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Editorial

Ophiolites and ophiolitic mélanges: Archives of Precambrian and Phanerozoic plate tectonics in orogenic belts

1. Rationale

Ophiolites and ophiolitic mélanges are among the key tectonic components of both accretionary- and collisional-type orogenic belts around the world, representing significant archives of the evolutionary history of the Earth. These tectonostratigraphic units are not simple rock assemblages; their formation and coexistence require specific geological conditions and environments, internal and external Earth processes, and preservation during certain time intervals in the past. Therefore, they offer most valuable insights and windows into the Earth's history. They occur widely in the Precambrian and Phanerozoic accretionary and orogenic belts, delineating major boundaries between disparate terranes, crustal blocks, and even lithospheric plates. Most geoscientists have traditionally considered these boundaries as '*suture zones*', and hence ophiolites and mélanges have been accepted as the signature hallmarks of suture zones, and the sites of former subduction and collision zones in orogenic belts (Dewey, 1977; Dilek, 2006; Festa et al., 2010; Furnes and Dilek, 2022).

Unlike their 1972 Penrose definition (Anonymous, 1972), ophiolites do not fit into a simple and uniform template of an oceanic lithosphere template (Dilek, 2003). They are highly diverse structurally, geochemically, and in terms of their tectonic settings of formation (Dilek and Furnes, 2011, 2014). The differences among different ophiolite types reflect variations in seafloor spreading rates, magma budgets, mantle melt sources and melting conditions, the extent of subduction influence on the melt column, and slab dip angle beneath oceanic spreading centers (Dilek and Furnes, 2014). Therefore, the stratigraphic and structural architecture, lithological makeup, and geochemical characteristics of ophiolites can provide significant information about: (i) the mode and tempo of magmatic and tectonic processes during oceanic crust generation; (ii) the pressure–temperature–time paths during the metamorphic evolution of ancient oceanic lithosphere within subduction zones; (iii) the fluid flux and element recycling in subduction–accretion systems. On the other hand, the stratigraphic and structural architecture, lithological makeup, and geochemical characteristics of ophiolitic mélanges can provide significant information about: (i) the processes of mélange formation during the accretion of fragments of oceanic lithosphere at both shallow and deep structural levels at slab interface in subduction zones; (ii) sedimentological, erosional and other physical processes that occur during the accretion of oceanic lithosphere into continental margins (Dilek and Furnes, 2011; Safonova et al., 2016; Festa et al., 2019, 2022; Furnes et al., 2020).

2. Organization of this special issue

The contributions in this Special Issue present case studies of various Precambrian and Phanerozoic ophiolites and ophiolitic mélanges exposed in different parts of the world (Fig. 1), discussing the nature and timing of Earth processes involved in their formation and how they were incorporated into accretionary and collisional orogenic belts. We have organized this Special Issue in five sections, according to the geographic locations of the case studies reported in the papers.

The first section includes four research papers on different ophiolite and ophiolitic mélange occurrences that are exposed along discrete suture zones in the Mediterranean Orogenic Belts. As such, these suture zones separate a series of ribbon continents, which were derived mainly from Gondwana (i.e., Apulia and Tauride Platform; Dilek, 2006), and represent distinct seaways within the Tethyan paleogeography (Dilek and Furnes, 2019). Two of the papers in this section focus on the geology of the Northern Calcareous Alps and the Western Carpathians (Fig. 1). The other two contributions deal with the internal structure of different suture zones within the Anatolian Peninsula, which occurs in a major transition from the Africa–dominated convergence front in the west to the Arabia–dominated convergence front in the east within the Alpine–Himalayan orogenic belt (Fig. 1).

The second section involves two case studies from the eastern Mediterranean region to the north of the Persian Gulf that represent the central sector of the Alpine-Himalayan orogenic system (Fig. 1). These orogenic belts include ophiolites and ophiolitic mélanges recording the complex tectonomagmatic evolution of the Neotethyan Ocean from its opening between the Arabian and Eurasian plates and its closure with multiple subduction zones associated with the northward drift of the Arabian plate.

The third section includes three papers documenting ophiolite and ophiolitic mélanges from two different Orogenic belts in Asia (Fig. 1) that are characterized by several suture zones formed from multi-stage related closure of oceanic basins and continental plates collision during a long-lived geodynamic evolution of the Neoproterozoic-Paleozoic Paleo-Asian Ocean (Junggar region) and the Mesozoic Neotethyan Ocean (Southern Tibet).

The fourth section includes a review of the Catalina Schist mélange within the westernmost part of the North American Cordillera. This mélange records tectonic and chaotic rock formation processes along a subducting plate interface between the downgoing Farallon plate and the North American continent in the upper plate during the Cretaceous. The fifth and last section

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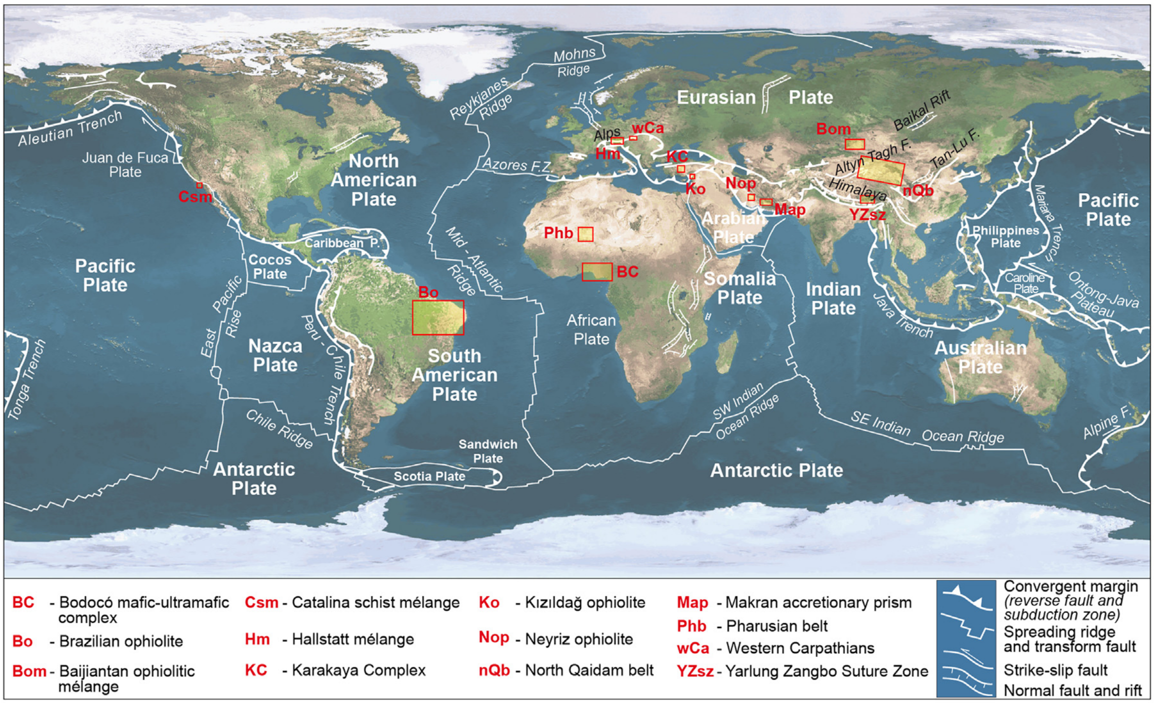

Fig. 1. World map showing the distribution of lithospheric plates, their boundaries (modified from Dilek et al., 2012), and the case studies of ophiolite and mélanges covered by the papers in this Special Issue (marked by red boxes).

includes a review paper dealing with the remnants of a Neoproterozoic oceanic lithosphere in the Precambrian orogenic belts in NE Brazil and NW Africa (Fig. 1).

In the following section, we first provide a brief nomenclature for the concepts of ophiolites and ophiolitic mélanges as a prelude to the ideas and interpretations presented in the papers. In the second part, we provide a synoptic review of the main topic, objectives, and findings of each paper in this Issue.

3. Nomenclature: ophiolite and ophiolitic mélange concepts

3.1. Definition of an ophiolite

The French mineralogist Alexandre Brongniart (1770–1847) used the term “ophiolite” for the first time in 1813 in reference to serpentinites in mélanges. In his 1821 paper he redefined an ophiolite (Brongniart,1821) as a suite of magmatic rocks (ultramafic rocks, gabbro, diabase, and volcanic rocks) that are exposed in the Apennines (Italy). He was, thus, the first geologist to recognize the significance of the coexistence ophiolites and mélanges in the field to signal their spatial association. However, it was Gustav Steinmann (1856–1929), who redefined the “ophiolite” term as a new concept representing spatially associated and genetically related rocks that formed as *in-situ* intrusions in axial parts of geosynclines (Steinmann, 1927). Although his interpretation of ophiolites as magmatic intrusions in deep marine sedimentary rocks was incorrect, his recognition of tripartite oceanic rocks as part of a magmatic sequence was highly insightful and important. This recognition helped many geologists around the world to be aware of the existence of these kindred rock assemblages in the mountain belts and ultimately led to the 1972 Penrose definition of ophiolites (see, Dilek, 2003 for the historical perspective).

A great number of multidisciplinary research on worldwide ophiolite since the first definition of this concept in 1821 (Brongniart, 1821) has for sure contributed to major advance in the scientific understanding of ophiolite and its rigorous classification based on forming processes and geodynamic setting of formation. In light of these data sets and observations, Dilek and Furnes (2011) proposed a new classification of ophiolites based on their distinctive internal structures, geochemical signatures, and regional tectonics. In this classification system, an ophiolite is as “an allochthonous fragment of upper-mantle and oceanic crustal rocks that is tectonically displaced from its primary igneous origin of formation as a result of plate convergence. Such a slice should include a suite of, from bottom to top, peridotites and ultramafic to felsic crustal intrusive and volcanic rocks (with or without sheeted dikes) that can be geochronologically and petrogenetically related; some of these units may be missing in incomplete ophiolites” (Dilek and Furnes, 2011). The major novelty of this classification lies in the fact that the diversity in the structural–stratigraphic architecture and geochemical fingerprints observed in ophiolite is related to variations of petrological, geochemical, and tectonic processes operating during ophiolite formation in different geodynamic settings. Thus, this modern classification of ophiolites provides as the first order criteria the geodynamic setting of formation, distinguishing the subduction-unrelated and subduction-related types. This classification has been effective for the recognition of different ophiolites in Phanerozoic and Precambrian accretionary and orogenic belts and to constrain their geodynamic evolution.

3.2. Definition of mélange and ophiolitic mélange

The term mélange was first used by Greenly (1919) in describing a tectonically disrupted and internally strained phyllite-sandstone succession in the Mona Complex (Gwna Group) in Anglesey, north Wales. Since its first introduction, this term has been extensively used to describe the occurrence of chaotic rocks assemblages, typically occurring in modern and exhumed (ancient) subduction – accretion complexes in orogenic belts. Several classification schemes and terminology have been made to categorize these chaotic units on the basis on field observations in different mélanges around the world (e.g., Berkland et al., 1972; Wood, 1974; Silver and Beutner, 1980; Raymond, 1984; Cowan, 1985; Pini, 1999; Festa et al., 2010, 2019, 2022 and references therein). According to these classifications, the term "mélange" should be used as a descriptive and nongenetic term to define mappable (at 1:25,000 or smaller scale) chaotic units composed of exotic rock blocks embedded in a pervasively deformed matrix. The term "exotic" includes all types of blocks that are "foreign" (i.e., out-of-place) with respect to the matrix, indicating that their source is not present in the surrounding lithological units and in the countryside within a mélange zone (Festa et al., 2019, for details). Mélanges may form through tectonic, sedimentary, and diapiric processes that facilitate mixing of exotic blocks within a matrix. The alternation and superposition of these processes through geological times and cycles commonly rework the structural fabric of different types of mélanges, producing polygenetic mélanges (e.g., Festa et al., 2019, 2020, and references therein). A rigorous definition of the term ophiolitic mélange is still lacking in the literature, and it is commonly used with different meanings to indicate tectonic elements of accretionary and collisional belts, in which fragments of ophiolites are mixed with different sedimentary rocks. This term is commonly used to define either chaotic rock units with a matrix enclosing blocks of an ophiolitic suite or an assemblage of different ophiolitic blocks tectonically juxtaposed without a clearly defined matrix (e.g., McCall, 1983; Elter et al., 1991; Kimura and Mukai, 1991). It is also very common that this term is used to refer to the products of tectonic dismembering of ophiolite suites.

4. Ophiolites and ophiolitic mélanges in Mediterranean Orogenic Belts

Drvoderic et al. (2023 – in this issue) defines and describes the Hallstatt Mélange in the Northern Calcareous Alps. This mélange consists of blocks derived from an Upper Triassic carbonate sequence of Adria continental margin and blocks and clasts of ophiolitic subunits and radiolarite originated from Neotethys, all of which are embedded in a matrix made of an upper Middle–lower Upper Jurassic argillite–radiolarite. The Hallstatt mélange appears to have formed as a result of a complex interplay between tectonic and sedimentary processes during the closure of Neotethys, ophiolite obduction, and tectonic stacking during the Mid to Late Jurassic. The interpretations and the tectonic model presented in this contribution provide new constraints for the Triassic–Jurassic geodynamic evolution of the Dinaride–Hellenide segment of the Alpine orogenic belt.

Putiš et al. (2023 – in this issue) present new petrological, geochemical, and geochronological data on meta-basaltic rocks from the Meliatic Bôrka Nappe in the Western Carpathians. Thermobarometric modelling results indicate that analysed rocks reached blueschist facies P–T conditions at a subduction interface, and that they were subsequently emplaced within an accretionary wedge of a Meliatic subduction zone. Based on the lithological types and metamorphic facies conditions the authors suggest the subdivision of the Inner Carpathian belt into two distinct accretionary wedges: one corresponds to the Late Jurassic – Early Cretaceous Meliatic–Gemeric–Veporic accretionary wedge with a *Neotethyan affinity*. The other one represents the Late Cretaceous – Eocene Fatric–Tatric–Infratatric wedge, defining the Alpine or Atlantic Tethys domain. Thus, the Inner Carpathians may represent a tectonic locale where two different Tethyan ocean domains may have intersected during the Late Mesozoic and earliest Cenozoic.

Sayit (2023 – in this issue) provides new geochemical data from Triassic mafic and ultramafic mega-blocks within a clastic mélange, which makes up a significant component of the Karakaya Complex, exposed in the Imrahor area near Ankara (north–central Turkey). Both ocean-island basalt – (OIB) and enriched mid-ocean ridge basalt – (E-MORB) type mafic rocks coexist in the mélange representing the products of partial melting of metasomatized oceanic lithospheric mantle, which was infiltrated by very low-degree melt fractions. These findings point to the chemical heterogeneity of the Neotethyan mantle even during the very early stages of the development of Neotethys and are consistent with similar findings reported from the Jurassic and Cretaceous mafic rock units within the Ankara Mélange exposed in the same region (Sarıfakıoğlu et al., 2014, 2017).

Simsek et al. (2023 – in this issue) presents the results of their geochemical analyses and ion-probe U-Pb zircon dating of various crustal rocks (plagiogranites, isotropic gabbros, and dikes) in the Cretaceous Kızıldağ ophiolite in southern Turkey. The new geochronological data show that the Neotethyan oceanic crust preserved in this ophiolite developed in a very short time span (i.e., within ~2 million years) between 92.9 ± 0.52 and 93.83 ± 0.46 Ma. The geochemical data presented in this paper and reported in earlier publications (Dilek and Furnes, 2009; Dilek and Thy, 2009) support the magmatic development of the Late Cretaceous Kizildag oceanic crust in a forearc tectonic setting of a North–dipping Neotethyan slab, analogous to the evolution of the coeval Troodos ophiolite to the southwest (Pearce and Robinson, 2010; Furnes et al., 2020). Rapid construction of forearc oceanic crust in a slab rollback tectonic setting during the very early stages of subduction initiation is a significant concept that is supported by most recent observations and data from *in-situ* subduction systems (i.e, the Izu–Bonin–Mariana forearc; Ishizuka et al., 2014) and the Oligocene ophiolites in the West Philippines orogenic belt (Yu et al., 2020, 2022).

Hall and Thomas (2023 – in this issue) report the occurrence of scarn (or tactite) at the contact between serpentinized peridotides of the the Neyriz ophiolite and the underlying recrystallized limestone within in the Zagros orogen in southern Iran. The origin of these rocks has been a subject of debate in the literature. The authors provide a synoptic review of the extant interpretations on the origin of these skarn rocks, and then present their field observations on their contact relationships, electron microprobe data on mineral compositions, and Raman micro-spectroscopy data from melt inclusions in the skarn minerals. They propose that the scarn rocks beneath the Neyriz peridotites represent a contact metamorphism zone in which the hot upper mantle rocks came into contact with the extended passive margin carbonates during the emplacement of the ophiolite.

Saccani et al. (2023 – in this issue) present a new interpretation for the origin of Early Cretaceous ophiolites in the Makran Accretionary Prism in SE Iran that is significantly different from what the current models suggest (i.e., Moslempour et al., 2015; Omrani et al., 2017). Using their new mineral chemistry, geochemical, and petrological data from the Remeshk–Mokhtarabad and Fannuj–Maskutan ophiolites, Saccani and co-authors show that the crustal rock units in these ophiolites have N-MORB and E-MORB geochemical affinities, suggesting a mantle source that was in places variably metasomatized and enriched by plume-type (OIB-) components. Similar findings have been reported previously from different domains of the Alpine–Himalayan orogenic belt (i.e., Saccani et al., 2015). The inferred enrichment might have occurred due to ridge–plume interactions beneath an oceanic spreading center, far from any subducting slab influence. If so, the mantle enrichment patterns deduced by high Ti, P, Y contents, significant Nb depletion, and higher Th/Ta and LREE/HREE ratios compared to MORBs may not necessarily characterize the influence of subducted slab derived fluids and melts beneath a backarc basin (Moslempour et al., 2015). These different interpretations of the melt evolution of the Makran ophiolites have important implications for the paleogeography of the Southern Neotethys and should be tested with further research on other Makran ophiolites in SE Iran and SW Pakistan.

5. Ophiolites and ophiolitic mélanges in Asian Orogenic Belts

Zhang et al. (2023 – in this issue) utilize detailed geological mapping, structural observations, and geochronological and geochemical analyses to characterize the age and geochemical affinities of magmatic rocks in four ophiolitic mélanges in the Junggar region of NW China. These ophiolitic mélanges include blocks of mafic and felsic rocks derived from different ophiolitic subunits incorporated into a matrix composed of argillaceous and serpentinite. The matrix displays tectonic imbrication and extensive ductile to brittle deformation fabrics. Ophiolitic material represents both subduction–influenced and non–subduction related crustal material, indicating the juxtaposition of oceanic crust originated from different tectonic settings during the assembly of tectonic mélanges via subduction–accretion and post–ophiolite emplacement, intracontinental deformation events. Thus, the mélange occurrences in the region keep a record of magmatic and tectonic events that were associated with rifting, subduction zone, ocean closure, and post–ophiolite emplacement stages during the development of the Junggar basin and its surrounding orogenic belts.

Xie and Dilek (2023 – in this issue) present new U-Pb detrital zircon ages, internal stratigraphy, depositional history, and tectonic model for the Upper Cretaceous – Lower Cenozoic Liuqu Conglomerate in southern Tibet. The Liuqu Conglomerate is a ∼5–km–thick terrestrial deposits, composed entirely of fluvial and alluvial fan deposits developed within an orogen-parallel transtensional basin that formed exclusively within the Yarlung Zangbo Suture Zone. This suture zone marks the collision front between the Tethyan Himalaya, which is rifted passive margin of Greater India, and the Late Jurassic–Cretaceous Trans-Tethyan arc-trench system within Neotethys. The results of new U-Pb detrital zircon dating of sandstones from the Liuqu Conglomerate reveal a youngest zircon age of 307 ± 13 Ma and an oldest zircon age of 3362 ± 51 Ma, with and age spectrum and peaks pointing to East Gondwana as the likely provenance of Liuqu sediments. The lack of any detrital zircon grains and clastic material originated from the Gangdese Magmatic Belt or the Lhasa block further points to the distal position of the Liuqu Conglomerate depocenter to the active margin of Eurasia. The complete, sedimentological, stratigraphic, structural, and geochronological record of the Liuqu Conglomerate support a Late Cretaceous arc-continent collision in sub-tropical latitudes within Neotethys, followed by a continent-continent collision between Greater India and Asia during the Oligo-Miocene. The tectonic model proposed in this paper is significantly different from most of the existing models on the collision history of the Tibetan–Himalayan orogenic belt in that the depositional, structural and tectonic history of the Liuqu geochronometer within the Yarlung Zangbo Suture Zone in Southern Tibet indicate two discrete collision events, first between an intraoceanic arc–trench system with the northern edge of Greater India in the Latest Cretaceous, and the second event between the Indian sub-continent with its accreted arc and the convergent margin of Asia in the Oligo–Miocene. This model of two separate subduction zone systems within Neotethys to the north of India that facilitated two separate and discrete collision events explains better why India's northward motion towards Asia in an accelerated mode throughout the late Mesozoic, and why the Xigaze basin was mainly the forearc basin of the Gangdese Magmatic Belt.

Fu et al. (2023 – in this issue) document the occurrence of polymetallic ore deposits in an Early Cambrian ophiolite exposed in the Lüliangshan area in the northern Tibetan Plateau. The Early Paleozoic ophiolite here consists of serpentinized peridotites, pyroxenite, chromitite, dolerite dikes that are spatially associated plagiogranite intrusions, lavas, chert, and limestone. The lavas that are intercalated with fine–grained clastic rocks host massive sulfide deposits. The authors propose that the Lüliangshan ophiolite and its massive sulfide deposits developed in a forearc setting during the early-stages of subduction within the Proto-Tethys Ocean in the early Cambrian. This massive sulfide ore formation within a forearc ophiolite, as reported in this contribution, is reminiscent of similar Cu deposits and their genesis in the Late Cretaceous Troodos ophiolite in Cyprus (Eddy et al., 1998).

6. Ophiolitic mélanges in the Western North American Cordillera

Penniston-Dorland and Harvey (2023 – in this issue) provide a review of the geology of the Cretaceous Catalina Schist, exposed on the Channel Islands off the Coast of Los Angeles in southern California, and discuss its origin along a subduction plate interface between the Farallon oceanic plate and the North American continent. The Catalina Schist represents an exhumed subduction complex that is composed of up to kilometer-scale sequence of both the downgoing slab and overring plate separated by mélanges with block-in-matric structures. The authors' geochemical data support the evidence of mechanical mixing of blocks in the matrix and elemental redistribution by fluid-rock interactions during fluids circulation along the plate interface shear zone. The observations, interpretations and discussions presented in this paper show effectively how the combination of deformation and fluid circulation patterns along subduction plate interface may impact seismic behaviour at convergent margins and may also influence the melt evolution and chemistry of arc magmas in the upper plate.

7. Ophiolites and ophiolitic mélanges in Precambrian orogenic belts in South America and West Africa

The Borborema province in NE Brazil consists of an amalgamation of high–grade Proterozoic metamorphic rocks (gneissic and migmatitic), metamorphosed supracrustal rocks, and Brasiliano intrusions that are dissected by numerous E–W– to NE–SW–oriented shear zones and strike–slip fault systems. These shear zones include mafic–ultramafic rock bodies and meta-sedimentary rocks and continue into the Cameroon, and East and West Nigerian Provinces to the east in Western Africa. These mafic–ultramafic rocks represent highly disfigured ophiolites of possible Pan–African origin. de Lira Santos et al. (2023 – in this issue) present new structural field observations, mineral, geochemical, isotopic data from some of these deformed ophiolitic subunits in the Borborema province, and propose that ophiolitic rocks may represent the remnants of intraoceanic and intracontinental rifting products, which subsequently became part of the Western Gondwana supercontinent as the Amazonian, West African, and São Francisco/Congo cratons were sutured. The geology of the Borborema province with crustal–scale shear zones containing ophiolitic rocks is reminiscent of the geology of the Arabian–Nubian Shield in eastern Africa (Dilek and Ahmed, 2003).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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