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Focus paper

Four billion years of ophiolites reveal secular trends in oceanic crust formation

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ABSTRACT

We combine a geological, geochemical and tectonic dataset from 118 ophiolite complexes of the major global Phanerozoic orogenic belts with similar datasets of ophiolites from 111 Precambrian greenstone belts to construct an overview of oceanic crust generation over 4 billion years. Geochemical discrimination systematics built on immobile trace elements reveal that the basaltic units of the Phanerozoic ophiolites are dominantly subduction-related (75%), linked to backarc processes and characterized by a strong MORB component, similar to ophiolites in Precambrian greenstone sequences (85%). The remaining 25% Phanerozoic subduction-unrelated ophiolites are mainly (74%) of Mid-Ocean-Ridge type (MORB type), in contrast to the equal proportion of Rift/Continental Margin, Plume, and MORB type ophiolites in the Precambrian greenstone belts. Throughout the Phanerozoic there are large geochemical variations in major and trace elements, but for average element values calculated in 5 bins of 100 million year intervals there are no obvious secular trends. By contrast, basaltic units in the ophiolites of the Precambrian greenstones (calculated in 12 bins of 250 million years intervals), starting in late Paleo- to early Mesoproterozoic (ca. 2.0–1.8 Ga), exhibit an apparent decrease in the average values of incompatible elements such as Ti, P, Zr, Y and Nb, and an increase in the compatible elements Ni and Cr with deeper time to the end of the Archean and into the Hadean. These changes can be attributed to decreasing degrees of partial melting of the upper mantle from Hadean/Archean to Present. The onset of geochemical changes coincide with the timing of detectible changes in the structural architecture of the ophiolites such as greater volumes of gabbro and more common sheeted dyke complexes, and lesser occurrences of ocelli (varioles) in the pillow lavas in ophiolites younger than 2 Ga. The global data from the Precambrian ophiolites, representative of nearly 50% of all known worldwide greenstone belts provide significant clues for the operation of plate tectonic processes in the Archean.

1. Introduction

Ophiolites are "suites of temporally and spatially associated ultramafic to felsic rocks related to separate melting episodes and processes of magmatic differentiation in particular oceanic tectonic environments (Dilek and Furnes, 2011). Their geochemical characteristics, internal structure, and thickness are strongly controlled by spreading rate, proximity to plumes or trenches, mantle temperature, mantle fertility, and the availability of fluids". In this new definition, ophiolites are categorized in subduction-unrelated and subduction-related groups. The subduction-unrelated ophiolites include **continental margin-, mid-ocean-ridge-** (*plume-proximal,*

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plume-distal, and trench-distal subtypes), and **plume** (*plume-proximal ridge and oceanic plateau* subtypes) **type** ophiolites, whereas the subduction-related ophiolites include **suprasubduction zone** (*backarc to forearc, forearc, oceanic backarc, and continental backarc* subtypes) and **volcanic arc types**. The subduction-unrelated ophiolites represent the constructional stage (rift-drift to seafloor spreading) of oceanic crust formation and contain predominantly mid-ocean-ridge basalts. The subduction-related ophiolite types represent destructive stages of ocean floor recycling (subduction with or without seafloor spreading), and their magmatic products are characterised by showing variable geochemical fingerprints, indicating subduction influence.

In this paper, we summarize the lithological and geochemical characters of 118 representative Phanerozoic ophiolites, as well as four young examples (Tihama Asir, Macquarie, Taitao and Iceland) unrelated to orogenesis (Fig. 1 and Table 1). Using well-established geochemical discrimination diagrams based on stable trace elements, we interpret our global geochemical dataset in light of the new ophiolite classification of Dilek and Furnes (2011). We also use our extensive dataset on the Precambrian greenstone sequences (de Wit and Ashwal, 1997; Furnes et al., 2013), in an attempt to synthesise oceanic crust evolution over 4 billion years of Earth history. Our choice of selected ophiolites and greenstone belts is largely restricted to those from which we have sufficient field observations and geochemical data for a comparative study, though a few well-known ophiolites for which we have not found appropriate geochemical data for this classification are mentioned (shown in italics).

2. Phanerozoic orogenic belts and selected ophiolites

We provide below a short description of the Phanerozoic orogenic belts in which different ophiolite types occur (Fig. 1). For a more complete overview, we refer the reader to Dilek and Robinson (2003), and the literature under the description of each orogenic belt and Table 1. The Paleozoic orogenic belts we describe below are represented by collisional and accretionary types (Isozaki, 1997; Condie, 2007; Windley et al., 2007; Cawood et al., 2009; Wilhem et al., 2011). The examples of the collisional orogenic type include: The Caledonian-Appalachian belt, the Hercynian belt, the Uralian belt, the Maghrebian-Alpine-Himalayan belt, and the Qinling/Qilian/Kunlun belts. The examples of the accretionary type are: the peri-Caribbean type, the Central Asian Orogenic Belt, the Gondwanide-Tasmanide belt, the Andes, and the western Pacific and Cordilleran belts. The Indonesian-Myanmar belt is currently in a transitional position from subduction-accretion in the west to collision with the Australian passive margin in the east (e.g., Timor).

2.1. Caledonian-Appalachian belt

The tectonic history of the Scandinavian Caledonides (e.g., Roberts et al., 1985, 2007; Stephens et al., 1985; Roberts, 2003; Gee, 2005; Gee et al., 2008; Andersen et al., 2012; Hollocher et al., 2012) demonstrates a "Wilson Cycle" evolution (e.g., Dewey, 1969; Dewey and Spall, 1975), lasting over a time period of ca. 200 million years (Gee et al., 2008), starting around 600 Ma with rifting and sedimentation, separating Baltica from Rodinia. For about 80 million years (ca. 500–420 Ma) magmatism associated with oceanic crust and island arc construction took place in the Iapetus Ocean. The first and main oceanic crust-building period was between ca. 500–470 Ma that resulted in the formation of several major ophiolite complexes, and a second but short-lived event during ca. 445–435 Ma that generated two ophiolites (Dunning and Pedersen, 1988; Pedersen et al., 1991; Dilek et al., 1997; Furnes et al., 2012a). The oldest generation is represented by the Lyngen, Leka, Trondheim area, Gulfjell and Karmøy ophiolites, and the youngest generation is represented by the Sulitjelma and Solund-Stavfjord ophiolites (Fig. 1, Table 1).

The northern Appalachians, even though in some respects different from the Scandinavian Caledonides (e.g., Dewey and Kidd, 1974; van Staal et al., 2009; Zagorevski and van Staal, 2011), show much the same timing of oceanic crust and island arc construction processes (e.g., Anniopsquotch, Bay of Islands, Betts Cove, Lac Brompton, Thetford Mines) as those in Ireland (*the Clew Bay ophiolite*, e.g., Chew et al., 2010, and Tyrone Igneous Complex, e.g., Hollis et al., 2013), Scotland (Ballantrae, e.g., Leslie et al., 2008; Sawaki et al., 2010), *the Unst ophiolite* in the Shetlands (Flinn et al., 1979; Prichard, 1985; Cutts et al., 2011) and Scandinavia (Fig. 1, Table 1).

2.2. Hercynian belt

The Hercynian (or Variscan) orogenic belt (e.g., Zwart, 1967) extends from western Europe (Portugal) in the west to the Czech Republic in central Europe and to Turkey in the eastern Mediterranean region (Fig. 1). It represents a complex subduction-accretion-collision belt, developed during the closure of a series of Paleozoic basins during the Ordovician to early Carboniferous, as a result of the convergence of Gondwana and Laurussia (e.g., Matte, 1991; Kroner and Romer, 2013). The Variscan orogeny lasted for about 110 million years (410–300 Ma). Subduction-accretion processes occurred between 410 Ma and 330 Ma, and during this time period ophiolite-, island arc-, continental intra-plate and granitoid magmatism took place; subsequent final magmatic activity was dominated by post-kinematic granitoids (Kroner and Romer, 2013; Uysal et al., 2013). Rifting of the Gondwana margin resulted in bimodal magmatism in the early Paleozoic (e.g., Furnes et al., 1994; Crowley et al., 2000; Floyd et al., 2002), and in the development of small ocean basins (e.g., Finger and Steyrer, 1995). Three of the Hercynian ophiolites, the early Ordovican Internal Ossa-Morena Zone ophiolite sequences (IOMZOS) in SE Spain, and the late Silurian Kaczawa Mts. and the early Devonian Sleza sequences in Poland (Fig. 1, Table 1) are included in our synthesis. Another important magmatic complex is the *Lizard Complex* in SW England, for which we do not have appropriate geochemical data for our magmatic evaluation. Kirby (1979) interpreted this complex of massive and layered gabbro, dikes and peridotites as an ophiolite, whereas Floyd (1984) interpreted it as a fragment of oceanic crust formed in a rifted continental margin. Nutman et al. (2001) suggested that it represents a magmatic complex formed as a result of intra-continental rifting.

2.3. Uralian belt

The Uralides (Fig. 1) define an arc-continent collision orogenic belt (e.g., Zonenshain et al., 1985; Ryazantsev et al., 2008) that is >4000 km long, and extend from the Kara Sea (north) to Kazakhstan (south). The remnants of the early Paleozoic subduction-accretion complexes occur along a suture zone between the East European and the West Siberian cratons (Spadea and D'Antonio, 2006; Pushkov, 2009). We have included three Uralian ophiolites, the Nurali, Magnitogorsk and Kempersay (Fig. 1, Table 1), in this synthesis.

2.4. Maghrebian-Alpine-Himalayan belt

The Magrhebian-Alpine-Himalayan belt, also referred to as the Alpides, extends from Morocco in the west, through the European Alps, the Anatolides, Zagros, Makran, and the Himalayas in the east, defining an orogenic belt with a length of ca. 9000 km. The