Ophiolite pulses, mantle plumes and orogeny

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Abstract: Ophiolites show a wide range of internal structure, pseudostratigraphy and chemical fingerprints suggesting various tectonic settings of their origin. In general, they are characterized as mafic–ultramafic assemblages and associated sedimentary and metamorphic rock units that formed during different stages of the Wilson cycle evolution of ancient oceans, and that were subsequently incorporated into continental margins through collisional and/or accretionary orogenic events. Distributions of ophiolites with certain age groups in different orogenic belts define distinct ophiolite pulses, times of enhanced ophiolite genesis and emplacement, in Earth history. These pulses coincide with the timing of major collisional events during the assembly of supercontinents (i.e. Rodinia, Gondwana and Pangaea), dismantling of these supercontinents, and increased mantle plume activities that formed widespread large igneous provinces (LIPs). Suprasubduction zone ophiolites in orogenic belts signify oceanic crust generation in subduction rollback cycles during the closing stages of basins prior to terminal continental collisions. Both collision-driven assembly of supercontinents and deep penetration of subducted slabs into the lower mantle may produce plumes that in turn facilitate continental rifting, sea-floor spreading and oceanic plateau generation, all of which seem to have contributed to ophiolite genesis. Accelerated LIP formation and sea-floor spreading that are associated with superplume events are likely to have caused widespread collisions and tectonic accretion of ophiolites at global scales. Together, these spatial and temporal relations suggest close links between ophiolite pulses, mantle plumes and orogenic events in Earth history.

The traditional definition of ophiolites as on-land fragments of fossil oceanic lithosphere developed at palaeo-spreading centres (Gass 1990) has played an important role on the formulation and advancement of the plate tectonic theory (Coleman 1977, and references therein), and ophiolites have been used extensively to make palinspastic reconstructions of ancient ocean basins and mountain belts (i.e. Dewey *et al.* 1973; Dercourt *et al.* 1986; Lemoine *et al.* 1986). Exposures of ophiolite complexes along curvilinear fault zones in orogenic belts have been interpreted to represent suture zones, where plate collisions (commonly involving continents and island arcs) occurred in the past (Burke *et al.* 1977). The 1972 Penrose definition of an ophiolite suite having a layer-cake pseudostratigraphy, complete with a sheeted dyke complex, resulting from sea-floor spreading has been central to the ophiolite studies and palaeogeographical reconstructions (Anonymous 1972). Although this ophiolite–oceanic crust analogy and the mid-ocean ridge origin of ophiolites were challenged early on, mainly by geochemists (e.g. Miyashiro 1973), it has been assumed that, in general, ophiolites represent the beginning stages (rift-drift and sea-floor spreading) of Wilson cycles.

This traditional view of ophiolites was modified in the mid- to late 1970s, when researchers recovered ophiolitic rocks from the Lau and Mariana back-arc basins, the inner trench walls of the Yap and Mariana trenches, and the Mariana forearc (Hawkins 1977). A new paradigm for ophiolite genesis emerged in the early 1980s, asserting that most ophiolites had developed in suprasubduction zone (SSZ) environments at convergent plate boundaries (Pearce *et al.* 1984). The widely accepted association of ophiolite genesis with subduction zone settings has shifted the temporal position of ophiolites within Wilson cycles from the beginning to the closing stages. This inference suggests that many ophiolites were produced in the closing stages of ocean basins prior to continental collisions. Dilek & Flower (2003) and Flower & Dilek (2003) have shown, based on actualistic models from the Western Pacific and Eastern Asia and their Tethyan examples, that mantle flow and slab rollback may have played a major role in the formation of SSZ ophiolites in the Alpine–Himalayan orogenic system during the final stages of the evolution of Tethyan basins. Slab rollback is driven by trenchward mantle flow and slab buoyancy forces and

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results in lithospheric-scale extension and associated magmatism in the upper plate that collectively play a major role in the formation of proto-arc, arc and back-arc 'oceanic crust'.

The Penrose definition of an ophiolite suite does not prescribe a specific tectonic setting of its genesis and states that 'the use of the term should be independent of its supposed origin' (Anonymous 1972). Extensive research by the international scientific community during the last 30 years has shown that individual ophiolites differ significantly in terms of their structural architecture, chemical fingerprints and evolutionary paths, indicating different tectonic environments of origin, even within the same orogenic belt (Nicolas 1989; Dilek *et al.* 2000). Ophiolites in the Alpine–Himalayan orogenic belt, for example, range from relics of intracontinental rift basins and embryonic normal oceanic crust with mid-ocean ridge basalt (MORB) affinity (Ligurian-type) to protoarc–forearc–back-arc assemblages with SSZ affinities (Mediterranean-type) (Dilek 2003). The peri-Caribbean ophiolites include tectonically emplaced fragments of oceanic crust, which in part represent a large igneous province (LIP), whereas some of the Pacific Rim ophiolites may have had protracted and polygenetic igneous histories that involved the evolution of ensimatic arc terranes through multiple episodes of magmatism, rifting and tectonic accretion, as documented from the Mesozoic ophiolites in the Philippines and the Sierra Nevada foothills (Sierran-type) (Dilek 2003). Ophiolites situated within the accretionary complexes of ancient active margins are commonly associated with mélanges and high-pressure metamorphic rocks and may represent fragments of abyssal peridotites and ocean island basalts (OIB), seamounts, island arcs and/or mid-ocean ridge crust scraped off from downgoing plates. These kinds of ophiolites (Franciscan-type) in ancient accretionary complexes do not show genetic and temporal relations (i.e. no melt–residua relationship or chronostratigraphic order) and commonly display diverse chemical affinities and metamorphic grades. Thus, ophiolites are highly diverse in terms of their tectonic origin and emplacement mechanisms (Wakabayashi & Dilek 2003).

Despite significant differences in their origin and emplacement mechanisms, ophiolites around the world appear to show distinct patterns of distribution through time and space, suggesting that their evolution may have been linked to some first-order global tectonic events. In this paper I present an overview of the spatial and temporal occurrences of major ophiolite belts in the Earth's history and discuss the possible causes of this 'ophiolite pattern' in a global tectonic framework. However, examples and the discussion in this paper are constrained to the Neoproterozoic and Phanerozoic occurrences of ophiolites because our knowledge of the Archaean ophiolites, specifically their igneous and emplacement ages and tectonic environment of origin, is still limited.

Distribution of ophiolite belts in space and time

Pan-African and Brasiliano ophiolites

Figure 1 shows the distribution of major ophiolites with certain age groups in semi-continuous, curvilinear belts around the world. The Late Proterozoic (<860 Ma) ophiolites appear to concentrate mainly in South America, Africa and Arabia, with minor occurrences in central and eastern Europe (Cadomian belts in NW France and Rhodope massif, respectively), the Lesser Caucasus (Transcaucasian massif), central Asia (i.e. Agardagh Tes-Chem, Songshugou and Jiangxi ophiolites) and northwestern India. The widespread existence of Neoproterozoic ophiolites in Afro-Arabia and South America is associated with the evolution of several Pan-African–Brazilide ocean basins (e.g. Mozambique Ocean) in the aftermath of the break-up of the supercontinent Rodinia and during the assembly of West Gondwana (Stern 1994; Dalziel 1997). These Pan-African–Brasiliano ophiolites are fragments of Proterozoic oceanic crust, juvenile island arcs and oceanic plateaux that were amalgamated during the evolution of both collisional- and accretionary-type orogens (Windley 1992). Ophiolites in the Arabian–Nubian Shield are diverse in origin and include Ligurian-type ophiolites associated with continental rifting and incipient sea-floor spreading (e.g. Nabitah, Hamdah ophiolites), Mediterranean-type SSZ ophiolites developed in forearc–infant arc settings, and Sierran-type, polygenetic ophiolites that evolved in mature island arcs (Dilek & Ahmed 2003). Neoproterozoic ophiolites in Afro-Arabia and South America thus represent a record of the Wilson cycle opening, narrowing and closing of ocean basins, indicating that modern-style plate tectonic processes were in operation by 1 Ga. Proterozoic ophiolites in Europe and the Caucasus are isolated fragments of the Pan-African oceanic crust separated from Afro-Arabia as a result of the opening of Palaeozoic and Mesozoic Tethyan basins (Zakariadze *et al.* 2002).

Eastern Australian ophiolites

Cambrian ophiolites in eastern Australia are part of the Tasmanides, which developed during the evolution of East Gondwana in the early Palaeozoic. These ophiolites show diverse chemical affinities (MORB, SSZ and OIB) and have complex origin and emplacement histories (Spaggiari *et al.* 2003). The age progression, internal structure and chemical fingerprints of the ophiolites in the eastern Tasmanides suggest that they developed in a complex rifted arc–back-arc system, fringing the eastern margin of East Gondwana during 530–485 Ma. The collapse of this fringing arc–back-arc system into the East Gondwana continental margin and the emplacement of the Eastern Australian ophiolites might have been related to far-field stresses associated with the collisional assembly of Greater Gondwana in the early Palaeozoic (Spaggiari *et al.* 2003).

Appalachian, Caledonian, Hercynian and Uralian ophiolites

Palaeozoic ophiolites occur mainly in the Appalachian, Caledonian, Hercynian, Uralian and Altaid orogenic belts, extending from eastern North America through Scotland, northern Europe (including the Iberian Peninsula) and Scandinavia, to polar–central Russia and central Asia (Fig. 1). Isolated occurrences of Early Palaeozoic ophiolites also exist in the crystalline basement of the Central Andes in South America (Ramos *et al.* 2000) and the Trinity terrane of the eastern Klamath Mountains in California (Metcalf *et al.* 2000). The Early Palaeozoic ophiolites in the Appalachian–Caledo-

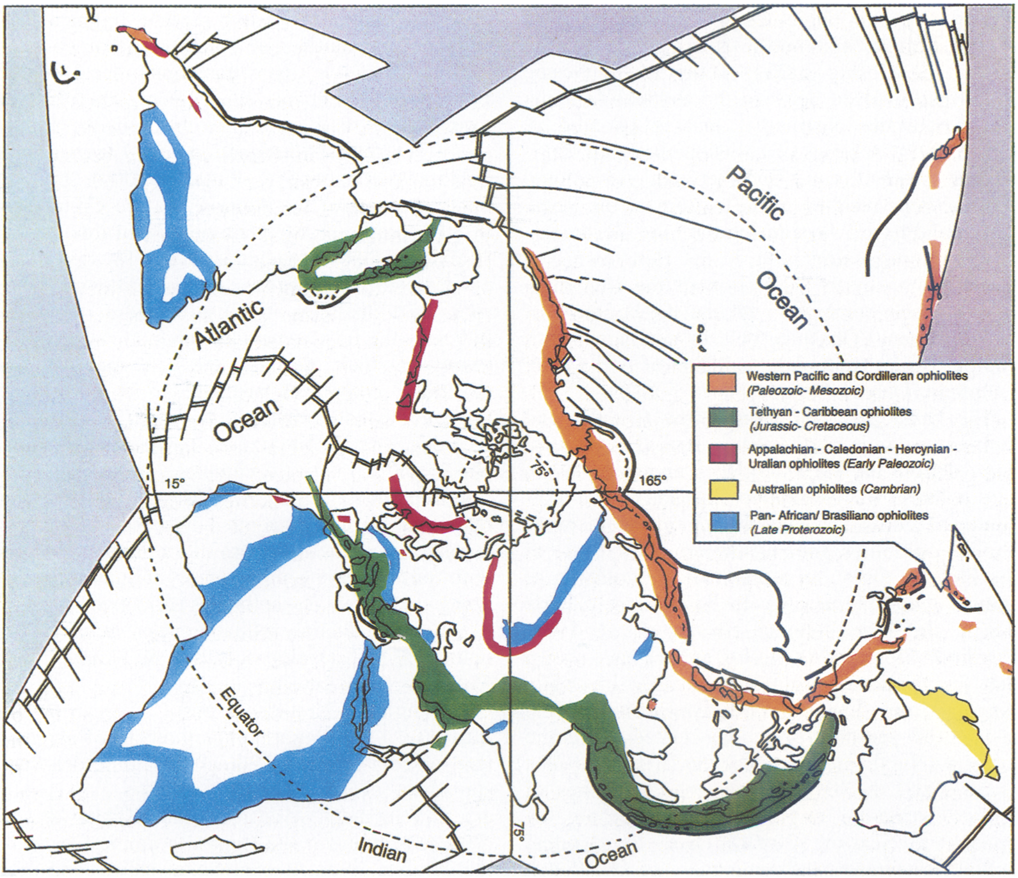

Fig. 1. Global distribution of Proterozoic and Phanerozoic ophiolite belts and modern mid-ocean ridge systems (fine double lines) on a North polar projection map (base map from Coleman 1977). Bold black lines represent trenches of modern subduction zones. Ophiolite data sources: Coleman (1977), IGCP (1979), Lippard *et al.* (1986), Nicolas (1989), Helmstaedt & Scott (1992), Windley (1995), Ramos *et al.* (2000), Spadea & Scarrow (2000), Giunta *et al.* (2002) and Spaggiari *et al.* (2003).

nian orogenic belts, such as the Bay of Islands in Newfoundland, Canada (Dewey & Bird 1971; Irvine & Findlay 1972; Casey *et al.* 1983), Ballantrae ophiolite in Scotland (Oliver & McAlpine 1998), and Karmøy and Solund–Stavfjord ophiolites in western Norway (Pedersen & Furnes 1991) are of SSZ origin, and they commonly show a complete Penrose pseudostratigraphy typical of Mediterranean-type ophiolites (Dilek 2003). The Caledonian–Appalachian orogenic belt developed as the Eastern Iapetus Ocean and its seaways between North America and Baltica–Avalonia closed during the Palaeozoic through a series of arc–continent and continent–continent collisions (Dalziel 1997). The Early Palaeozoic ophiolites in the Central Andes have MORB to SSZ affinities (Ramos *et al.* 2000) and are likely to have developed during the Early Cambrian–Ordovician evolution of the Western Iapetus Ocean between Laurentia and South America (Dalziel 1997).

The Hercynian ophiolites in Iberia, western and central Europe, and northwestern Africa formed during the closing stages of the Rheic Ocean, which had evolved between the Baltica–Avalonia and Gondwana continental masses (Condie & Sloan 1998). A series of collisions between Baltica and south Europe and between Africa and south Europe resulted in the closure of the Rheic Ocean and its seaways during the Late Devonian–Carboniferous, culminating in the Hercynian orogeny. Timing of the formation of the Hercynian orogenic belt coincides with the development of the Alleghany–Ouachita belt in southern North America as a result of the collision of Africa with Laurentia (Dalziel 1997).

The Palaeozoic ophiolites in the Uralides and their extension in north–central Asia (Fig. 1) were derived from the Pleionic Ocean and its seaways. The collapse of marginal basins and island-arc–continent collisions caused the emplacement of Uralian ophiolites prior to the terminal closure of the Pleionic Ocean as a result of the collision of Baltica–Eastern Europe with Kazakhstan–Siberia during the Late Permian (Brown *et al.* 1998; Condie & Sloan 1998). Recent studies have shown that the Uralian ophiolites are diverse in origin, ranging from Ligurian-type, continental rifting and initial sea-floor spreading-related peridotite massifs (Nurali and Mindyak massifs of Spadea *et al.* 2003) to Mediterranean-type ophiolites of forearc–island-arc origin (Magnitogorsk arc of-Spadea & Scarrow 2000). Thus, the Uralian ophiolites represent different stages of the Wilson cycle evolution of the Pleionic Ocean. The distribution, origin and geodynamics of the Palaeozoic ophiolites in central Asia, specifically those in China and Inner Mongolia, have been discussed by Zhang *et al.* (2003).

Tethyan–Caribbean ophiolites

Jurassic–Cretaceous Tethyan ophiolites occur in the Betic–Rif and Pyrenees (*c.* 157–145 Ma), Alpine–Apennine mountain systems (Corsica, Sardinia, Eastern Alps, Internal and External Ligurides; *c.* 200–145 Ma), Carpathians (Apusseni, Bodva; 160–140 Ma), Dinaride–Albanide–Hellenide mountain belt (190–150 Ma), Lesser Caucasus (*c.* 230–220 Ma), Intra-Pontide and Izmir–Ankara–Erzincan suture zones in northern Turkey (Triassic–Late Jurassic), Tauride and Zagros mountain belts (98–90 Ma), Himalaya–Tibet orogenic system (128–70 Ma) and Andaman Sea–Indonesian region (*c.* 140–110 Ma; Fig. 1). These ophiolites developed in Palaeo- and Neo-Tethyan oceans and their seaways that had evolved between Gondwana and Eurasia (Stampfli 2000). Neo-Tethyan ophiolites west of the Aegean Sea are Jurassic in age and contain fertile lherzolite peridotites that, in part, represent fragments of exhumed subcontinental mantle lithosphere situated in ocean–continent transitions (see Dilek & Flower 2003; Müntener & Piccardo 2003). Typical examples of these ophiolites occur in the Ligurides (hence the designation of Ligurian-type ophiolites; Rampone & Piccardo 2000). Tethyan ophiolites east of the Aegean Sea are Cretaceous in age, progressively younging eastwards in the Himalaya–Tibet orogenic system. The existence of depleted harzburgites, calc-alkaline extrusive rocks and boninites in most of these ophiolites indicates the involvement of subduction-zone processes in their development, although mature island-arc complexes are rare to absent. Well-preserved Mediterranean ophiolites (i.e. Troodos, Kizildag, Semail, Neyriz) have sheeted dyke complexes and a relatively complete, layer-cake Penrose pseudostratigraphy. Most Neo-Tethyan ophiolites were incorporated into their respective mountain belts by collisions of arc–trench systems with trailing passive continental margins in downgoing plates. Such collisions effectively terminated the subduction rollback cycles in which the ophiolites had developed (Dilek & Flower 2003; Flower & Dilek 2003).

The Jurassic–Cretaceous peri-Caribbean ophiolites (Fig. 1) display a complex record of magmatism associated with continental rifting, sea-floor spreading, oceanic plateau accretion and island-arc development. According to Giunta *et al.* (2002), opening of the Central Atlantic Ocean in the Jurassic initiated continental rifting and sea-floor spreading in the Caribbean region, producing the MORB-type proto-Caribbean oceanic lithosphere, fragments of which are found in Costa Rica, Guatemala, Hispaniola and Cuba. Mantle plume magmatism in the Early Cretaceous caused thickening of this proto-Caribbean oceanic crust in the west and development of an oceanic plateau (Caribbean–Colombian Cretaceous Igneous Province; Kerr *et al.* 1998, and references therein). Burke (1988) suggested that the Caribbean–Colombian oceanic plateau originally formed in the Pacific and was pushed into the Caribbean basin as a result of the eastward movement of the Farallon plate in the Late Cretaceous–Early Tertiary. Opening of the South Atlantic in the Early Cretaceous caused the northwestward encroachment of South America on the Caribbean basin, resulting in regional compression and development of intra-basinal subduction zones and associated arc magmatism. Oblique convergence and wrench tectonics associated with the motion of South America facilitated the emplacement of ophiolites and oceanic plateau scrapings along the periphery of the basin. Unlike the coeval Tethyan ophiolites, the Caribbean ophiolites thus include fragments of LIP-generated oceanic crust (Caribbean-type ophiolites of Dilek 2003).

Western Pacific and Cordilleran ophiolites

The Western Pacific and Cordilleran ophiolites (Fig. 1) range in age from Palaeozoic to Cenozoic and are commonly associated with subduction–accretion complexes. Typical examples occur in the Indonesia–New Guinea region Philippines, Japan, Koryak–Kamchatka orogenic belt, Verkhoyansk–Chukotka fold belt, Alaska and North American Cordillera (Dilek *et al.* 1990; Saleeby 1992; Encarnacion *et al.* 1993; Ishiwatari 1994; Harper 2003; Harris 2003; Hirano *et al.* 2003; Ishiwatari *et al.* 2003; Sokolov *et al.* 2003). Ophiolites in the Indonesia–New Guinea region are diverse in age and composition and commonly show SSZ chemical affinities. Some Indonesian ophiolites may include exhumed subcontinental mantle fragments, reminiscent of Ligurian-type ophiolites (i.e. lherzolite bodies of the Banda arc in Timor). Emplacement of the Indonesian–New Guinea ophiolites was facilitated by the collision of the northern edge of the Australian continent with the subduction–accretion systems of the Pacific Plate during the Cenozoic. Ophiolites in the Philippines constitute the oceanic basement of volcanic arc complexes that underwent magmatic and tectonic extension through multiple phases of back-arc basin opening (Encarnacion *et al.* 1993), and thus they have a polygenetic evolutionary history typical of Sierran-type ophiolites (Dilek 2003).

The ophiolites in Japan, Kamchatka–Koryak and Verkhoyansk–Chukotka commonly occur as imbricated thrust sheets in blueschist-bearing accretionary complexes, with older ophiolitic units generally occupying structurally higher positions (Ishiwatari 1994; Ishiwatari *et al.* 2003). They show a wide range of geochemical diversity (MORB, OIB, SSZ and LIP) and metamorphic gradients, and they represent tectonic slices of oceanic rocks scraped from downgoing plates at active continental margins. Dilek (2003) classified these types of ophiolites in subduction–accretion complexes as Franciscan-type to distinguish them from Mediterranean-type SSZ ophiolites that are generally underlain by collided passive continental margins. The Jurassic Cordilleran ophiolites in the western USA commonly represent forearc–arc–back-arc assemblages that locally display tectonic and geochemical evidence for intra-arc or back-arc spreading, episodic and polygenetic magmatism, and mature arc volcanism. Some of these Cordilleran ophiolites might have evolved adjacent to the North American continental margin (e.g. Josephine ophiolite; Harper 2003); some others may represent fragments of an intra-oceanic island arc terrane that were accreted to the North American continental margin during an arc–continent collision (e.g. Smartville arc terrane of Dilek *et al.* 1990; Guerrero island arc terrane of Dickinson & Lawton 2001).

Ophiolites, plumes and orogeny

The Precambrian ophiolite record is still poorly constrained in part because of intense deformation and reworking of continental crust through multiple episodes of orogenic events over time. However, it is also possible that some Precambrian ophiolites may have gone unrecognized because of the search for an ideal, Penrose-type ophiolite sequence showing a layer-cake pseudostratigraphy, complete with a sheeted dyke complex. Some Archaean greenstone belts, for example, may represent dismembered ophiolites (Helmstaedt & Scott 1992). Additionally, it is likely that the Archaean oceanic crust was fundamentally different from its Phanerozoic counterpart in terms of its thickness and internal architecture (Moores 2002). A survey of the reasonably well-documented pre-1 Ga ophiolites shows that their igneous ages appear to cluster at times of 1.0–1.5 Ga, 1.8–2.3 Ga, *c.* 2.5–2.7 Ga and *c.* 3.4 Ga (Moores 2002). It is difficult to relate these 'ophiolite pulses' in the early Precambrian to any global tectonic events because of our limited knowledge of the early history of the Earth.

When we consider the occurrence of Late Proterozoic and Phanerozoic ophiolites, we see discrete pulses of ophiolite generation and emplacement in Earth history (Fig. 2). The most prominent ophiolite pulse was during 180–140 Ma when the Tethyan, Caribbean and some of the Circum-Pacific (Western Pacific and North

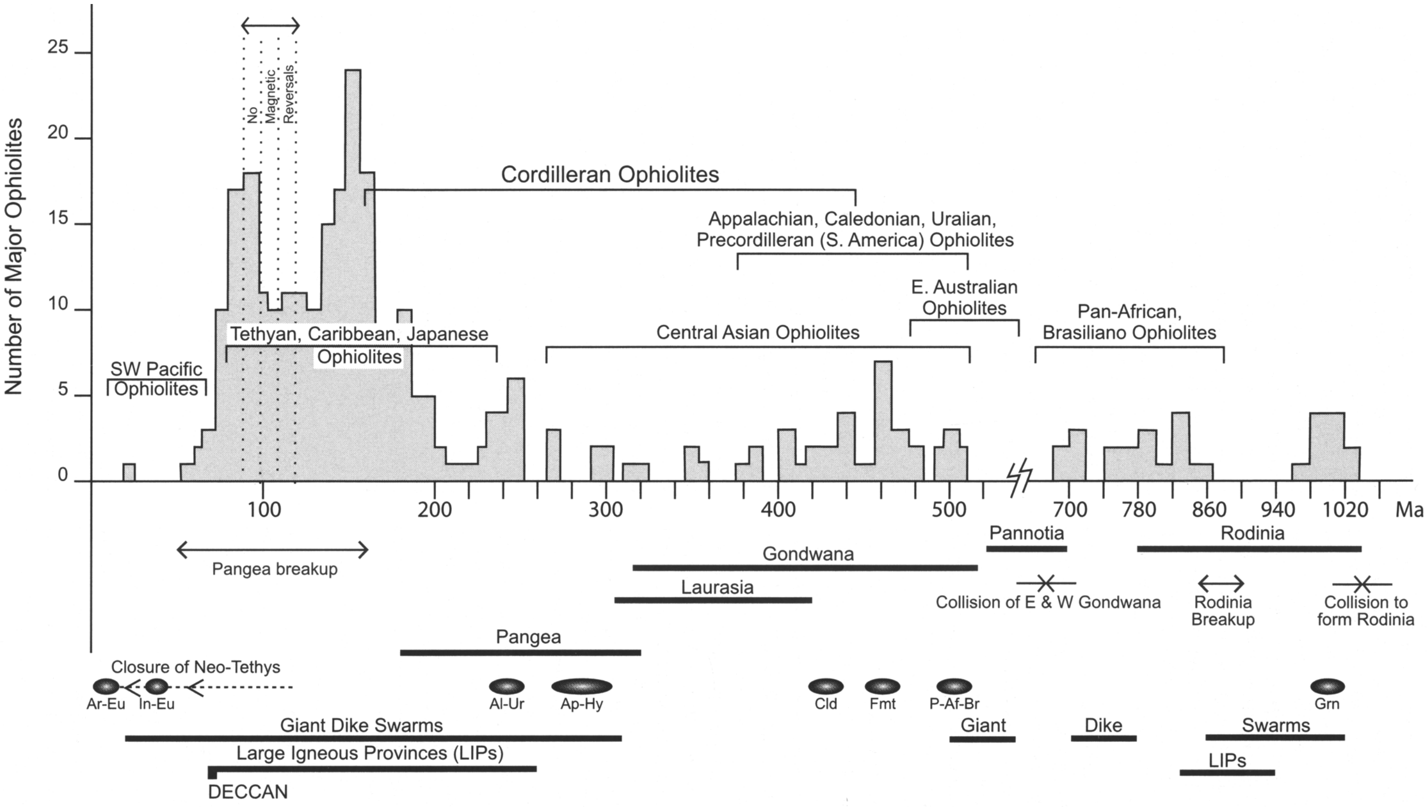

Fig. 2. Histogram showing the occurrence of major ophiolites and ophiolite pulses through time. Also shown are the life spans of supercontinents and major collisional–orogenic events that led to their assembly, and formation of large igneous provinces (LIPs) and Giant Dyke Swarms. The change in time scale about the Phanerozoic–Proterozoic boundary should be noted. Abbreviations for orogenic events (from youngest to oldest): Ar-Eu, Arabia–Eurasia collision; In-Eu, India–Eurasia collision; Al-Ur, Altaid–Uralian orogenies of central Asia; Ap-Hy, Appalachian–Hercynian orogenies; Cld, Caledonian orogeny; Fmt, Famatinian orogeny; P-Af-Br, Pan-African–Brasiliano orogenies; Grn, Grenville and related orogenies. Period of 'No Magnetic Reversals' between 120 and 80 Ma coincides with the mid-Cretaceous 'superplume' event (Larson 1991). Ophiolite data sources: Coleman (1977), Abbate *et al.* (1985), Lippard *et al.* (1986), Nicolas (1989), Ishiwatari (1994), Yakubchuk *et al.* (1994), Ramos *et al.* (2000), Giunta *et al.* (2002) and Spaggiari *et al.* (2003). Data sources for supercontinental cycles and orogenic events: Stern (1994), Windley (1995), Rodgers (1996), Dalziel (1997), Condie & Sloan (1998) and Moores *et al.* (2000). Data sources for LIPs and Giant Dyke Swarms: Yale & Carpenter (1998) and Coffin & Eldholm (2001). (See text for discussion.)

American Cordilleran) ophiolites were forming. The second important peak in ophiolite production was during the Late Cretaceous (mostly Tethyan ophiolites), following the mid-Cretaceous 'superplume' event (Fig. 2; Larson 1991). Then, we see second-order ophiolite pulses in the latest Permian–Early Triassic (*c.* 250–230 Ma), early Devonian–Silurian (*c.* 400–440 Ma) and Late Cambrian–Early Ordovician (460–500 Ma). The existing record of well-studied Neoproterozoic ophiolites shows ophiolite generation at times of 700 Ma, 740–780 Ma and 820–860 Ma (Fig. 2). A distinct ophiolite pulse around 1 Ga is also apparent.

Correlation of these ophiolite pulses with specific global tectonic events reveals apparent patterns and possible links between them. To a first approximation, the observed ophiolite pulses overlap with major orogenic events that led to the assembly of supercontinents, particularly during the Proterozoic (Meso- and Neoproterozoic) and Palaeozoic (Fig. 2). We see this temporal relation during the build-up of Rodinia around 1 Ga, the collision of East and West Gondwana and the construction of Pannotia (*c.* 700 and 600 Ma), Pan-African–Brasiliano orogenies (520–500 Ma), Caledonian–Famatinian orogenies (460–440 Ma), Appalachian–Hercynian orogenies (*c.* 300–270 Ma), Altaid–Uralian orogenies in central Asia (*c.* 240 Ma), and smaller-scale continental collisions within the Alpine–Himalayan system throughout Mesozoic–early Cenozoic time that are not depicted in Figure 2. Most of the ophiolites that originated and were emplaced within narrow time spans during these orogenic events probably represent subduction rollback cycles. As such, they constitute parts of subduction–accretion systems that were accreted onto continental margins prior to terminal closures of ocean basins. Rapid opening of small basins in the upper plates of subduction zones operating along irregular continental margins, reminiscent of the modern Tyrrhenian Sea, can also produce oceanic crust or ophiolites during the late stages of orogenesis.

In addition to SSZ ophiolites generated during the late stages of Wilson cycle evolution of ocean basins, some ophiolites are clearly rift-related mafic–ultramafic assemblages (i.e. exhumed subcontinental mantle fragments) and/or fragments of embryonic ocean floor, as documented from the Arabian–Nubian Shield, Uralides, Central and NE Asia, Precordillera of South America and Tethysides. The most prominent ophiolite pulse during the Mesozoic coincides with the break-up of Pangaea (Fig. 2) through discrete episodes of continental rifting during the Late Triassic and Jurassic (Dilek 2001). The Mesozoic Neo-Tethyan Ocean developed, for example, as a result of continental rifting along the northern periphery of Gondwana that began in the Late Triassic. Upper Triassic rift assemblages consisting of basaltic extrusive and intrusive rocks that are intercalated with pelagic to hemipelagic sedimentary sequences are common throughout the Mediterranean region (Dilek & Flower 2003) and may represent the precursor and/or the upper-crustal units of Late Triassic oceanic crust. There are no Late Triassic ophiolites preserved in the region, but it is thought that this inferred Late Triassic oceanic crust within the Neo-Tethyan realm was consumed entirely to produce Jurassic to Cretaceous SSZ ophiolites (Dilek & Flower 2003, and references therein). This interpretation is compatible with the buoyancy analysis of subducting lithosphere that suggests that 10 Ma and older oceanic lithosphere is inherently susceptible to deep subduction (Cloos 1993). Indeed, this is why mid-ocean ridge generated normal oceanic lithosphere has rarely been preserved in the geological record; almost all of it has been consumed during the Phanerozoic (Coleman 1977).

Major ophiolite pulses also appear to overlap with the production of plume-related LIPs and giant dyke swarms (Fig. 2). Of particular interest are the LIPs generated as oceanic plateaux, rifted volcanic margins and ocean-basin flood basalts because of their potential contribution to ophiolite-forming processes (Coffin & Eldholm 2001). Although some LIP production has been recognized in the early history of the Earth (Yale & Carpenter 1998), major LIP pulses occur between 250 Ma (Siberian Traps) and 65 Ma (Deccan Plateau), coinciding with the generation of the Tethyan, Caribbean, Japanese and some SW Pacific ophiolites. The enhanced LIP formation and peak ophiolite generation in the Cretaceous are particularly striking. The Cretaceous 'superplume', marked by a long period of no magnetic reversals between 120 and 80 Ma (Fig. 2), is interpreted to be responsible for the development of oceanic plateaux in the Pacific and Indian Oceans, global high sea levels, and increased seafloor spreading rates (Larson 1991). This is also when the majority of the Phanerozoic ophiolites formed in different ocean basins and their seaways. The abrupt ending of LIP formation and ophiolite generation in the Cenozoic is conspicuous (Fig. 2) and further suggests probable spatial and temporal links between plume activity and oceanic crust generation.

The temporal relations between supercontinent cycles and LIPs are also revealing and may be inherently linked to ophiolite genesis. LIPs and giant dyke swarms appear to overlap in time with the late stages of supercontinent existence throughout Earth history. The most important case is the coupling of Pangaea's existence with extensive LIP formation. Some of the most prominent LIPs, such as the Siberian Traps (*c*. 250 Ma), Central Atlantic magmatic province (*c*. 225 Ma), Weddell Sea volcanic margin (184 Ma), Shatsky Rise (147 Ma) and Ontong Java Plateau (121–90 Ma; Coffin & Eldholm 2001) formed when the Pangaean supercontinent was still in existence. Some researchers have suggested that construction of a supercontinent insulates the underlying mantle, which initiates major convective activities and elevated fluxes that in turn result in the formation of plumes (Gurnis 1988; Yale & Carpenter 1998). These plumes probably played a major role in the subsequent break-up of the supercontinents (Storey 1995; Dalziel *et al.* 2000).

Some ophiolites associated with rifted volcanic margins and oceanic plateaux (i.e. peri-Caribbean ophiolites) are clearly related to LIP production. Moores *et al.* (2000) suggested spatial and temporal links between LIP formation and regional collisional events. They proposed that major orogenic events driven by slab-pull forces might have supplied cold subducted slabs that penetrated into and depressed the core–mantle boundary, causing large upwellings in the lower mantle (mantle push-ups) at some distance from subduction zones. Their model suggests that these upwelling zones fed mantle plumes that led into continental rifting, sea-floor spreading and LIP formation. Thus, in this model, the production of LIPs is likely to follow times of rapid subduction and major orogenic events. It is also possible that increased LIP production during certain time periods, such as the mid-Cretaceous superplume activity, and increased sea-floor spreading rates induced widespread compression at convergent margins (Vaughan 1995) by carrying more buoyant geological material (i.e. seamounts, thick oceanic plateaux, microcontinents, island arcs) into trenches and thus causing collisions, subduction zone arrests and ophiolite emplacement.

Conclusions

Ophiolites in orogenic belts occur as curvilinear zones of mafic–ultramafic rock assemblages (with associated metamorphic and sedimentary rocks) within certain age groups, and they represent relics of different stages of the Wilson cycle evolution of ancient ocean basins. There is no single 'blueprint' model of ophiolite formation; ophiolites within even the same orogenic belt may have developed in different tectonic settings before being incorporated into continental margins during the closing stages of ocean basins.

Ophiolite pulses in Earth history, times of enhanced ophiolite genesis and emplacement, largely coincide with discrete orogenic events leading to the assembly of supercontinents, break-up of supercontinents, and formation of plume-generated LIPs. Spatial and temporal relations between these global tectonic events suggest possible links through complex mantle dynamics. Collision-induced mantle flow results in subduction rollback and one or more episodes of arc splitting and basin opening, producing a collage of 'forearc oceanic lithosphere' (future ophiolites). The collision of these arc–trench systems with continents terminates subduction rollback cycles and facilitates ophiolite emplacement. Assembly of supercontinents may lead to insulation of the mantle that in turn sets up thermal instabilities and plumes. Plume activities weaken the continental lithosphere and cause the break-up of supercontinents, followed by continental rifting, sea-floor spreading and oceanic crust formation. The onset of plumes may also be induced by deep penetration of subducted slabs into the lower mantle that causes mantle push-ups to form; thus, major orogenic events driven by rapid subduction may trigger the formation of plumes and hence the production of LIPs. Global ophiolite emplacement events overlap with superplume activities in certain periods of time (e.g. the mid-Cretaceous). These possible links and the feedback mechanisms between major global tectonic events need to be further investigated by systematic structural, geochemical and geochronological studies of ophiolites, LIPs and ancient continental margins.

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