arcs, to triple junctions along convergent margins [16]. Once a sequence is identified as ophiolitic, then geologists need to identify the tectonic environment in which it formed before making realistic comparisons to younger environments to determine how plate tectonic style has changed with time.

3 Processes of ophiolite and oceanic crust formation

The sequence of rock types described above are a product of specific processes that occurred within the oceanic spreading centers along which the ophiolites formed [3, 6, 10, 11, 15, 16, 25, 31]. Variations in the rock sequence, mineralogy, chemistry, or structure of ophiolites with time may be related to variations in the processes that produced the ophiolites. With higher heat production in the early Earth, it is important to document these variations to determine how the Earth may have lost heat in early times of high heat production. It is not clear whether the early mantle responded to the higher heat production by a significant increase in temperature, a change in viscosity and greater ease in convective overturn, or some other process [44–59]. Studies of Precambrian ophiolites and related rocks have great potential to unravel the secrets of early heat loss from the planet.

As the mantle convects and the asthenosphere upwells beneath mid ocean ridges, fertile mantle undergoes partial melting of 10%–15% in response to the decreasing pressure, leaving residual harzburgites beneath the crustal section. The percentage of partial melt may have been different in early times if mantle temperatures were significantly higher. So far, estimates of partial melt fractions (greatly affected by the availability of water) estimated from Precambrian ophiolites have not determined whether or not the Precambrian melt fractions were on average greater than, less than, or similar to those of the younger record. The melts derived from the harzburgites rise to form a magma chamber beneath the ridge, forming the crustal section of the oceanic crust. As the magma crystallizes the densest crystals gravitationally settle to the bottom of the magma chamber, forming layers of ultramafic and higher mafic cumulate rocks. Above the cumulates, a gabbroic fossil magma chamber forms, typically with layers defined by varying amounts of pyroxene and plagioclase crystals. In several examples the layering in ophiolites has been shown to be parallel to the fossil margins of the magma chamber. An interesting aspect of the magma chamber is that periodically new magma is injected into the chamber, replenishing the magmatic system and changing its chemical and physical properities [60, 61]. These new magmas are injected during extension of the crust so the magma chamber may effectively expand infinitely if the magma supply is continuous as in fast spreading ridges. In slow spreading ridges the magma chamber may freeze over and completely crystallize before new batches of melt are injected. Studies of ancient ophiolites, therefore, have the potential to estimate relative rates of extension and magma supply, a line of research that has not yet matured in Precambrian ophiolite studies.

As extension occurs in the oceanic crust, dikes of magma shoot out of the gabbroic magma chamber, forming a doleritic (fine-grained rapidly cooled magma with the same composition as gabbro) to gabbroic sheeted dike complex. The dikes have a tendency to intrude along the weakest, least crystallized part of the previous dike, which is usually in the center of the last dike to intrude, or along the contacts between previously intruded dikes. In this way many dikes intrude the center of the previous dike, forming a sheeted dike complex characterized by dikes that have only one chill margin, most of which face in the same direction. In some Phanerozoic ophiolites, variations in the thickness and character of the dikes with depth have been related to temperature changes with depth. The dike complex thus represents a potential indicator of geothermal gradients in ancient ophiolites, but extracting such information from Precambrian ophiolites may be difficult due to the paucity of Precambrian dike complexes plus the effects of deformation and metamorphism have obscured many original relationships.

Many of the dikes reach the surface of the sea floor where they feed submarine lava flows. These lava flows on the sea floor are typically in the form of bulbous pillows that stretch out of magma tubes, forming the distinctive pillow lava section of ophiolites. The top of the pillow lava section is typically altered by sea floor metamorphism, including mineralized veins that culminate in deposits of black smoker-type hydrothermal vents [22, 62]. Early life forms probably flourished around these deep sea hydrothermal vents, but few studies have focused on searching for early life forms around Precambrian sea floor black smokers [63, 64], although recent studies have identified primitive life forms in the pillow lavas of Archean ophiolites, and gabbro sections of the modern sea floor [65, 66]. Studies of lava vesicularity, and the nature of interpillow sediments, have the potential to yield clues about the water depth (yet this is dependent on the abundance of volatiles), and hence crustal thickness, of ancient ophiolites, but few studies have yet explored these potentially critical relationships.

The pillow lavas are overlain by sediments deposited on the sea floor. In the Phanerozoic oceans, if the oceanic crust formed above the calcium carbonate compensation depth, the lowermost sediments may be calcareous. These would be succeeded by siliceous oozes, pelagic shales and other deep water sediments as the sea floor cools, subsides, and moves away from the mid ocean ridge. There has been no comprehensive analysis of the types of sediments expected to be deposited on Precambrian oceanic crust as it moved away from spreading centers nor how this sequence may have changed systematically with time. A third sequence of sediments may be found on the ophiolites. These would include sediments shed during detachment of the ophiolite from the sea floor basement and its thrusting (obduction) onto a continental margin or incorporated into an accretionary prism. The type of sediments deposited on ophiolites should have been very different in some of the oldest ophiolites that formed in the Precambrian. For instance, in the Proterozoic and especially the Archean, organisms that produce the carbonate and siliceous oozes were not present, as the organisms that produced these sediments had not yet evolved. Thus, study of the sedimentary sequences deposited on Precambrian ophiolites may yield important information about Precambrian sea water and atmospheric conditions, sedimentation processes and about the development and evolution of life in the early oceans.

Many ophiolites have been found to contain more than one generation of magmas, including the Semail ophiolite in Oman, many Tethyan and Cordilleran ophiolites [26, 67], and several Precambrian examples [16, 25, 68]. Most of these have an early N-MORB magma series formed at an oceanic, or fore-arc spreading center, later intruded by a fore-arc boninitic or IAT tholeiite series. Such relationships are expected for oceanic crust that eventually finds its way to the overriding plate in a juvenile arc system, and such an environment favors obduction and preservation of the ophiolite suite.

4 Historical recognition of Proterozoic ophiolites

Numerous ophiolites have been recognized and generally accepted in Proterozoic terranes for a number of years (Figure 2). The late Proterozoic Arabian-Nubian Shield hosts a number of ophiolite-decorated sutures [69–73], and boasts one of the highest ophiolite densities known for a Proterozoic terrane on the planet. The Arabian-Nubian Shield is part of the East African Orogen that stretches from the Arabian-Nubian Shield in the north, through parts of India, east Africa and Madagascar, and has uncertain links with Neoproterozoic orogens in Antarctica and elsewhere around the globe. The East African Orogen has a complex history including a record of the break-up of Rodinia at circa 900–800 Ma and the evolution of numerous arc systems, oceanic plateaux, oceanic crust, and sedimentary basins, but the relationship between collisional events in the north and the southern blocks including southern Africa, Sri Lanka, India, and South America is disputed [74]. Neoproterozoic closure of the Mozambique Ocean sutured East and West Gondwana along the length of the East African Orogen [75, 76]. An accretionary collage of arc, ophiolitic, and microcontinental terranes formed during closure of the Mozambique Ocean is now preserved in the Arabian-Nubian shield. Some of the arc terranes appear to represent juvenile additions to the continental crust during this time period, whereas others may have been built on older continental basement on the margins of the Mozambique Ocean. Many of the ophiolites in the East African Orogen and Arabian-Nubian shield record different aspects of this complex history. Field mapping, geochronology, geochemistry, and structural analyses of some of these ophiolites has led to significant improvements in understanding heat loss from the Neoproterozoic Earth, continental growth, and preservation of juvenile crustal terranes. Neoproterozoic ophiolites, spanning an age range of ca. 1000 Ma to the end of the Neoproterozoic are also abundant in the Central Asian Orogenic belt [77, 78]. These ophiolites are in a wide accretionary orogen that has not yet experienced cratonization, and are reviewed below.

Paleoproterozoic and Mesoproterozoic ophiolites are less abundant than the Neoproterozoic ophiolites, which are so well preserved in the Arabian-Nubian Shield. A notable exception is the circa 2.0 Ga Paleoproterozoic Usagaran eclogite with a MORB-like mantle source, that forms a 35 km long belt in Tanzania, which Möller et al. [79] interpreted as ophiolitic. A few Mesoproterozoic ophiolitic and oceanic plateau terranes have been described from the Karelian Shield, Cape Smith Belt, West Africa, and the SW USA [80–85]. However, until recently, few Mesoproterozoic ophiolites were known, with a notable exception being the the ophiolites in NE Jiangxi Province from South China, dated at ca. 1040 Ma [86]. Subduction of this NE Jiangxi oceanic crust resulted in formation of ca. 970 Ma adakitic granites [87].

5 Proterozoic ophiolites and related rocks

Until the recent discovery of the 2.5 Ga Dongwanzi ophiolite, and the 3.8 Ga Isua ophiolitic fragments, many students of Precambrian geology regarded the circa 1.96–2.0-Ga Jourma ophiolite of Finland and the 1.99 Ga Purtuniq ophiolite from the Cape Smith Belt as the world's oldest, nearly complete well-preserved ophiolites. The Jourma ophiolite (Figure 2) is a remarkable polyphase ophiolite that preserves evidence for formation at an ocean-continent transition. Peltonen and Kontinen [39] presented a detailed description and review of recent work on the Jourma ophiolite by the Finnish Geological Survey and other teams. They concluded that the Jormua Ophiolite is an allochtonous mafic-ultramafic rock complex, thrust onto the Karelian Craton margin that formed within a passive margin environment ~100 km southwest of its present position. This complex consists of two distinct units: (1) fragments of ancient subcontinental lithospheric mantle that became exposed in the Archean craton by detachment faulting following the final break-up of the craton, and (2) alkaline and tholeiitic igneous suites that were emplaced within and through the lithospheric mantle at ~2080 and 1950 Ma, respectively. The mantle peridotites had yielded melt already before they were intruded by the oldest suite of dikes at >2800 Ma. These old dikes are "dry" clinopyroxene cumulates being products of an Archean magmatic episode. Later, during the initial stages of continental break-up at ~2080 Ma, this same piece of mantle became extensively intruded by hydrous alkaline magmas that resulted in formation of high-pressure hornblendite-garnetite cumulates deep in the ophiolite sequence and fine grained OIB-type dikes at shallower levels. Simultaneously, the residual peridotites became metasomatized due to porous flow of the melt in the peridotite matrix. Alkaline magmatism was soon followed by lithospheric detachment faulting that exposed the subcrustal peridotites at the seafloor where they became covered by tholeiitic (E-MORB) pillow and massive lavas and intruded by coeval

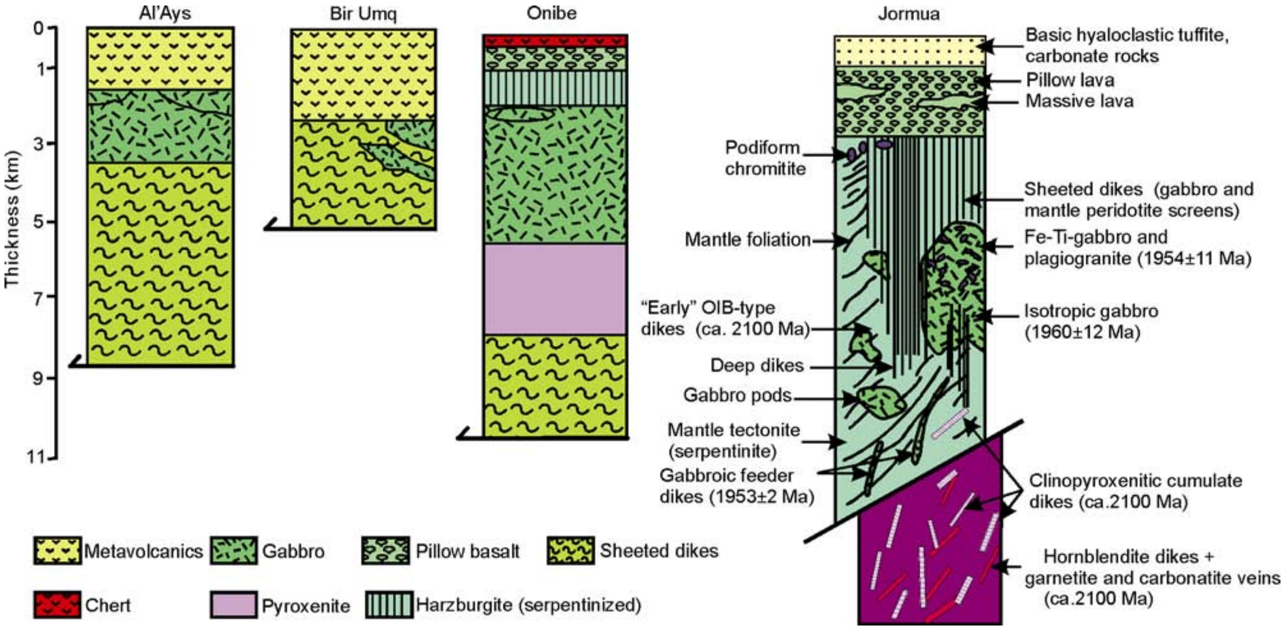

Figure 2 Simplied tectono-magmato sections of some of the Proterozoic ophiolites discussed in text.

dikes and gabbros. Because transitional contacts between all main ophiolite units can be demonstrated, the Jormua Ophiolite Complex is interpreted to represent a practically unbroken sample of seafloor from an ancient ocean-continent transition (OCT) zone, strikingly similar to that reported from the Cretaceous West Iberia non-volcanic continental margin [88].

Dann [82] described the well-exposed, yet unusual 1.73 Ga Payson ophiolite in Arizona, as a shallow-dipping, layered sequence of coeval gabbro, sheeted dikes, and submarine volcanic rocks, partly disjointed by later intrusion and deformation. A sheeted dike complex is spectacularly exposed on cliffs and in stream sections in shallow canyons. The dike complex is rooted in underlying gabbro as shown by gabbro-dike mingling and mutual intrusion. An unusual continuous zone of intense alteration marks the transition from sheeted dikes to submarine volcanics. The Payson ophiolite has many arc-like characteristics. A tonalite/dacite magmatic suite occurs as rare lavas and as dikes and hypabyssal plutons mutually intrusive with the basaltic sheeted dikes and gabbro. An older basement complex occurs as roof pendants in gabbro and screens in the sheeted dike complex. Dann [82] suggested a model for the Payson ophiolite in which an intra-arc basin formed by seafloor spreading along an arc-parallel strike-slip fault system and relates its emplacement within the arc and accretion to North America to events associated with the ca. 1.70-Ga Yavapai Orogeny.

Proterzoic ophiolites were first widely recognized in the Arabian-Nubian Shield [69, 70]. Stern et al. [72], Johnson et al. [89], and Dilek and Ahmed [71] reviewed the Neoproterozoic ophiolites of the Arabian-Nubian Shield. These range in age from 690 to 890 Ma and in the northern part of the shield occur as nappe complexes marking suture zones between terranes. Although dismembered and altered, all of the diagnostic components of ophiolites can be found scattered among the different belts (Figure 2), including harzburgite, cumulate ultramafics, layered and higher level gabbro and plagiogranite, sheeted dikes, and pillow basalts. Allochthonous mafic-ultramafic complexes in the southern part of the shield in Ethiopia and Eritrea [72] are interpreted as ophiolites but are more deformed and metamorphosed than those in the north. Reconstructed ophiolitic successions have crustal thicknesses of 2.5 to 5 km.

The Arabian-Nubian shield ophiolitic mantle was mostly harzburgitic and exhibits chemical compositions comparable to modern forearcs, distinctly different from mid-ocean ridges and backarc basin peridotites [72]. In addition, Zimmer et al. [90] reported a circa 750-Ma N-MORB type ophiolite from the Gabal Gerf complex in the southern Nubian Shield, and suggested that this ophiolite formed in a major ocean basin, and was tectonically stacked with island arc and back-arc basin rocks during obduction at 600–700 Ma ago. Basta et al. [91] describe a C (contaminated) MORB from the late Proterozoic Wadi Ghadir ophiolite in the Eastern Desert of Egypt, and suggest the contamination is from slightly older arc-oceanic crustal rocks. Some of the Arabian-Nubian shield ophiolites are associated with a thick (1–3 km) sequence of cumulate ultramafic rocks which define a transition zone between the seismic and petrologic Mohos. These cumulates are dominated by dunite, with subordinate pyroxene-rich lithologies. Cumulate ultramafics grade upwards into layered gabbro. Both tholeiitic and calc-alkaline affinities are present, and a significant, although subordinate, amount of boninites have been identified in Eritrea and Ethiopia [72]. The Arabian-Nubian shield ophiolitic lavas include both LREE-depleted and LREE-enriched varieties, but as a group are slightly LREE-enriched. On a variety of discrimination diagrams, the lavas plot in fields for MORB, BABB, arc tholeiite, and boninite [72]. Nd -isotopic compositions indicate derivation from a long-depleted mantle source. Mineral and lava compositions are consistent with the hypothesis that most Arabian-Nubian shield ophiolites formed in 'suprasubduction zone' (SSZ) settings, and the high $Cr^{\#}$ of Arabian-Nubian shield ophiolitic harzburgites suggests a forearc environment. Stern et al. [72] concluded that studies of deep-water sediments deposited on Arabian-Nubian shield ophiolites are needed to better characterize and understand the Neoproterozoic oceanic crust.

Johnson et al. [89] described field relationships from a number of the Arabian Shield ophiolites. Where most complete, they consist of serpentinized peridotite, gabbro, dike complexes, basalt, and pelagic rocks. However, because of folding and shearing, the majority of the ophiolites lack one or more of these diagnostic lithologies. Nonetheless, the incomplete assemblages are identified as ophiolites because they minimally include peridotite and gabbro, in many cases associated with basalt, and in all cases show evidence of emplacement by thrusting and shearing rather than intrusion. The ophiolites range in age from ~870 to ~695 Ma, documenting a 200 Ma period of oceanic magmatism in the Arabian shield and are caught up in ~780-to~680-Ma suture zones that reflect a 100-million year period of terrane convergence. All of the ophiolites are strongly deformed, metamorphosed, and altered by silicification and carbonatization. Low-grade greenschist-facies metamorphism predominates, but in places the rocks reach upper amphibolite grade. Alteration resulted in the development of listwaenite, particularly in shear zones, and locally the only evidence that mafic-ultramafic rocks underlie a given area is the presence of upstanding ridges of listwaenite that are resistant to erosion. Kinematic indicators in shear zones indicate that the ophiolites were affected by both strike-slip and vertical displacements. Variations in senses of shear observed along- and across-strike demonstrate considerable strain partitioning during deformation. However, prevailing senses of shear can be discerned for several of the ophiolites that, in conjunction with other structural observations, indicate the main shear trajectories of the shear zones containing the ophiolites. Jabal Ess, Jabal Tharwah, and Bi'r Umq ophiolites (Figure 2) were emplaced during periods of dextral transpression on the Yanbu and Bi'r Umq sutures, respectively [89]. The Bi'r Tuluhah ophiolite was emplaced during sinistral transpression of the Hulayfah-Ad Dafinah-Ruwah suture, and the Halaban ophiolite was emplaced during west-directed convergence on the Halaban suture.

Hussein et al. [92] described aspects of the 808 ± 14-Ma Wadi Onib mafic-ultramafic complex, located within the Onib-Sol Hamed suture in the northern Red Sea Hills of the Sudan, and relate these features to suprasubduction zone processes. The Wadi Onib ophiolite (Figure 2) consists, from bottom to top, of a basal peridotite unit, an exceptionally thick (2–3 km) transitional zone of interlayered cumulates, isotropic gabbroic with plagiogranite bodies, a sheeted basic dike complex, and pillowed basaltic lavas containing fragmentary lenses of ribbon chert and/or graphitic to shaly carbonates. Whereas the basal unit is strongly serpentinized and/or carbonatized, the transitional zone comprises abundant and well preserved pyroxenites. The transition zone also shows a polycyclic cumulate arrangement that possibly originated from multiple magma pulses rather than from tectonic interslicing. Moreover, mineral grading, gravity stratification and a spectrum of folds with varying geometrical dispositions and amplitudes within discrete layers as well as a vertical metamorphic zonation (suggesting seafloor hydrothermal processes) are evident within the Onib ophiolitic sequence. In particular, the volcanic component is Ti-rich, has a transitional IAT/MORB character and is indistinguishable from anomalous MORB and/or marginal basin basalts. Thus, the Onib is envisaged to be of arc/back-arc (marginal) basin affiliation, and it classifies as a supra-subduction zone (SSZ) rather than normal MORB-type ophiolite. The ophiolitic sequence probably resulted from parental magma(s) generated through multi-stage partial fusion of mantle peridotite.

Although not in a shield area, the Central Asian Orogenic Belt (CAOB) and polar Urals contain many fragments of Neoproterozoic ophiolites [93]. Khain et al. [94] described a number of ophiolite complexes from the eastern Sayan Range of southern Siberia, the polar Urals, and the Dariv and Khantaishir Ranges of western Mongolia. The circa 1000-Ma Dunzhugur and Nyurudukan complexes are the oldest known ophiolites in the CAOB, followed by the Shishkid in northern Mongolia (800 Ma) [95], then the Bayankhongor ophiolite (655 Ma) [96], which is the largest ophiolite in Central Asia. The Dunzhugur ophiolite is strongly deformed and dismembered, including tectonic slices of dunite-harzburgite and serpentinite mélange with blocks of dunite, harzburgite, wherlite, pyroxenite, gabbro and dolostone. Diabase dikes (locally with high-Mg chemistry) associated with metabasalt, including pillow lavas and breccia are locally preserved, in places overlain by andesite, and the entire sequence is thrust over a late Neoproterozoic to early Cambrian terrigeneous schist unit and is overlain by carbonate-shale turbidites [94]. The circa 800-Ma [95] Shishkid ophiolite is a 13-km-thick assemblage grading up from a 6-km-thick mantle tectonite section into 4.5 km of layered and isotropic grabbro, a thin (up to 0.5 km) sheeted dike complex, then into a 2-km-thick bimodal assemblage of basalt and rhyolite, along with andesite and pyroclastic rocks. The ophiolitic assemblage is overlain by a 3-km-thick sedimentary sequence that records subsidence of the volcanic edifice after volcanism ceased, then unconformably overlain by Ediacaran-Cambrian platform sediments. Kuzmichev et al. [95] interpreted the Shishkid ophiolite as a rifted back-arc ophiolite and correlated it with other ophiolites that extend along strike for approximately 600 km. The circa 655-Ma Byankhongor ophiolitic mélange forms a belt about 30 km long and 20 km wide in Central Mongolia and represents the largest and best-preserved ophiolite in the CAOB and is associated with a 2 km-thick accrectionary mélange named the Delb Khairkhan mélange [96]. Rocks of the Byankhongor ophiolite occur mainly as blocks in mélange and include all of the main ophiolitic components including ultramafic rocks, mafic and ultramafic cumulates, and gabbros, pillow basalt and chert. The ultramafic rocks include harzburgite, dunite, wherlite, clinopyroxenite, and orthopyroxenite. Gabbros include foliated and isotropic varieties and are locally associated with anorthosite and plagiogranites. A dike complex is present, but is significantly younger than the other ophiolitic components [96]. Jian et al. [96] suggested that the Byankhongor ophiolite formed in a large ocean basin, then experienced intraoceanic rifting, subduction/arc formation, then arc/microcontinent collision before final oceanic terrane accretion some 92 Ma after the initial formation of the ophiolite. The youngest Neoproterozoic ophiolite in the CAOB is the Khantaishir ophiolite [97, 98] in western Mongolia, where Khain et al. [94] dated a trondhjemite intrusion as 568 ± 86 Ma. The ophiolite includes a layered series of dunite, wherlite, clinopyroxinite and websterite, and gabbronorite, plus another series of dunite, pyroxenite, gabbronorite with plagiogranite veins and pillow lavas and dolerite sills, cut by dolerite dikes and sills. Khain et al. [94] interpreted this ophiolite to have formed in a forearc suprasubduction zone setting.

Pfäender and Kröner [99] presented field, geochronologic, and geochemical data on the tectono-magmatic evolution, age and emplacement of the 570 Ma old Agardagh Tes-Chem ophiolite in Tuva, Central Asia. This ophiolite is located in the Palaeozoic Central Asian Orogenic Belt which formed during subduction-accretion processes lasting from the late Mesoproterozoic to the late Palaeozoic [77, 78, 94, 100–103]. The ophiolite was obducted onto the Tuva-Mongolian Massif (microcontinent?) in the early Palaeozoic towards the SE along N- and NW-dipping faults and is embedded within a tectonic mélange and thus is part of an accretionary wedge. Dating of three small zircon fractions from a plagiogranite by the evaporation technique yielded a ^{207}Pb/^{206}Pb age of 569.6 ± 1.7 Ma [99], which reflects the crystallization age of the plutonic section of the ophiolite. Geochemical data reveal an island arc-related origin for the ophiolite, where typical island arc volcanic rocks predominate over MORB-like pillow lavas. In contrast to the highly incompatible element-enriched volcanic rocks, all plutonic rocks of the ophiolite are depleted, and mineral compositions of ultramafic cumulates indicate the presence of boninitic parental melts. The ophiolite, therefore, consists of an association of island arc and back-arc related sequences that have been amalgamated during subduction-accretion and collisional obduction. Isotopic and trace element data reveal the existence of a depleted and refractory mantle source beneath Central Asia from which the volcanic and plutonic rocks of the ophiolite were formed. However, source contamination occurred by sediment subduction before the parental melts of the island arc volcanic rocks were formed.

6 Historical recognition of Archean ophiolites

Very few complete (with a notable exception being the Dongwanzi ophiolite in China) Phanerozoic-like ophiolite sequences have been recognized in Archean greenstone belts, leading some workers to the conclusion that no Archean ophiolites or oceanic crustal fragments are preserved [38]. However, as emphasized by Sylvester et al. [14], the original definition of ophiolite [3] includes “dismembered”, “partial”, and “metamorphosed” varieties, and there is no justification for new arbitrary definitions that attempt to exclude portions of Archean greenstone belts that contain three or more parts of the full ophiolite sequence, especially in structurally complex settings such as found in greenstone belts [17, 104–112]. Similarly, many Neoproterozoic ophiolites are dismembered, or partial sequences [113–115].

Archean oceanic crust was possibly thicker than Proterozoic and Phanerozoic counterparts, resulting in accretion predominantly of the upper section (basaltic) of oceanic crust [116–121]. The crustal thickness of Archean oceanic crust may in fact have resembled modern oceanic plateaux [34, 122]. If this were the case, complete Phanerozoic-like MORB-type ophiolite sequences would have been very unlikely to be accreted or obducted during Archean orogenies. In contrast, only the upper, pillow lava-dominated sections would likely be accreted [117, 123, 124].

Portions of several Archean greenstone belts have been interpreted to contain dismembered or partial ophiolites (Figure 3). Accretion of ophiolites has been proposed as a mechanism of continental growth in a number of Archean, Proterozoic, and Phanerozoic orogens [123]. It is worthwhile to investigate these claims to better understand the crustal structure and tectonic setting in which these Archean ophiolites formed. Several suspected Archean ophiolites have been particularly well documented. One of the most disputed is the so-called circa 3.5 Ga Jamestown ophiolite in the Barberton greenstone belt of the Kaapvaal Craton [125]. De Wit et al. [105] described a 3-km-thick tectono-magmatic sequence including a basal peridotite tectonite unit with chemical and textural affinities to Alpine-type peridotites, overlain by an intrusive-extrusive igneous sequence, and capped by a chert-shale sequence. This partial “ophiolite” is pervasively hydrothermally altered and shows chemical evidence for interaction with sea water with high heat and fluid fluxes [126]. SiO_2 and MgO metasomatism and black-smoker like mineralization is common with some possible hydrothermal vents traceable into banded iron formations and subaerial mudpool structures. These features led De Wit et al. [127, 128] to suggest that this possible ophiolite formed in a shallow sea and was locally subaerial, analogous to the Reykjanges ridge of Iceland. In this sense, Archean oceanic lithosphere may have looked very much like younger oceanic plateaux lithosphere. De Wit et al. [129] presented an updated description and interpretation of the Barberton belt and Jamestown ophiolite, incorporating years of additional mapping from his original (1982) controversial work. However, more recent work has shown that the different components of the Jamestown "ophiolite" have different ages, and can not be considered to be part of a single ophiolitic slab [130]. Furnes et al. [131] presented new field data in which they have mapped and recognized seven different fault-bounded complexes of volcanic and intrusive rocks in the Onverwacht suite in the Barberton greenstone belt, spanning a total age range of ~120 Ma. Geochemical fingerprinting suggests that the Onverwacht suite in the Barberton greenstone belt includes thrust slices of island arc, back-arc basin, and ophiolitic tholeiites to transitional basalts in the Kromberg Formation.

Several partial or dismembered sequences interpretd as ophiolites have been described from the Slave Province, although these too have been disputed (e.g., King and Helmstaedt [132]; see review of both sides of the debate by Corcoran et al. [40]). From the Point Lake greenstone belt in the central Slave Province, Kusky [107] described a fault-bounded sequence grading downwards from shales and chemical sediments (umbers) into several kilometers of pillow lavas intruded by dikes and sills, locally into multiple dike/sill complexes, then into isotropic and cumulate-textured layered gabbro. The base of this partial Archean ophiolite is marked by a 1-km-thick shear zone composed predominantly of mafic and ultramafic mylonites with less-deformed domains including dunite, websterite, wherlite, serpentinite, and anorthosite. By using down-plunge projections and section-balancing techniques, Kusky [107] estimated that the shear zone at the base of this ophiolite accommodated a minimum of 69 km of slip. Although this still allows the ophiolite to have formed at or near extended older continental crust that forms the Anton terrane to the west [133], the actual amount of transport was probably much greater. Syn-orogenic conglomerates and sandstones were deposited in several small foredeep basins and are interbedded with mugearitic lavas (extremely rare in ophiolites), and associated dikes, all deposited/intruded in a foreland basin setting.

Kusky [106] suggested that portions of the Cameron and Beaulieu River greenstone belts of the southern Slave Province contain ophiolitic components. The belts are cut by numerous layer-parallel shear zones, but some sections are composed mostly of tholeiitic pillow basalts, others contain approximately equal quantities of pillows and dikes, and a few sections consist of nearly 100% mafic dikes. The bases of these greenstone belts are marked by up to 500-m-thick shear zones (locally containing mélanges), with tectonic blocks of gabbro, mafic volcanics, peridotite, and slivers of the underlying quartzofeldspathic gneiss (with extensive mafic dike complexes) and its autochthonous cover. Original relationships between dikes in the basement complex and dikes in the basal parts of the greenstone belts have not been established, but older-generation mafic dikes do not cut intervening sedimentary sequences nor the shear zone that separates the greenstone belt from the basement. Helmstaedt et al. [134] described a pillow lava sequence that grades down into sheeted dikes and gabbro from the Yellowknife greenstone belt (Figure 3) but interpreted the basal contact of the belt as an unconformity on a banded iron formation, an interpretation questioned by Kusky [135]. The dikes and pillow lavas are geochemically similar to MORB [136]. However, Isachsen et al. [137] and Isachsen and Bowring [138] have shown that the Yellowknife greenstone belt contains several different, and probably unrelated, volcanic and sedimentary sequences, separated by as much as 50 Ma and spanning an age interval of 200 Ma. Corcoran et al. [40] presented a review of the current status of the ophiolitic interpretation of some of the greenstone belts in the Slave Province, synthesizing fifteen years of debate on the interpretation. They concluded that many of the greenstone belts in the Slave Province show some ophiolitic characteristics, but that some seem to be transitional continental margin ophiolites, and others may represent fore-arc or MORB-type ophiolites, while other mafic-ultramafic sequences may have formed entirely in arcs or rifted continental margins.

Harper [104] and Wilks and Harper [139] described rocks of the South Pass area in the Wind River Range, Wyoming, as containing a dismembered metamorphosed Archean ophiolite. This ophiolite contains all of the units of a complete ophiolite except the basal peridotite tectonite, and contacts between all units are shear zones. Cumulate textures in ultramafic rocks and gabbros are present as are small exposures of a sheeted dike complex. Pillow lavas are associated with metapelites and banded iron formation.

It has been argued that the paucity of well-developed sheeted dike complexes in Archean greenstone belts indicates that mafic-ultramafic rock assemblages and associated rock units in them are not ophiolites [38]. However, sheeted dikes are not well-preserved in many Phanerozoic ophiolites, being preserved in only about 10% of recognized ophiolites [19], especially when they are metamorphosed and deformed to the extent that most Archean greenstone belts are. Abbott [140] argued that sheeted dikes are not necessarily formed in every ocean floor sequence. Despite this, sheeted dike complexes have been discovered in several of the ophiolitic greenstone belts described above. Well-developed sheeted dike complexes have also been mapped in several locations in the Kalgoorlie terrane of the Yilgarn Craton [141]. Multiple cooling units of dolerite, high-Mg mafic rocks, and serpentinite are truncated at an angle between

35° and 80° by an unconformably overlying mafic volcanic breccia, pillow breccia, and lenses of pillow lava that strike parallel to bedding in overlying sedimentary rocks in the Kanowna Lake area. Fripp and Jones [141] interpreted this unit as a sheeted dike complex overlain by a volcanic carapace. At the Cowan Lake Six Islands locality, Fripp and Jones [141] described lherzolite and dunite that grade up into websterite and gabbro with pyroxenite layers. These rocks are overlain by high-Mg mafic and picritic basalts that occur in multiple tabular cooling units, interpreted as sheeted dikes that exhibit both one-way and two-way chill margins. These are overlain by chert, silicified mudstone, shale and graywacke turbidites which locally occur as partially assimilated xenoliths (containing zircons) within the intrusive rocks. Fripp and Jones [141] interpreted the Lake Cowan greenstone locality to include the peridotitic lower plutonic sequence that marks the transition zone between mantle and crust in ophiolite suites. This transition zone sequence is overlain by a sheeted dike complex, but the extrusive magmatic carapace is omitted by faulting at this locality. Fripp and Jones [141] noted many similarities between the Kalgoorlie ophiolites and Phanerozoic ophiolites such as the Semail, Troodos, and Bay of Islands massifs.

Kimura et al. [142] interpreted parts of the Larder Lake and Beardmore-Geraldton greenstone belts in the Abitibi and Wabigoon subprovinces of the Superior Province to include ophiolitic fragments accreted in arc environments. The Larder Lake belt occurs in the southern part of the Abitibi greenstone belt and consists of pillow basalts and banded iron formation (BIF) tectonically stacked with terrigeneous turbidites. The pillow basalts and BIF were interpreted to be the upper part of an oceanic plate stratigraphy, offscraped and interdigitated with trench turbidites in an accretionary wedge setting similar to Alaska [143–146] or Japan [147]. Kimura et al. [142] and Williams et al. [148] also suggested a similar exotic origin for basalts and iron formation tectonically interleaved with terrigeneous turbidites in the Beardmore-Geraldton area in the southern part of the Wabigoon subprovince. In both of these examples, the accreted trench turbidites and ophiolitic slivers are intruded and overprinted by arc-related plutons and lavas, formed when the trench stepped back and subduction-related magmas intruded their own accretionary wedge. A similar accretionary wedge setting and oceanic crustal origin for slivers of basalt in greenstone belts of the Pilbara craton has been proposed by Isozaki et al. [149]. Other workers dispute this interpretation of the Pilbara [130], claiming that the thin shear zones are not significant, and that the Pilbara preserves essentially intact stratigraphy. Van Kranendonk et al. [130] recognize older basement to the eastern Pilbara terrane and define four deformation events, but focus on the main folding events and D3 shear zones associated with doming related to intrusion of granitic plutons, but do not attribute significance to thin shear zones related to earlier deformation events [149]. Further work is needed here to understand the complexities of the early deformation, and lessons must be learned from comparative studies of modern accretionary orogens [150, 151], where mm thick shear zones separate tectonically diverse slices of accreted ocean plate stratigraphy. Once these thin shear zones are metamorphosed beyond greenschist-facies they become extremely difficult to recognize, but nonetheless, still form an important part of the early structural history of these belts, and are crucial for correct tectonic interpretations [120].

7 Archean ophiolites and related rocks

A number of well-exposed Archean mafic-ultramafic sequences have been suggested as possible ophiolites. Recognizing ophiolites in the Archean record has been more controversial than calling similar sequences in the Proterozoic record ophiolites with most examples reported resulting in years of controversy before they are generally, if ever, accepted as ophiolites by the international community.

The possibility that some mafic greenstone belts in the Slave Craton of northern Canada and Nunavut may be ophiolites has been a contentious issue with debate spanning much of the late 1980’s, 1990’s, and early 2000’s. Corcoran et al. [40] discuss a controversy that some greenstone belts in the Slave craton may contain dismembered partial ophiolites. They focus on three belts in the Slave Province, including the 1) Yellowknife, 2) Point Lake, and 3) Beaulieu and Cameron River volcanic belts. In all these cases, the mafic-ultramafic sequences that have some ophiolitic characteristics rest structurally over continental crust, reminiscent of the Tethyan-type ophiolites [26, 41]. The six km-thick Chan Formation of the Yellowknife volcanic belt resembles modern ophiolites (Figure 3) with tholeiitic massive to pillowed flows, abundant gabbro dikes and sills, interflow sedimentary rocks, and a mafic sheeted dike swarm. The base of this crustal-floored sequence is sheared and locally stitched by late-tectonic plutons yet the dunite-peridotite-gabbro segment is lacking, so if it is an ophiolite, it only contains the upper parts of the sequence. The inferred base of the Point Lake volcanic belt is composed of mafic mylonite with low-strain domains of gabbro, pyroxenite, dunite, and peridotite. The mafic mylonite is overlain by gabbro, layered gabbro, minor mafic dikes, pillowed flows, massive flows, hyaloclastite, and locally chert. A well-defined sheeted dike swarm is absent although mafic dikes are locally preserved in the crustal sequence, and other dikes cut underlying granite. The Beaulieu and Cameron River volcanic belts are spatially associated with mafic dike swarms that intrude the Sleepy Dragon basement complex. However, the currently juxtaposed dike swarm and mafic volcanic belt are not necessarily directly related, since they are everywhere separated by a major shear zone with significant displacements. Mafic massive and pillowed flows and sub-volcanic sills are predominant above the

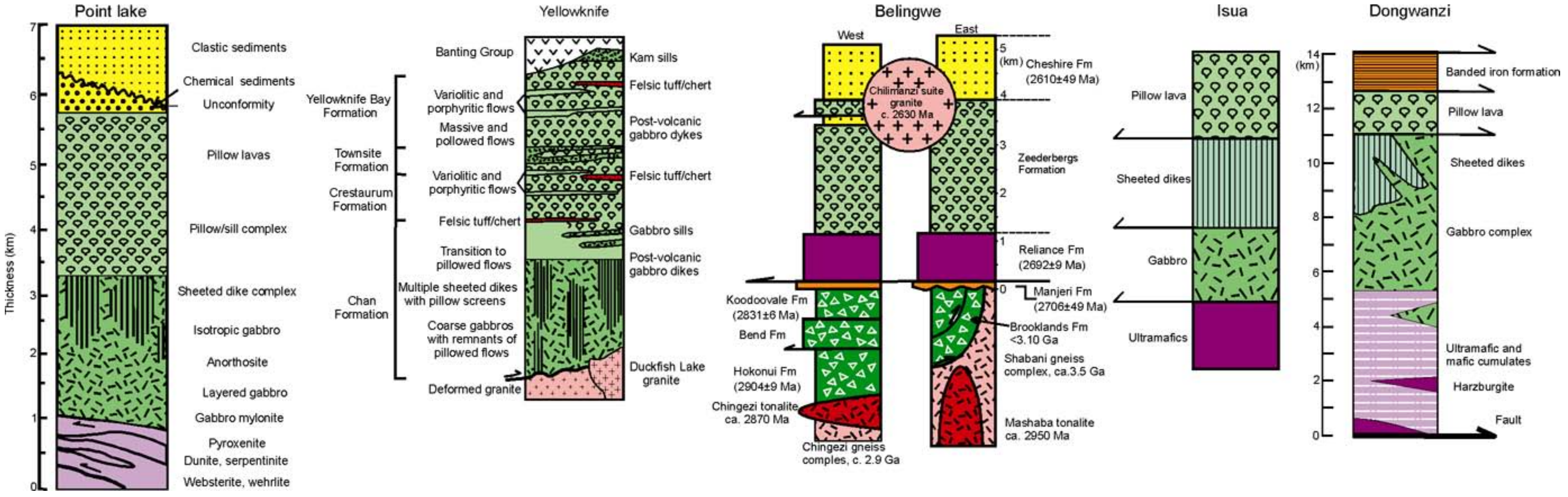

Figure 3 Simplied tectono-magmato sections of some of the Archean ophiolites discussed in text.

sheared basement contact. In the strict sense, these belts or belt segments do not fit the Penrose-definition of a complete ophiolite but do meet the general requirements in that they are allochthonous mafic sequences consisting of submarine volcanics and intrusives. Results of seismic reflection surveys [152] support models [133] of a collision of an ancient gneiss complex in the western Slave Province, with a circa 2.7 Ga juvenile oceanic-arc terrane at 2.65–2.58 Ga.

Ophiolites form in numerous tectonic settings, and complete preservation from tectonized mantle to surficial ocean floor products is highly unlikely, especially for Archean rocks. Therefore, the nature of the basement contacts is particularly significant. If the contacts are tectonic, then parts of the ophiolitic sequences may have been sheared off, which is commonly the case for the mafic-ultramafic intrusive component in younger ophiolites. Recent models have compared parts of certain Slave Province greenstone belts with supra-subduction zone settings including arcs and back-arcs, as well as extensional settings such as mid-ocean ridges [40]. Some of the ophiolitic Slave Province greenstone belts have characteristics that suggest they formed along ocean-continent transition zones, similar to the Jourma ophiolite of Finland and the Cretaceous west Iberian continental margin.

One of the important points that Corcoran et al. [40] developed is that identifying ophiolite sequences based solely on geochemistry is overly simplistic, and regional geological context, structure, and stratigraphy is required. Ophiolites are generally considered a distinct suite of obducted ocean floor rocks with a highly varied geochemical affinity depending on tectonic setting [14, 15]. As pointed out by Moores [7] the "ophiolite conundrum" marks a discrepancy between structural and stratigraphic setting and geochemical characteristics. Moores argues that the mantle is heterogeneous at all scales and geodynamic settings and that a distinct geochemical signature for ophiolites is lacking. If true, this has ramifications especially for the Archean in which volcano-sedimentary sequences are generally incomplete, structures are complex, Fe-tholeiites and komatiites are abundant (rare to non-existent in modern ophiolites), and mantle compositions and temperatures were possibly different. Identifying the tectonic setting of a dismembered mafic (-ultramafic) volcanic sequence thus becomes enigmatic. Must there be a complete stratigraphic sequence (i.e. dunite-peridotite, tectonite, gabbro, sheeted dykes, pillows, pelagic sedimentary rocks) to qualify a specific sequence as an ophiolite? What portion of the succession is necessary in order to be called an ophiolite? Is there a distinction between Phanerozoic and Archean ophiolites?

Kusky et al. [153] and Kusky [17] proposed that a sequence of mafic and ultramafic rocks, named the Dongwanzi ophiolite (Figure 3), in the North China Craton may be one of the world's oldest preserved complete, but dismembered and metamorphosed ophiolites. This suggestion was initially challenged [154] on the basis that the base maps used by Kusky et al. [153] were not the most accurate (the detailed maps were prohibited to be used by foreigners at that time, see Kusky and Li [155, 156], and on the basis of some ambiguous field relationships. After visiting the field sites together, M. G. Zhai and others changed their objections and later wrote papers together discussing the tectonic implications of the Dongwanzi ophiolite [157]. Further documentation led to more (but not universal) acceptance of this idea, though many geologists, especially in China, still debate the issue [158, 159]. Based on new, more detailed mapping, geochemistry, and geochronology, Kusky [17], Kusky and Li [156], and Polat et al. [160, 161] described the general field characteristics of the 2.5 Ga Dongwanzi ophiolite and other mafic/ultramafic potential ophiolites in the Central Orogenic belt that separates the Eastern and Western blocks of the North China Craton [157], and discuss the tectonic setting, age, and petrogenesis of the ophiolites. At Dongwanzi, banded iron formation structurally overlies several tens of meters of variably deformed pillow lavas and mafic flows. These are in structural contact with a 2-km-thick mixed gabbro and dike complex with gabbro screens, exposed discontinuously along-strike for more than 20 km. The dikes consist of metamorphosed dolerite, basalt, hb-cpx-gabbro, and pyroxenite. The dike/gabbro complex is underlain by several kilometers of mixed isotropic and foliated gabbro, which develop compositional layering approximately two kilometers below the dike/gabbro complex, and then over several hundred meters merge into strongly compositionally layered gabbro and olivine-gabbro. The layered gabbro becomes mixed with layered pyroxenite/gabbro marking a transition zone into cumulate ultramafic rocks including serpentinized dunite, pyroxenite and wherlite, and finally into strongly deformed and serpentinized olivine and orthopyroxene-bearing ultramafic rocks interpreted as depleted mantle harzburgite tectonites. A U/Pb zircon age of 2.505 Ga [153] from gabbro of the Dongwanzi ophiolite makes it the world's oldest recognized, laterally-extensive complete ophiolite sequence. The age of the gabbro in the the Dongwanzi-Zunhua complex is the same as the age of the ultramafic rocks as determined by a Lu-Hf isochron age of 2528 ± 130 Ma [161], and a 2.5–2.6 Ga Re-Os age of associated podiform chromites [23], showing that the different components of this possible ophiolite are all the same age (Figure 4). Characteristics of this remarkable ophiolite may provide the best constraints yet on the nature of the Archean oceanic crust and mantle and offer insights to the style of Archean plate tectonics and global heat loss mechanisms.

Huson et al. [162] compared major and trace element concentrations of rocks from the Dongwanzi ophiolite with known concentrations from well-studied ophiolites and rocks from different tectonic settings to determine the tectonic environment of formation. Major element analysis shows that some samples are subalkalic (in particular, calc-alkaline) and others are alkalic, suggesting at least two generations of magmatism in different tectonic settings, possibly separated widely in age. Calc-alkaline geochemical characteristics of oceanic rocks have predominantly been identified in suprasubduction zone settings, and their occurrence in the Donwangzi ophiolite suggests a similar tectonic setting for the older suite of rocks. Trace element signatures are also similar to suprasubduction zone ophiolites, indicating formation above a subduction zone.

The Dongwanzi ophiolite is but one of the largest well-preserved greenstone belts in the Central Orogenic belt that divides the North China Craton into eastern and western blocks. More than 1000 other fragments of gabbro, pillow lava, sheeted dikes, harzburgite, and podiform-chromite bearing dunite occur as tectonic blocks (tens to hundreds of meters long) in a biotite-gneiss and BIF matrix, intruded by tonalite and granodiorite, in the Zunhua structural belt, extending several tens of km SW of the Dongwanzi ophiolite belt. Blocks in this metamorphosed Archean ophiolitic mélange preserve deeper levels of oceanic mantle than the Dongwanzi ophiolite [63]. The ophiolite-related melange marks a suture zone across the North China Craton, traced for more than 1600 km along the Central Orogenic belt. Many of the chromitite bodies are localized in dunite envelopes within harzburgite tectonite and have characteristic nodular and orbicular chromite textures, known elsewhere only from ophiolites [63]. The chromites have variable but high chrome numbers (Cr/Cr + Al = 0.74–0.93) and elevated P [163], also characteristic of suprasubduction zone ophiolites. The high chrome numbers, coupled with TiO_2 <0.2 wt% and V_2O_5 <0.1 wt% indicate high degrees of partial melting from a very depleted mantle source and primitive melt for the chromite.

Li et al. [63] and Huang et al. [64] described a remarkably well-preserved suite of microstructures from the Zunhua podiform chromite, a southern extension of the Dongwanzi ophiolite, and discuss implications for the deformation and rheology of the Archean oceanic lithospheric mantle. The Zunhua podiform chromite preserves typical magmatic fabrics including nodular and orbicular textures and magmatic flow structures. The magmatic textures indicate that the Zunhua podiform chromite was formed through five-stages of evolution with the following time sequence: disseminated chromite, net-like veins, antinodular, orbicular and nodular textures. The evolution of the texture series can be interpreted to result from fast flowing magmatic systems. They resulted from vertical accretion of the oceanic mantle.

The podiform chromite ores show strong deformation with development of pull-apart structures, banding, folds, and mylonitic foliation. These structures were formed at high temperature in the oceanic mantle during the oceanic ridge spreading as the ores were caught up by plastic flow and sheared transversely [64]. The Zunhua podiform chromite bodies resulted from active magmatic accretion and strong high-temperature plastic flow, therefore a fast spreading oceanic ridge is suggested for its formation. Silicate mineral inclusions within the chromium spinel and geochemical characteristics of the Zunhua ophiolite support a geological setting in a suprasubduction belt.

Kusky et al. [164] reported Re-Os data from the Zunhua podiform chromites at the southern end of the Dongwanzi ophiolite including a circa ~2.6 Ga isochron from the chromites, showing that they are the same age as the Dongwanzi ophiolite, within error (Figure 4). The range in initial Os isotopic compositions in the chromites in these ophiolitic blocks is small and well within the range seen in modern ophiolites. The chondritic to sub-chondritic initial ratio also shows more similarity to the values found for abyssal peridotites than OIB's, pointing to an ocean-ridge rather than plume setting for the initial formation of these peridotites. The ultramafic and ophiolitic blocks in the Zunhua melange are therefore interpreted as dismembered and strongly deformed parts of the Dongwanzi ophiolite. Comparison between the Zunhua chromite ores and younger examples reveals a surprising similarity in textures, structures, and mineral compositions. Podiform chromitites are present almost exclusively in ophiolites, being generated in the uppermost oceanic mantle beneath active spreading ridges or intraoceanic suprasubduction zone [165, 166]. The documentation of the Zunhua chromitites provides convincing evidence for the operation of sea-floor spreading and plate tectonics during the late Archean. $^{187}Os/^{188}Os$ ratios of podiform chromitites separated from different ophiolites record Os isotopic compositions of the convecting upper mantle. The $^{187}Os/^{188}Os$ ratios of three massive chromitites having highest Os concentrations (N300 ppb) in the Zunhua ophiolite range from 0.11021 to 0.11030, averaging 0.11026 ± 0.00004, between 0.11034 and 0.10921 at t=2.6 Ga, providing a new data point for understanding the Os isotopic composition of the convecting upper mantle in the Archean (Figure 4). Significantly, the chondritic Os isotope composition deduced from ophiolite podiform chromitites is also the oldest reported, showing that plate tectonic processes created and recycled oceanic crust in Earth's early history [156, 164].

The interpretation of Dongwanzi as an ophiolite was subject to a recent challenge by Zhao et al. [159]; however, this criticism has largely been based on different interpretations of the data and omission of many key points. Zhao et al. [159]. used the reconnaissance maps of Kusky et al. [153] and did not use the more detailed maps from the same paper in 2001, or 2004, that clearly show many young, circa 300 Ma intrusions in the central belt of the Dongwanzi ophiolite. Their maps exclude units mapped as intrusions younger than 1.85 Ga (2001) since they contained inclusions of, and intrude, the Changcheng system, then claimed that Kusky et al. [153] stated the whole central belt was 2.5 Ga in age. All of the samples dated by Zhao et al. [159] as circa 300 Ma from the central belt were from small dikes, plugs, or outcrops with many circa 300-Ma dikes as reported by Kusky et al. [163]. In addition, they claimed that "they are not

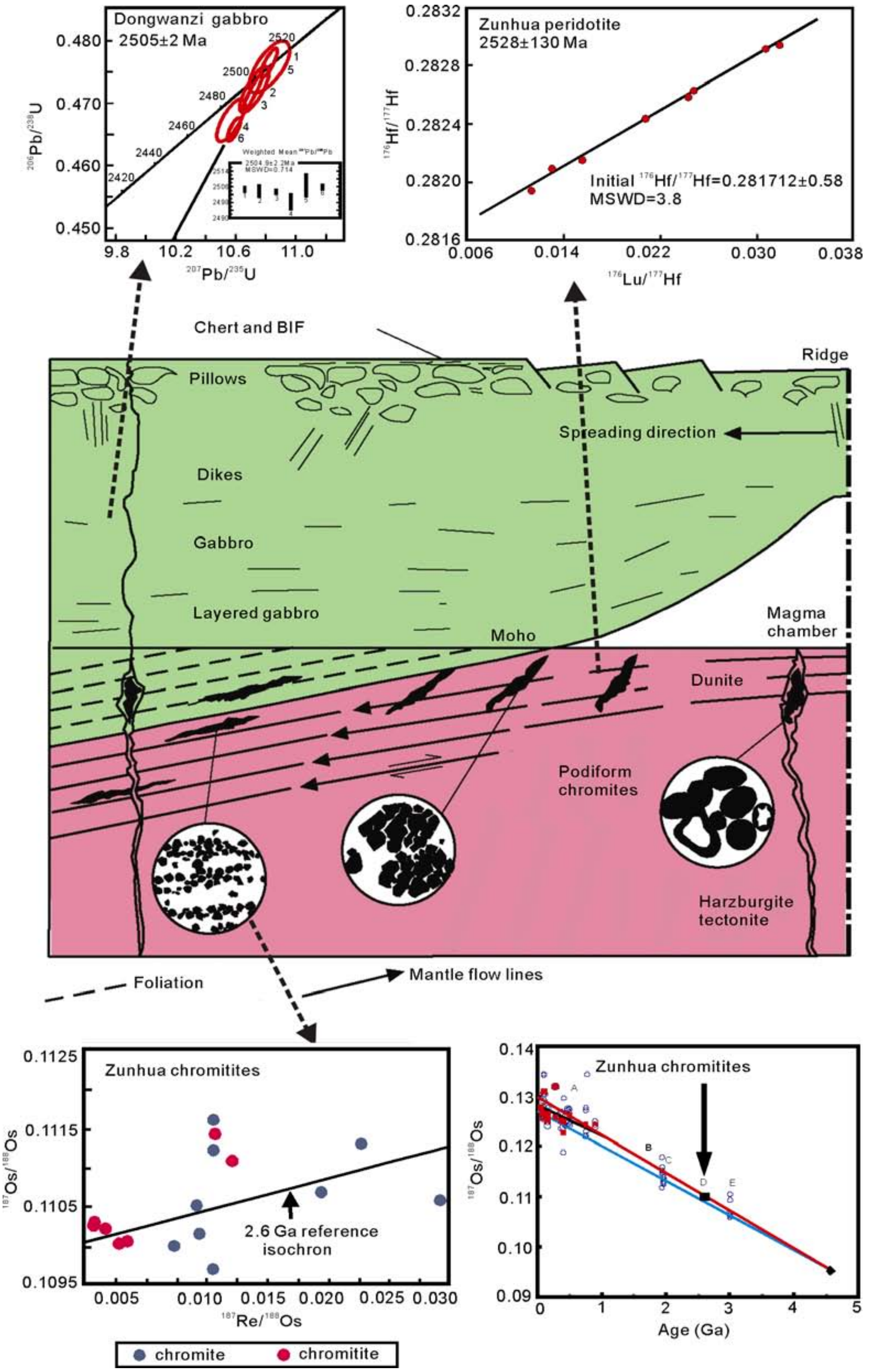

Figure 4 Model for the evolution of the Dongwanzi ophiolite and Zunhua podiform chromites, showing formation of oceanic lithosphere at oceanic ridge, generating pillow lavas, dike complex, gabbro, layered gabbro, dunite, harzburgite tectonite, and podiform chromites. Gabbro from the crustal section of the ophiolite has yielded a 2505 ± 2 Ma U-Pb age (upper left panel, after ref. [153]), and peridotites from the mantle section have yielded a Lu-Hf age of 2528 ± 130 Ma (upper right panel, after ref. [160]). Podiform chromites from the Zunhua peridotite have yielded a poorly-constrained Re-Os isochron of ~2.6 Ga (lower left panel after ref. [164]), and plot on the chondritic evolutionary trajectory for the convecting upper mantle (lower right panel, after ref. [164]). Together, these data show that the crustal and mantle components of the Dongwanzi ophiolite and Zunhua ophiolitic mélange formed at the same time, and are consistent with the Os isotopic composition of the mantle at circa 2.5 Ga.

aware of any geochronology published by Kusky and his colleagues from any or the proposed ophiolites in the Central Orogenic Belt", missing the data (Figure 4) from the ophiolitic rocks dated by Kusky et al. [153], Polat et al. [160, 161], and related arc volcanics and plutonics dated by Kröner et al. [167–169] and Wilde et al. [170–172] and Kusky et al. [157], yielding dozens of ages ranging from 2.55 to 2.50 for these same rocks (although with different tectonic interpretations). In particular, it is important to note that Polat et al. [161] used the Lu-Hf isotopic system to date peridotites in the Zunhua structural belt, and obtained ages of 2528 ± 130 Ma, indistinguishable from the U-Pb ages from the crustal sequence of the ophiolite reported by Kusky et al. [153]. Therefore, the criticisms brought up by Zhao et al. [159] do not change the earlier interpretations of the Dongwanzi ophiolite [156].

Several hundred kilometers to the southwest of the Dongwanzi ophiolite, Li et al. [22] described the textures and mineralogy of a Neoarchean massive sulfide deposit in the Wutai Mountains, recognizing a black smoker chimney and mound complex within 2.50 Ga-old oceanic crust. The Wutai VMS is one of largest sediment-hosted sulfide deposits in China [22]. It forms small lenses, thin sheets, and tabular bodies of massive to layered sulfide, disseminated through a forearc mélange belt. Although they are reworked by late deformation, sulfide deposits formed at different crustal levels still can be identified, including relicts of chimneys, pyritic siliceous exhalite, massive crystallized sulfides, talus of massive sulfides and stockwork zones. The country rock of the Wutai VMS ores show intense silicification and chloritization. Epidosites have been identified within mafic rocks, similar to younger epidosites formed by seafloor metamorphism. Under microscopic observations, porous sulfides show a mineralogical zonation around micro-conduits. The colloform textures developed delicate banding and concentric textures. The vuggy cavities are commonly lined by concentric layers consisting of idiomorphic pyrite and silica. The Wutai VMS are spatially associated with convergent plate boundaries, formed in the upper sequence of a former Neoarchean oceanic basin. They have been overthrust by foreland-thrust belts following closure of an oceanic basin. The presence of sulfide chimneys preserved in the Wutai Mountains suggests that seafloor black smoker activity at about 2.5 Ga played an important role for generation and accumulation of Wutai VMS.

From the Aldan Shield in eastern Siberia, Puchtel [173] described a 3.0-Ga partial ophiolitic sequence from the Olondo greenstone belt. The Olondo greenstone belt is distinguished from the other such belts in the Aldan Shield by the abundance and great facies diversity of mafic-ultramafic rocks. The rocks are relatively well preserved both geologically and geochemically compared to other Archean ophiolite-like sequences worldwide and thus can be regarded as valuable witnesses of the early history of the Earth. The Olondo greenstone belt contains one of the oldest ophiolite-like sequences on the planet. The age of the Olondo greenstone belt at 3.0 Ga is intermediate between the two most commonly cited periods of global crust-forming activity, namely, 2.7 and 3.4 Ga [48, 174]. Thus, the study of this belt can help fill the gap in our understanding of the significance of the tectonothermal and chemical evolution of the Earth between the early and late Archean.

Shchipansky et al. [175] described Neoarchean subduction-related assemblages of the North Karelian greenstone belt in the northeast part of the Baltic Shield, Russia. This belt contains some of the world's oldest known boninite series rocks, which occur in at least two areas of the belt, although Polat et al. [176] and Smithies et al. [177] describe boninite-like rocks extending back in time as far as 3.8 Ga from Greenland and the Pilbara craton, respectively. The first area, referred to as the Khizovaara structure, is interpreted as a late Archean ocean-island volcanic arc collage formed during two tectonic episodes nearly 2.8 Ga ago. The second area, named the Iringora structure, preserves distinctive features of an ophiolite pseudostratigraphy, including not only gabbro and lava units, but also remnants of a sheeted dike complex. The major and trace element chemistry of the Iringora ophiolitic gabbro, dike and lava units suggests a comagmatic series with a continuous compositional variation from primitive mafic to strictly boninitic melts. In terms of major and trace element abundance, the boninite series of the North Karelian greenstone belt is practically indistinguishable from the Groups I and II of the Troodos upper pillow lavas. These occurrences suggest that Neoarchean subduction-related processes including boninite-hosting supra-subduction zone ophiolites have not changed substantially over the past 2.8 Ga [121, 178].

The Belingwe belt in Zimbabwe (Figure 3) is probably the best-known well-preserved late Archaean greenstone belt in the world. Despite the presence of well-exposed rocks of very low metamorphic grade and low strain, the tectonic evolution of the Belingwe belt has been a matter of much controversy with debates focusing on whether the parts of the greenstone succession are oceanic in nature or whether they were erupted through underlying continental crust. Hoffman and Kusky [179] summarized the geology of the Belingwe belt and assessed various tectonic models for the belt's origin. The Belingwe greenstone belt comprises two distinct greenstone successions. The lower, 2.9–2.8 Ga old Mtshingwe Group consists of four stratigraphic units, an intermediate to felsic volcanic and volcaniclastic unit, an ultramafic to mafic lava plain sequence, a conglomerate-shale sedimentary sequence, and a unit of tectonically imbricated sedimentary and volcanic rocks. Although geochronological, geochemical and lithological characteristics are broadly known, the tectonic evolution of the Mtshingwe Group remains a matter of speculation. Controversy surrounds the intensely studied, 2.7 Ga old Ngezi Group which consists of a thin basal sedimentary sequence, a thick ultramafic to mafic volcanic sequence, and an upper sedimentary succession. The basal unit rests unconformably on up to 3.5 Ga old granitoid gneisses and Mtshingwe Group rocks and consists of fluvial to shallow-marine sedimentary rocks, similar to cratonic cover successions. The overlying volcanic unit is in fault contact with the underlying sedimentary sequence [35] and consists of a submarine sequence of massive and pillow basalts with komatiites near the base and andesites near the top. The upper sedimentary unit represents a foreland basin sequence and consists of karstified carbonate ramp limestones overlain by deeper-water turbidite deposits. Autochthonous versus allochthonous models have been proposed for the tectonic evolution of the Ngezi Group. Proponents of the autochthonous model regard the Ngezi Group as a conformable sequence that formed in an ensialic rift setting above a mantle plume [180]. Other workers regard the volcanic sequence as an allochthonous unit of oceanic crust that was obducted onto continental basement [34–36]. A great number of arguments have been proposed in recent years from structural, sedimentological, and geochemical studies for and against the different models. A critical reappraisal of the various arguments indicates the lack of convincing evidence for an ensialic and autochthonous origin. Arguments for an allochthonous origin are strong, and an oceanic origin is inferred by assuming that modernistic plate tectonic processes were operating in the late Archean.

From the 3.8 Ga Isua belt in Greenland, Furnes et al. [68, 181, 182] described a strongly dismembered and metamorphosed possible ophiolitic sequence (Figure 3) that includes strongly deformed pillow lavas, layered amphibolites interpreted by them (and contested by others) as remnants of a sheeted dike complex, gabbros, ultramafic rocks, and two generations of amphibolites interpreted to represent formation initially at an ocean spreading center, then with a second generation of island arc tholeiites and boninites formed in an extensional forearc. Oxygen isotopes are consistent with alteration of the lavas by seafloor metamorphism. This contention was debated [183, 184] as some geologists claim that the proposed sheeted dike complex is misinterpreted and that the work of Furnes et al. [68, 181, 182] grouped together rocks of two different ages, from circa 3.8 and 3.7 Ga. However, the rock types and geochemistry all strongly support an ophiolitic origin for some of these rocks [185], making them likely candidates for preserving a strongly dismembered vestige of Earth's oldest ophiolite. Further work is clearly needed to demonstrate that the different components of this proposed early Archean ophiolite are the same age and petrogenetically related, yet the possibility that this sequence preserves a vestige of Earth's earliest oceanic lithosphere is tantalizing.

Evidence for the creation and obduction of oceanic crust in the Archean is not limited to field relationships as described above. Jacob et al. [186] reported that the geochemistry of diamondiferous eclogites from the Udachnaya Mine, Siberia [187], is consistent with derivation from subducted slabs of Archean oceanic crust that were extensively hydrothermally altered prior to subduction. Similarly, many eclogite samples from South African kimberlites are also interpreted as remnants of subducted Archean oceanic crust [188–190].

In summary, dismembered ophiolites are a component of Archean greenstone belts, and many of these apparently formed as the upper parts of Archean oceanic crust. Most of these appear to have been accreted within forearc and intra arc tectonic settings. The observation that Archean greenstone belts have such an abundance of accreted ophiolitic fragments compared to Phanerozoic orogens suggests that thick, relatively buoyant, young Archean oceanic lithosphere (The crust is generally interpreted as being thick, whereas the lithosphere is more likely to be thin) may have had a rheological structure favoring delamination of the uppermost parts during subduction and collisional events [117, 123].

8 Models for the evolution of oceanic crust with time

Archean greenstone belts are known for their hallmark deposits of komatiites, magnesium-rich lavas that some petrologists have suggested indicate significantly higher temperatures for the Archean mantle, despite the fact that komatiites occur very rarely in Phanerozoic settings such as the Tertiary komatiites on Gorgona Island [191]. These estimated temperatures were, in turn, used by many workers to derive unusual non-uniformitarian and non-actualistic models for tectonics on the early Earth [2]. Parman and Grove [57] show field and petrologic data from the Barberton Greenstone belt, South Africa, that suggest an alternative interpretation, that the Archean mantle may not have been so different from that of today. Their work is, therefore, very signficant in that it removes any reason for assuming that plate tectonics should have been drastically different from today. The Barberton Greenstone Belt is one of several early- to mid-Archean greenstone belts that lie along the eastern margin of the Kaapvaal Craton [125]. With an age of 3.52–3.46 Ga [130, 192], the BGB is among the oldest (together with the Nondweni) of the Kaapvaal Craton's greenstone belts and is part of the nucleus around which the late Archean greenstone belts to the north (e.g., Murchison and Giyani) and to the south (e.g., Commondale) were attached. Parman and Grove [57] placed the Barberton data in the context of the global komatiite data set, showing that komatiites do not require exceptionally high mantle temperatures to form a contentious view recently supported by Kamenetsky et al. [191].

Polat and Kerrich [193] synthesized data on known occurrences of boninites, adakites, magnesian andesites, and Nb-enriched basalts, and related these to Precambrian arc associations. Boninitic lavas have recently been reported from several Precambrian terranes, including the ~3.8-Ga Isua terrane of West Greenland; 2.8-Ga Opatica and the 2.7-Ga Abitibi terranes of the Superior Province; the 2.8-Ga North Karelian terrane of the Baltic Shield; the 1.9-Ga Flin Flon terrane in the Trans-Hudson orogen, the 2.5-Ga greenstones in Wutaishan in the North China Craton [160, 177], and also in the Pilbara [194]. In the Isua belt, boninitic flows coexist with pillow basalts and picrites. Boninitic lavas, and low-Ti tholeiitic basalts, crop-out over a 300-km-wide corridor in the Abitibi volcanic-plutonic subprovince. They are intercalated with a stratigraphically lower association of komatiites and basalts interpreted as an oceanic plateau, and an upper volcanic arc association of tholeiitic to calc-alkaline arc basalts; accordingly there was contemporaneous eruption of neighboring plume and arc magmas. The 2.8-Ga Opatica boninitic lavas are spatially and temporarily associated with arc-type volcanic rocks. The 2.8-Ga Baltic Shield boninitic rocks are related to a supra-subduction ophiolite complex. All of these Precambrian boninitic lavas share the low-TiO_2, high Al_2O_3/TiO_2 ratios, U-shaped REE patterns, and negative Nb but positive Zr anomalies of Phanerozoic counterparts; however, SiO_2 contents are variable.

Boninites of Phanerozoic age occur in ophiolites or intra-oceanic island arcs, such as the Izu-Bonin-Mariana arc system [26]. These primary liquids are interpreted as second-stage hydrous, low-pressure melts of a depleted refractory mantle wedge fertilized by fluids and/or melts, above a subduction zone. Precambrian boninitic lavas are likely products of the same conjunction of processes. Low-Ti tholeiites lack the LREE enrichment coupled with negative Nb anomalies of the boninites. They had a similar depleted wedge source, but without the addition of a subduction zone component.

An association of adakites, magnesian andesites (MA), and Nb-enriched basalts (NEB) with ‘normal’ tholeiitic to calc-alkaline basalts and andesites has recently been described from the 2.7 Ga Wawa and Confederation volcanic-plutonic terranes of the Superior Province [193]. Cenozoic adakites are considered to have formed by slab melting, whereas MA are interpreted as the products of hybridization of adakite liquids with the peridotitic mantle wedge; and NEB are thought to represent melting of the residue of the MA wedge source. This volcanic association is found in Cenozoic arcs characterized by shallow subduction of young, hot oceanic lithosphere. Archean equivalents likely formed under comparable tectonic settings.

U-shaped REE patterns in conjunction with positive Zr anomalies of Archean and Phanerozoic boninites can be modeled by a depleted peridotitic wedge fertilized by adakite liquids and/or hydrous fluids in a convergent margin. Consequently, Phanerozoic-type arcs were likely to have operated in Archean convergent margins. Imbrication of komatiite-basalt ocean plateau volcanic sequences with arcs solves the apparent $Mg^{\#}$, Ni deficit of some models for Archean upper continental crust. Higher geothermal gradients in Archean subduction zones may have played an important role for the growth of continental crust.

De Wit [129] synthesized data from Archean greenstone belts around the world and concluded that “Archean greenstone belts do contain fragments of ophiolites”. Although many other scientists dispute this view, De Wit et al. [129, 130, 195] noted that most Archean greenstone belts are so severely tectonised that reconstruction of their rock assemblages and original autochthonous relationships is a daunting task [13, 120]. There are about 260 individual Archean greenstone belts worldwide. Few of these have been studied in sufficient detail to provide relatively reliable information about pre-2.5 Ga geological processes [13]. Greenstone belts represent some of the earliest records of Earth history but they are not restricted to the Archean. For example, the large Neoproterozoic Arabian-Nubian shield has an Archean-like cratonic crust with at least 7 major belts that include ophiolitic fragments, most of which comprise island arc-like successions and associated (but often dismembered) ophiolite-assemblages [72, 89, 92, 196]. Similarly, the Baltic shield contains greenstone belt sequences ranging in age from >3.1 Ga (Mesoarchean) to 1.9 Ga (Paleoproterozoic). Some of the Paleoproterozoic greenstone belts share characteristics of many Archean greenstone belts (e.g. abundant komatiites), whereas others share characteristics of Phanerozoic ophiolites [197].

A wide spectrum of tectonic environments is preserved within Archean greenstone belts, and many individual belts are mixtures of components from different tectonic environments and in particular from island arc terranes [13, 120]. It is claimed nevertheless by some geologists that oceanic crust-forming environments are not preserved among this mixture of tectonic regimes because in their views no rock assemblages in Archean greenstone belt sequences exhibit sufficient features to warrant definitive classification as an ophiolite [37, 38, 198, 184]. De Wit [129] outlined some probable and some possible ophiolite sequences that have been reported from a number of Archean greenstone belts around the world. He also commented on the likely tectonic implications of these examples to better resolve Archean processes.

9 Modern analogues to Precambrian ophiolites

The northern Philippines is a possible modern analogue for some Precambrian greenstone belts [199]. It has a ~150 Ma history of multiple and overlapping periods of oceanic crust generation, arc volcanism, sedimentation, and deformation dominated by wrench tectonics. At least five ophiolite complexes of distinct age make up most of the basement—all having a distinct suprasubduction zone signature, relationships reminiscent of the Yellowknife Belt in the Slave Province. Arc plutons are predominantly of the dioritetonalite series with minor alkali feldspar-bearing rocks. Sedimentary basins probably floored by oceanic crust are dominated by immature sediments and volcaniclastic rocks and are locally up to ~10 km thick. The entire arc and ophiolitic complex is in the process of being accreted to Eurasia where it may be preserved in a broad "suture zone" between Eurasia and Australia and/or the Americas.

Southern Alaska's Mesozoic-Cenozoic Chugach-Prince William terrane is an unusual forearc in that it contains belts of graywacke-dominated flysch, melange, and ophiolitic fragments, all intruded by a suite of tonalite-trondhjemite-granodiorite plutons, and large parts of the accretionary prism are metamorphosed to greenschist-, amphibolite-, or granulite-facies. Kusky et al. [200] described the overall structural geometry, abundance and types of rocks and rock suites present, the petrogenetic relationships between rock suites, and the metamorphic style that are all strongly reminiscent of Archean granite-greenstone terranes. As such, the southern Alaska forearc represents one of the world's best modern analogues to early stages in the evolution of Archean granite-greenstone terranes. Belts of flysch, mélange and accreted ophiolites, including the 57 ± 1-Ma Resurrection Peninsula ophiolite, are a remarkable analogue to some Archean greenstone belts. The Resurrection ophiolite formed in a near-trench environment as the Kula-Farallon ridge was being subducted beneath North America. The magmatic sequence includes pillow lavas, sheeted dikes (see cover photo), gabbros, trondhjemites, and a poorly-exposed ultramafic section. The lavas show mid-ocean ridge basalt and arc-like geochemical signatures, interpreted to reflect compositionally diverse melts derived from near-fractional melting of a variably depleted mantle source, mixed with variable amounts of assimilated continentally-derived flysch. A sedimentary sequence overlying the ophiolite preserves a continuous record of turbidite sedimentation deposited on the ophiolite as it was transported to North America and emplaced in the Chugach accretionary prism. The top of the sedimentary section is truncated by the Fox Island shear zone, a 1-km-thick, greenschist-facies, west-over-east thrust related to the emplacement of the ophiolite into the accretionary wedge. The Fox Island shear zone is intruded by a 53.4 ± 0.9-Ma granite [201], showing that the ophiolite formed, was transported to the North American continent, overthrust by a major accretionary prism-related thrust, and intruded by granite, all within 3.6 ± 1.4 Ma.

Geological relationships in the southern Alaskan forearc are instructive in that if similar relationships were found in an Archean granite-greenstone terrane they would probably currently be interpreted to reflect calc-alkaline mafic-felsic volcanic-plutonic complexes intruded and erupted through a complex metasedimentary sequence in an arc setting. Many Precambrian forearc ophiolites and accretionary prisms may have gone unrecognized because the processes of forearc ophiolite emplacement and intrusion by near-trench magmas at triple junctions have been poorly documented [17, 202, 203].

10 Komatiites, boninites, BIF's, and podiform chromites

It has long been held that komatiites are abundant in Archean greenstone belts and that the Archean oceanic crust may have been dominantly komatiitic, reflecting early higher mantle temperatures. However, komatiites are much less common than many workers orginally thought, and they do not necessarily mean much hotter mantle [57]. There has been a disproportionate number of studies of komatiites from Archean greenstone belts compared to other rock types, because petrologists have focused on the unusual aspects of these rocks, but they typically do not form more than a few percent of any greenstone terrain. However, they do appear to be more abundant in Archean terrains than in younger ophiolites [204].

Boninites are geochemically distinct mafic rocks that have been suggested to be absent from Archean terrains. As reported in several recent papers [72, 121, 193, 205], boninites have now been identified in several ophiolitic Proterozoic and Archean greenstone belts extending back in time to the 3.8-Ga Isua belt, suggesting that these ophiolites formed in environments similar to their modern counterparts. Boninites of Phanerozoic age occur in ophiolites or intra-oceanic island arcs such as the Izu-Bonin-Mariana arc system. These primary liquids are interpreted as second-stage, hydrous, low-pressure melts of a depleted refractory mantle wedge fertilized by fluids and/or melts, above a subduction zone. Precambrian boninitic lavas are likely products of the same conjunction of processes, suggesting that mantle melting processes above subducting slabs were broadly similar in the Archean to those of today [121].

Podiform chromites form very distinctive deposits in many Phanerozoic ophiolites and have been found in a few places on the modern ocean crust. Podiform chromites form small clusters of typically orbicular and nodular textured chromite in dunite pods, enclosed within mantle harzburgite tectonite. These chromite pods are distinctive, both physically and chemically, from layered chromite of layered ultramafic intrusive complexes in continents (such as the Bushveld) and arcs [165, 166, 206–209]. Until recently, podiform chromites were not known from any Archean greenstone belts, but their documentation in the Zunhua ophiolitic melange and Dongwanzi ophiolite of North China [17, 63, 64, 164] shows not only that these rocks are ophiolitic but that mantle melting processes in the Archean were similar to those of younger times. We suggest that since podiform chromites are only known from ophiolites, they are as distinctive for recognizing a rock sequence as an ophiolite or ophiolitic fragment as the presence of the entire Penrose sequence.

Banded Iron Formations (BIF's) are a major component of many Archean greenstone terranes and are described from numerous possible Archean ophiolites. Whereas the origin of BIF's has been controversial, and there are several different origins (e.g., Fowler et al. [210], Coward and Ries [211], Simonson [212]). Kusky and Winsky [35] and Hoffman and Kusky [213] have shown how some BIF's in low-grade greenstone terranes may mark sites of regional structural detachment with iron and sulfide mineralization focused along early shear zones. Workers in other greenstone terranes, particularly those that are more strongly deformed and metamorphosed, should note the relationships at Belingwe and re-assess whether or not BIF's in other greenstones and Precambrian ophiolite terranes may mark the sites of major regional detachment and displacement.

Several authors have noted that some Precambrian greenstone belts show evidence of contamination by continental-type material and have then suggested that this means that they cannot be fragments of oceanic crust and lithosphere [37, 38]. These authors failed to note that greenstone belts preserve rocks formed in a large diversity of tectonic environments, both continental and oceanic, and that many modern and Phanerozoic ophiolites (e.g., Josephine ophiolite in California) also show such contamination [7], questioning those arguments. Nonetheless, apparent contamination by continental crustal material presents interesting constraints on the origin of these ophiolites. For instance, apparent crustal contamination can mean lavas were derived from unusual mantle, such as an older forearc environment, where subduction-related processes may have depleted the mantle leading to unusual, apparently contaminated geochemical signatures [57]. Alternatively, some ophiolites may be truly contaminated, having formed near a stretched continental margin. Some ophiolites seem to preserve magmatism near these margins, and some even have subcontinental lithospheric mantle and/or crust preserved. Kusky [17] coined a new term for these ophiolites, transitional ophiolites.

11 Transitional ophiolites

Several of the ophiolites described in this paper appear to have formed within the transition from rifted continental margins to ocean spreading centers during early stages of ocean opening, then were structurally detached and/or deformed and incorporated into convergent margins during ocean closure. These ophiolites are distinctive from classical Penrose-style ophiolites and others formed in forearc and back arc environments. During early stages of ocean formation, continental crust and lherzolite of the subcontinental mantle are extended, forming graben on the surface and ductile mylonites at depth. Sedimentary basins may form in the graben, and as the extension continues magmatism sometimes affects the rifted margin, either forming volcanic rifted margins or migrating to a spreading center forming an oceanic spreading center. New asthenospheric mantle upwells along the new ridge and may intrude beneath the extended continental crust. In some cases, wedges of extended mid- to lower continental crust overlying mylonitic lherzolitic sub-continental mantle become intruded by numerous dikes and magmas from this new asthenospheric mantle. In this case, magmas may pool both above and below the stretched continental crust, forming mafic/ultramafic cumulates in igneous contact with older continental crust (see Figure 1). Dikes from these magma chambers may then feed a crustal gabbroic magma chamber closer to the surface which, in turn, may feed a dike complex and basaltic pillow/massive lava section. If preserved, this unusual sequence forms what we term a “transitional ophiolite”, grading down from subaquatic sediments, to pillow lavas, dikes, sheeted dikes, layered gabbro, dunite and pyroxenite cumulates, then into stretched, typically mylonitic granitic mylonites, underlain by lherzolite. The lherzolite tectonite may be underlain by harzburgite tectonite or harzburgite. Recognition of this relationship represents a major advance in understanding some of the ophiolitic complexes described above.

Examples of this type of transitional ophiolite are found in the Proterozoic Jourma complex, and in some of the Slave Province ophiolites [39, 40]. Modern analogues for such transitional ophiolites are found around the Red Sea, including at Tihama Asir, Saudi Arabia, where a 5–10-Ma transitional ophiolite has a dike complex overlying layered gabbro which, in turn, overlies continental crust [26]. Also, on Egypt’s Zabargad Island, oceanic mantle is exposed [43], and it is likely that the crustal structure near this region preserves transitional ophiolites as well.

The main lesson here is that ophiolites may form in many tectonic settings from extended continental crust, to mid ocean ridges, to forearcs, arcs, back arcs, to triple junctions along convergent margins.

12 A modern concept of ophiolite as applied to Precambrian terranes

The many works summarized in this review have presented clear, even unequivocal, evidence that Precambrian ophiolites are preserved in many Precambrian terranes. Proterozoic examples are abundant, especially in the Arabian Nubian Shield and in central Asia, where ophiolites have been recognized for many years. Archean examples are more controversial, but a number of excellent examples of complete but dismembered (e.g., Dongwanzi in China), and metamorphosed ophiolites have been described from around the world, extending back in age to the 3.8-Ga Isua assemblage. This concluding section offers a review of what, if anything, we have learned about the early Earth from the identification of specific sequences as ophiolitic. In addition, a new list of criteria to help discriminate between ophiolitic and other sequences is presented which is more comprehensive than the original 1972 Penrose definition of ophiolites.

The recognition that many of the allochthonous mafic/ultramafic complexes in Archean and Proterozoic greenstone belts are ophiolites provides researchers with a much longer record of oceanic processes than the record from Phanerozoic ophiolites alone. From this record we are able to deduce that the classical Penrose model [3] for the structure of ophiolitic lithosphere is too simplistic to explain the great variations found in ophiolites over this greater sample of time. The Penrose model for ophiolite stratigraphy is too restrictive to explain even present-day sea floor and Paleozoic ophiolites which all show much greater diversity (related to spreading rate, temperature, magma supply, etc.). Since modern environments and young ophiolites rarely conform to this strict definition, it makes little sense for Precambrian ophiolites to be held to this standard for recognition. It is more sensible to allow the diversity of modern ophiolites to be a guide to recognizing older ophiolites and their tectonic settings and then to try to determine, through comparison, if there are any significant secular changes in ophiolitic structure and stratigraphy with time.

With this caveat in mind, the research summarized above has identified dozens of Precambrian ophiolites that contain an ophiolitic igneous pseudostratigraphy. This basic recognition opens the way for a myriad of other studies on the chemistry, structure, thickness, rheology, biology, and other aspects of ancient oceanic crust and lithosphere that are only beginning to be appreciated. Once this recognition becomes more widespread and accepted, even greater insight to processes on the early Earth will be obtained.

13 Conclusion: a new list of criteria to identify ophiolites

Several authors have presented various schemes to purportedly discriminate between ophiolitic and other sequences [214, 215], although most of these are either arbitrary or based on models of what the authors believe Precambrian ophiolites should have looked like [38]. Here, we present an uniformitarian list of criteria that can be used to determine the liklihood of whether or not a partial, dismembered, or complete sequence is ophiolitic, through comparison with better-understood Phanerozoic sequences. For comparison, the Dongwanzi ophiolite is compared to Phanerozoic ophiolites, and it stands up well to such comparison and would clearly be called an ophiolite if it were preserved in a Phanerozoic orogen. Table 1 can be used for other questionable sequences by replacing the column for the Dongwanzi ophiolite with the sequence in question.

Table 1 A list of criteria to recognize deformed and metamorphosed ophiolitic mafic/ultramafic rock sequences in ancient mountain belts[a)]

Indicator	Importance	Status in Phanerozoic ophiolites	Status in Dongwanzi	Conclusion
Full Penrose sequence In order	Diagnostic	Rare, about 10%	Suggested, needs documentation and verification	Not conclusive
Podiform chromites with nodular textures	Diagnostic	About 15%	Present	Diagnostic
Full sequence dismembered	Convincing	About 30%–50%	Dismembered units present	Convincing
3 or 4 of 7 main units present	Typical for accepting Phanerozoic ophiolite	About 80%	6 of 7 units known dikes still unconvincing because of uncertain age	Convincing
Sheeted dikes	Cistinctive, nearly diagnostic	About 10%–20%	Suggested, age needs verification	Not conclusive
Mantle tectonites	Distinctive	About 20%–30%	Present	Distinctive
Cumulates	Present, not distinctive	About 70%	Present	Supportive
Layered gabbro	Typical	About 70%	Present	Supportive
Pillow lavas	Typical, not distinctive	About 85%	Present	Supportive
Chert, deep water seds	Typical	About 85%	Present	Supportive
Co-magmatic dikes and gabbro	Necessary, rare to observe	About 15%	Present	Distinctive
High-T silicate defm. As inclus. in melt pods	Rare, but distinctive	About 10%	Present	Distinctive
Basal thrust fault	Necessary (except in rare cases), not diagnostic	About 60%	Present	Supportive
Dynamothermal sole	Distinctive, almost diagnostic	About 15%	Not determined	Inconclusive
Sea floor metamor	Distinctive	All	Present	Supportive
Hydrothermal vents black smoker type	Distinctive	Rare	Present	Strongly supports

(*To be continued on the next page*)

(*Continued*)

Indicator	Importance	Status in Phanerozoic ophiolites	Status in Dongwanzi	Conclusion
MORB chem.*	Common	About 40%	Present	Distinctive
Arc tholeiite chem.*	Common	About 60%	?	Distinctive
Flat REE*	Distinctive	About 65%	Present	Distinctive
Calc-alkaline chem.*	Common	About 25%	Present in some units	Inconclusive
Boninite chem.*	Distinctive	About 40%	?	?

a) Ophiolites are defined on the basis of field relationships and the overall rock sequence. Many workers have added chemical criteria to the ways to recognize and distinguish between different types of ophiolites. Some of the more common traits are denoted by *.

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