

The ‘subduction initiation rule’: a key for linking ophiolites, intra-oceanic forearcs, and subduction initiation

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Abstract We establish the ‘subduction initiation rule’ (SIR) which predicts that most ophiolites form during subduction initiation (SI) and that the *diagnostic* magmatic chemostratigraphic progression for SIR ophiolites is from less to more HFSE-depleted and LILE-enriched compositions. This chemostratigraphic evolution reflects formation of what ultimately becomes forearc lithosphere as a result of mantle melting that is progressively influenced by subduction zone enrichment during SI. The magmatic chemostratigraphic progression for the Izu–Bonin–Mariana (IBM) forearc and most Tethyan ophiolites is specifically from MORB-like to arc-like (volcanic arc basalts or VAB ± boninites or BON) because SI progressed until establishment of a mature subduction zone. MORB-like lavas result from decompression melting of upwelling asthenosphere and are the first magmatic expression of SI. The contribution of fluids from dehydrating oceanic crust and sediments on the sinking slab is negligible in early SI, but continued melting results in a depleted, harzburgitic residue that is progressively metasomatized by fluids from the sinking slab; subsequent partial melting of this residue yields ‘typical’ SSZ-like lavas in the latter stages of SI. If SI is arrested early, e.g., as a result of collision, ‘MORB-only’ ophiolites might be expected. Consequently, MORB- and SSZ-only ophiolites may represent end-members of the

SI ophiolite spectrum. The chemostratigraphic similarity of the Mariana forearc with that of ophiolites that follow the SIR intimates that a model linking such ophiolites, oceanic forearcs, and SI is globally applicable.

Keywords Ophiolites · Forearcs · Intra-oceanic arcs · Subduction initiation · Tethys · Izu–Bonin–Marianas arc

Introduction

Although ophiolites may form in many tectonic settings, a general consensus exists that most formed above a subduction zone (supra-subduction zone or SSZ ophiolites; Pearce et al. 1984; Pearce 2003). Evidence for the origin of many SSZ ophiolites increasingly points to forearc extension during the earliest stage of forming a new subduction zone. In particular, Late Jurassic (~165 Ma) and Late Cretaceous (~90 Ma) ophiolites in the Eastern Mediterranean–Persian Gulf region (Fig. 1a; Robertson 2004; Pearce and Robinson 2010; Moghadem et al. 2010) are often considered as ones formed during subduction initiation (SI; Shervais 2001; Stern 2004).

The recognition that most ophiolites have a SSZ origin is due in large part to the occurrence of basalts that are compositionally similar to those erupted in volcanic arcs (volcanic arc basalts (VAB) or island arc tholeiites (IAT)) and occasionally boninites, the latter of which are thought to form via melting of refractory mantle in SSZ environments (Crawford et al. 1989). Nonetheless, uncertainty about the tectonic setting where such ophiolites formed lingers due to the common occurrence of MORB-like lavas in addition to those more diagnostic of a SSZ setting. This geochemical duality is often explained as due to formation of the two suites in discrete tectonic environments (Bortolotti et al.

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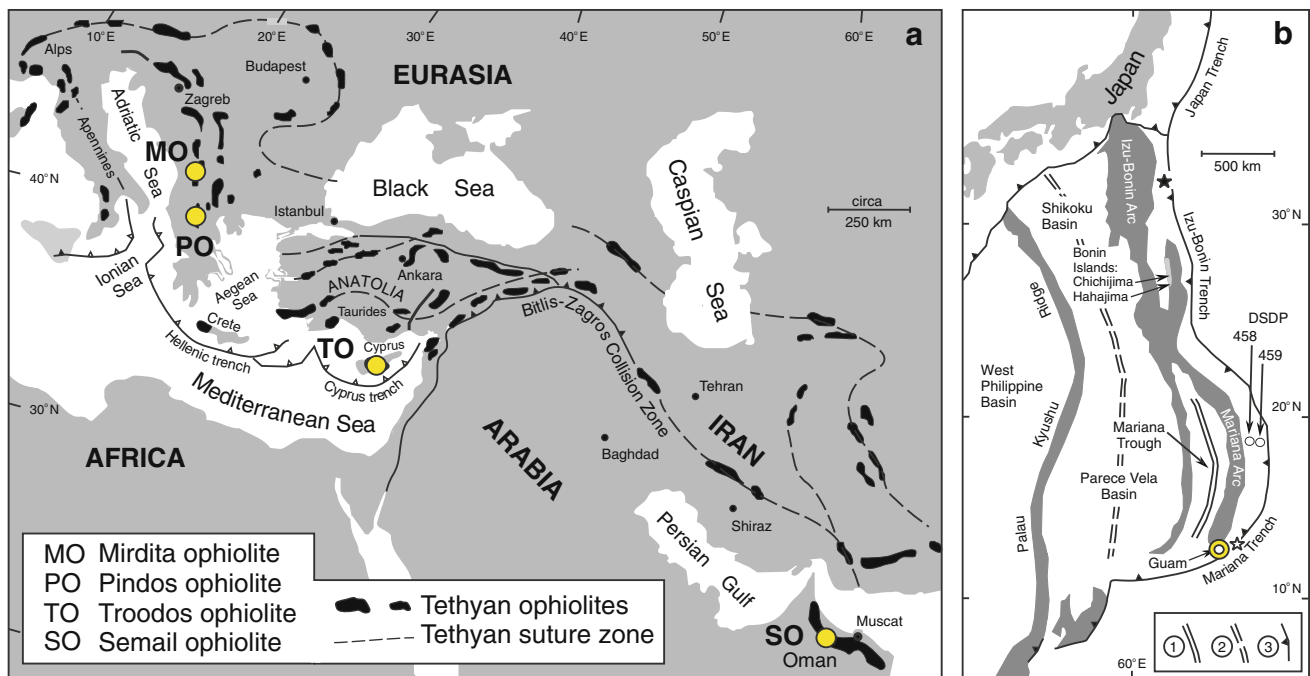


Fig. 1 **a** Tectonic map of the Eastern Mediterranean–Persian Gulf region (modified from Dilek et al. 2007) showing the distribution of Late Jurassic and Late Cretaceous Tethyan-type ophiolites. Stratigraphically studied ophiolites used here include the Mirdita (MO), Pindos (PO), Troodos (TO), and Semail (SO) ophiolites. **b** Location of the Izu–Bonin–Marianas arc system in the North Pacific (modified after Taylor 1992). The smaller circle inside the larger circle on the map encloses the island of Guam and the open star to the immediate

east of Guam represents the Mariana forearc region in which FAB and related rocks were recovered (Reagan et al. 2010); the filled star to the immediate east of the Izu–Bonin arc represents the region in which the dive sites of DeBari et al. (1999) were conducted. Circled numbers 1, 2, and 3 represent active spreading ridges, extinct spreading ridges and convergent margin or trenches (i.e., subduction zones), respectively

1996; Robertson and Shallo 2000; Shallo and Dilek 2003; Dilek and Flower 2003, Flower and Dilek 2003; Beccaluva et al. 2004; Saccani and Photiades 2004). More recently, the compositional bimodality has been ascribed to progressive depletion and metasomatism of a common melt source over the course of ophiolite formation (Shervais 2001; Beccaluva et al. 2005; Dilek et al. 2007, 2008; Dilek and Furnes 2009). In other words, all magmatic components (i.e., MORB, VAB, and boninite) may have formed in the same proto-forearc environment, which witnessed eruption of MORB-like lavas followed by VAB and boninites.

We show below that the best-studied Tethyan ophiolites comprise a lower succession of tholeiitic, MORB-like lavas overlain by VAB/IAT and sometimes boninite units. As boundaries between the lower and upper units are conformable and not fault bounded, the geochemical duality observed in these ophiolites reflects progressive evolution of the mantle source and not superimposed tectonic settings.

Crucially, we can now compare ophiolite chemostratigraphy (vertical variations in lava chemistry) with that of the Izu–Bonin–Mariana (IBM) forearc (Fig. 1b; Reagan et al. 2010). The IBM forearc formed during the Eocene (~50 Ma; Ishizuka et al. 2006) as subduction of the Pacific Plate beneath the eastern Philippine Sea Plate began. Vast

regions of this forearc near Guam are floored by tholeiitic MORB-like basalts (forearc basalt or FAB of Reagan et al. 2010) that dominate the inner trench wall between 6,500 and 2,500 m depth (Reagan et al. 2010). Similar basalts recovered from the base of Mariana forearc DSDP sites 458 and 459 drill cores (Meijer et al. 1980, 1982), from diving in the Izu forearc (DeBari et al. 1999) and Bonin forearc near Hahajima seamount (Ishiwatari et al. 2006) (or “Ogasawara Paleoland”, Ishii 1985) were reinterpreted by Reagan et al. (2010) as the tops of a FAB sequence. At each locality, FAB underlies and/or is trenchward of boninites and younger arc lavas (Reagan et al. 2010). The IBM forearc thus exhibits a similar chemostratigraphy to that of well-preserved and well-studied Tethyan ophiolites. These observations allow new insights into the relationship between ophiolites, forearcs, and subduction initiation (SI) that can be encapsulated as the subduction initiation rule (SIR).

The subduction initiation rule

We use the term ophiolite to refer to an on-land remnant of allochthonous or autochthonous ancient oceanic crust and upper mantle incorporated into an orogenic belt. In the

former case, ophiolite emplacement occurred upon a former continental margin via collision; in the latter case, the ophiolite was gradually exposed in situ as a result of underplating of buoyant intra-oceanic crust or due to isostatic uplift when subduction stopped. For ophiolites that form in forearcs, it can be difficult to determine whether the ophiolite is autochthonous or allochthonous, but for our purposes it does not matter, even though the base of all true ophiolites is marked by a thrust fault.

Here, we articulate the ‘subduction initiation rule’ (SIR): that magmatic sequences preserved in ophiolite volcanic sections record a stratigraphic progression (from bottom to top) from less to more HFSE-depleted and LILE-enriched compositions and (a) generally comprise a lower, usually MORB/FAB unit and an upper VAB unit, sometimes along with boninites, both of which (b) form in a proto-forearc setting during subduction initiation (Fig. 2). An exception to this general trend is the Troodos ophiolite. The lower lavas of Troodos are more VAB-like than MORB-like; however, the lower lavas are clearly less HFSE-depleted and LILE-enriched than the upper lavas and hence exhibit an identical chemostratigraphic progression as other SIR ophiolites and the Marianas forearc, which yield lower lavas that more closely resemble MORB. The MORB/FAB tholeiites form first as oceanic lithosphere begins to sink accompanied by seafloor spreading along the margin of the adjacent plate. This seafloor spreading occurs as asthenosphere floods over the sinking plate into the widening void above, melting due to decompression (Fig. 2b). For the most part, these early basalts are chemically indistinguishable from MORB. Fluid contribution from the sinking slab to depleted MORB-type mantle (DMM) asthenosphere is minor during earliest SI. Similar basalts comprise the sometimes thicker lower magmatic succession of most Tethyan ophiolites. If SI progresses unabated—as was the case for Tethyan ophiolite formation—more recognizable ‘SSZ’ lavas, i.e., VAB/IAT ± boninites form at a later stage of SI via slab-derived, fluid-assisted melting of an increasingly depleted and metasomatized harzburgitic residue (Fig. 2c).

As we will show, most ophiolites follow the SIR; those that do not are mostly the ones that lack a complementary mantle or uppermost crustal section (e.g., Chilean and Ligurian ophiolites, respectively).

Methods

We compile whole-rock geochemical data from lavas and dykes of four well-studied Tethyan ophiolites: Mirdita (Dilek et al. 2008), Pindos (Saccani and Photiades 2004), Troodos (Flower and Levine 1987), and Semail (Alabaster et al. 1982; Ishikawa et al. 2002; Godard et al. 2003), and

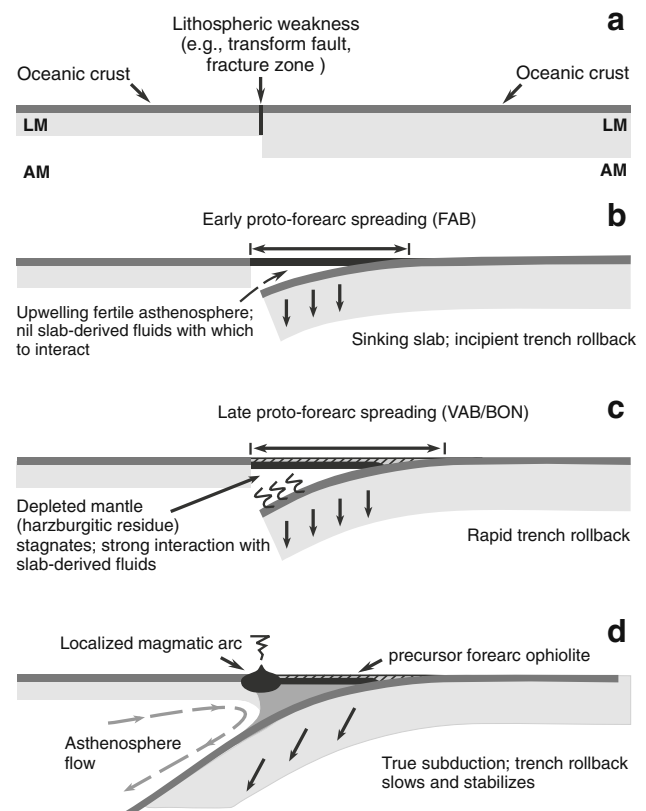


Fig. 2 Cartoon depicting the generation of Tethyan-type ophiolites and intra-oceanic FAB and related forearc rocks during subduction initiation, based on the subduction infancy model (Stern and Bloomer 1992 as modified by Metcalf and Shervais 2008). The volumetrically dominant lower tholeiitic suite is generated in the earliest stages of subduction initiation via decompression melting of a fertile hercynitic (MORB-like) asthenospheric source; **b** contribution of fluids from the sinking slab during this stage is small. In contrast, the upper HFSE-depleted lavas and boninites are generated via melting of residual harzburgite that has been progressively depleted and hydrated **c** as the subduction initiation process continues. *BON* boninite, *FAB* forearc basalts (of Reagan et al. 2010), and *VAB* volcanic arc basalts in this and subsequent figures

from FAB and related lavas of the Mariana forearc (Reagan et al. 2010). We restrict our geochemical comparisons to lavas of these ophiolites and the Marianas forearc as the magmatic chemostratigraphy for these is adequately documented. Only representative lava samples constrained stratigraphically as being either lower or upper ophiolite/forearc lava section components of a cohesive unit and which have complementary lower or upper samples are used in our geochemical plots. This is essential because we are trying to evaluate chemostratigraphic variations (i.e., changes in magma chemistry with relative stratigraphic position and hence time). In most cases, this meant using only data from lavas. An exception is our use of ‘latest stage (ophiolite) dykes’. Such dykes can be used to evaluate chemotemporal variations, as these clearly cut both lower and upper pillow lava units (e.g., Dilek et al. 2008;

Saccani and Photiades 2004; Ishikawa et al. 2002). Compositional data have been filtered to include samples with reported major oxide totals of 98–102% and loss on ignition (LOI) < 7%. Total iron is expressed as FeO*, whereby Fe₂O₃ (usually measured on fused glass beads via XRF) was multiplied by 0.89. In our geochemical plots, oxides are reported as wt% and were recalculated and plotted on an anhydrous (volatile-free) basis where the oxide sum is normalized to 100%. Rare earth element (REE) and other trace element concentrations are expressed in ppm.

Establishment of the subduction initiation rule via Tethyan ophiolite chemostratigraphy

It is important to stress that the SIR established herein is based upon selected Tethyan ophiolites in which chemostratigraphic relations are sufficiently clear, thanks to many detailed studies over the past three decades. We do not think this geographic focus jeopardizes the significance of our conclusions. Arguably, no other ophiolite ‘type’ has been as scrutinized as the Tethyan ophiolites of the Eastern Mediterranean–Persian Gulf region. Indeed, the ophiolite concept itself was based largely upon field, petrological, and geochemical studies of the Semail and Troodos ophiolites (see Dilek 2003 and references therein).

Chemostratigraphies have been established for some of the best-preserved and best-studied Neotethyan ophiolites of the Eastern Mediterranean–Persian Gulf region in Albania, Greece, Cyprus, and Oman (the Mirdita, Pindos, Troodos, and Semail ophiolites, respectively). These ophiolites display vertical variations in lava chemistry that allow us to reconstruct how their magma sources evolved. Detailed stratigraphic relations and lava geochemistry (Figs. 3, 4, 5, 6, 7, 8, 9) of the Mirdita, Pindos, and Semail ophiolites illustrate lower units of FAB/MORB tholeiites overlain by predominantly calc-alkaline, high-field strength element (HFSE)-depleted, VAB/IAT lavas and rare boninites as latest stage dykes. We show in these same plots the recently documented chemostratigraphy of Izu–Bonin–Marianas forearc lavas (Reagan et al. 2010) and discuss the relevance of this in the next section.

Chondrite-normalized REE patterns for lower tholeiites of the Mirdita and Semail ophiolites are moderately depleted in light REE (LREE; Fig. 6). Relatively high total REE concentrations (up to ~30 × chondrite) indicate a relatively fertile (Iherzolitic) DMM asthenospheric source. Upper VAB/IAT lavas have much lower total REE (and especially HREE) contents, indicating derivation from a depleted (harzburgitic) mantle source. This probably reflects progressive melt depletion of the same mantle source that yielded FAB, as inferred by Morishita et al. (2011) for IBM forearc peridotites. Similar up-section

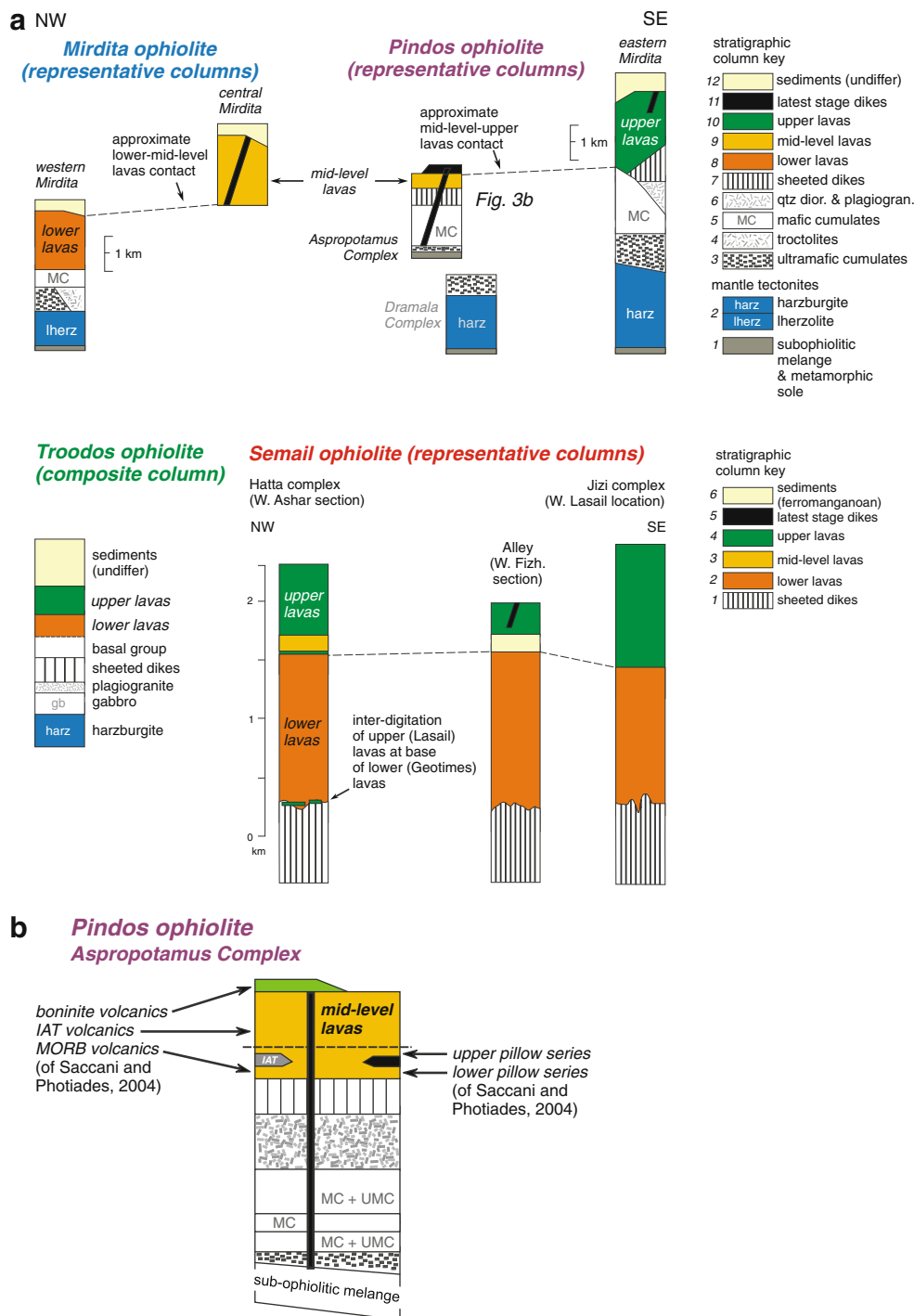
progressive depletion is seen in HFSE (e.g., Ti, Zr, and Y; Fig. 7). Th/Yb–Nb/Yb systematics demonstrate that all oceanic island basalts (OIB) and MORB plot within the N-MORB/E-MORB/OIB mantle array (shaded region, Fig. 8a). SSZ lavas, however, are displaced above the mantle array due to remobilization of Th from subducted sediments (Pearce 2008). The lower MORB-like lavas from our compiled datasets plot within or near the mantle array. Upper suite lavas and latest stage boninitic dykes, on the other hand, lie above the mantle array indicating progressive subduction-related enrichment of the ophiolitic mantle source with time.

On the Zr–Zr/Y discriminant plot (Fig. 8b; Pearce and Norry 1979), lower suite tholeiitic lavas plot almost exclusively as MORB, whereas upper suite lavas plot as VAB. The Ti/V discriminant plot (Shervais 1982) is similar; lower tholeiitic lavas have Ti/V = 50–20 typical of MORB, whereas upper calc-alkaline lavas have Ti/V = 20–10 characteristic of SSZ lavas (Fig. 8c). The upper lavas and latest stage dykes, which plot as boninites based on concentrations of MgO vs. TiO₂ (Fig. 5) have Ti/V < 10. On Cr/Y discriminant plots (Fig. 9), chemical comparisons are also similar to those in Fig. 8. For example, Mariana FAB and lower Mirdita lavas plot within the MORB field, whereas the stratigraphically higher, later-formed upper lavas and latest stage dykes of Mirdita and the upper Mariana forearc lavas plots instead along a VAB–boninite trend.

The Aspropotamus Complex of the Pindos ophiolite is considered as part of the Mirdita ophiolite on the basis of stratigraphic correlation with Central Mirdita (Fig. 2; Beccaluva et al. 2004). The volcanic section of the Aspropotamus Complex was subdivided into upper IAT and lower MORB sections with the latter further subdivided into lower and upper pillow series (LPS, UPS; Saccani and Photiades 2004) (Figs. 3b, 10). These “mid-level” lavas reflect a stratigraphic position midway between the lower lava suite of Western Mirdita and the upper suite of Eastern Mirdita (Fig. 3). Although both LPS and UPS lavas were identified as MORB (Saccani and Photiades 2004) and both series display REE patterns similar to lower Mirdita tholeiitic lavas (Fig. 10a), other geochemical plots (Fig. 10b–f) illustrate that the LPS only display a MORB-like affinity similar to the lower Mirdita tholeiitic suite; the UPS alternatively, display an affinity for VAB similar to the upper Mirdita calc-alkaline lavas. For example, the LPS have higher concentrations of HFSE (Zr, Y, and Ti) (Fig. 10c) than the UPS and plot within the mantle array on the Th/Yb–Nb–Yb diagram (Pearce 2008; Fig. 10d), whereas the UPS plot on the cusp of or above the mantle array. This relationship indicates progressive HFSE depletion and subduction zone enrichment with stratigraphic height and hence time, similar to the relationship

Fig. 3 a Representative and composite stratigraphic columns of the four Neotethyan ophiolites documented here, i.e., the Mirdita, Pindos, Troodos, and Semail ophiolites.

b Provides a more detailed representation of the Pindos ophiolite and the relative stratigraphic locations of the lower pillow series (LPS) and upper pillow series (UPS) of Saccani and Photiades (2004) (see also Fig. 10 for detailed chemostratigraphic evolution of the Mirdita-Pindos complex). *IAT* Island Arc Tholeiite and *MORB* Mid-ocean Ridge Basalts in this and subsequent figures. *UMC* ultramafic cumulates; other abbreviations (e.g., MC) are as in a



between the lower and upper lavas of Mirdita, Troodos, and Semail, but at a more modest scale.

There is no reported hiatus between the lower and upper lava sequences of any of these ophiolites, as might be revealed by an unconformity or intervening sedimentary layers, so this ophiolitic chemostratigraphy is unlikely to be due to different tectonic environments, for example, a mid-ocean ridge that became a convergent

margin. Such a tectonic reorganization should be reflected by an unconformity or hiatus marked by sedimentary layers, which is never seen. Similarly, as the transition between the two suites is commonly marked by lavas that are compositionally intermediate to MORB-like and VAB (e.g., Saccani and Photiades 2004), this chemostratigraphy appears to reflect the progressive evolution of the ophiolite-forming magmatic system. In the case of

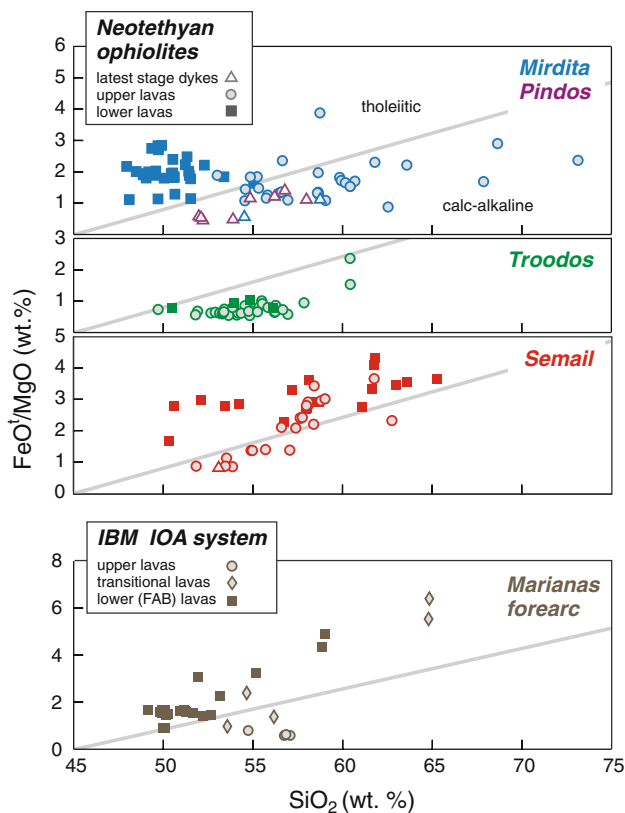


Fig. 4 Plot of data of stratigraphically constrained (i.e., lower vs. upper) subalkaline lavas and latest stage dykes of the Mirdita, Pindos, Troodos, and Semail ophiolites vs. FAB and related lavas of the Mariana forearc on the SiO_2 vs. FeO^*/MgO subalkaline affinity discrimination diagram (Miyashiro 1974). Datasets used here and in subsequent figures are cited in the “Methods” section. *IOA* Intra-oceanic arc. Note that the *symbol scheme* (as indicated on the plots) and the color scheme for the symbols in this and subsequent figures are the same, whereby Mirdita = blue, Pindos = purple, Semail = red, Troodos = green, and Marianas forearc = brown

these Tethyan ophiolites, such chemostratigraphy is characteristic; preservation of dual tectonic histories in an ophiolite may occur occasionally, but it is not likely to be common.

These observations are the basis of the SIR, which specifies that the expected magmatic chemostratigraphic progression recorded by a group of well-preserved and well-characterized ophiolitic lavas samples a mantle source region that evolves from less to more depleted and from less to more subduction influenced. In the case of many Tethyan ophiolites specifically, this progression is manifest as volcanic successions consisting of lower MORB-like and upper VAB-like suites that are closely related in space and time. This systematic progression records the products of a mantle melting regime that first taps upwelling asthenosphere but is increasingly influenced by inputs from the evolving subduction zone as the sinking lithosphere descends.

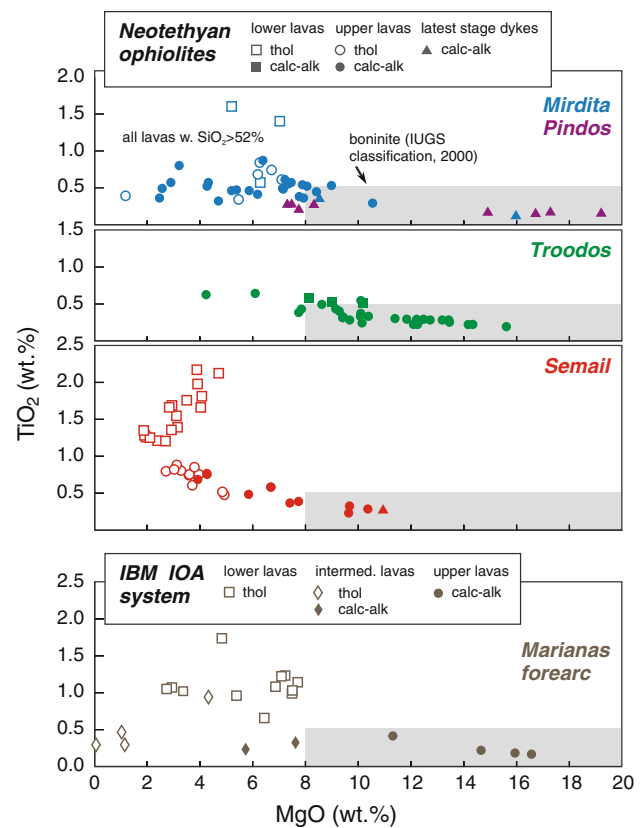


Fig. 5 Discrimination of ophiolite lavas and latest stage dykes and FAB and related Mariana forearc rocks with $\text{SiO}_2 > 52$ wt% into boninitic and non-boninitic affinities on the basis of MgO and TiO_2 wt% (Le Bas 2000). Boninites (boxed region, lower right-hand side) are lavas with $\text{SiO}_2 > 52$ wt%, $\text{MgO} > 8$ wt%, and $\text{TiO}_2 < 0.5$ wt%. Acronyms: *calc-alk* calc-alkaline, *IOA* intra-oceanic arc, *thol* tholeiitic. *Symbol color scheme* is as in Fig. 4

Comparison of subduction initiation rule ophiolites to Mariana forearc lithosphere

Here, we confirm and further illuminate the mantle and magmatic response to subduction initiation via comparison of those ophiolites that satisfy the SIR (SIR ophiolites) to the Mariana intra-oceanic forearc. This is the only place that we know where the igneous basement of an intra-oceanic forearc (Stern 2010) has been studied in sufficient detail to characterize its magmatic evolution. The Mariana forearc has become a focus of study because it formed in situ when subduction began ~ 50 Ma (Stern and Bloomer 1992; Ishizuka et al. 2006; Reagan et al. 2010). Mariana forearc lavas are compositionally similar to the Tethyan ophiolites we studied. For example, REE patterns of lowermost Mariana FAB are similar to those of lower Mirdita tholeiites, whereas upper Mariana forearc lavas generally plot with upper Mirdita VAB (e.g., Fig. 6). Most Marianas FAB show major element compositions similar to lower MORB-like

Fig. 6 REE concentrations of lavas and latest stage dykes of the Mirdita, Pindos, Semail, and Troodos ophiolites and lavas of the Mariana forearc normalized to chondritic concentrations (of Nakamura 1974). Gray-shaded fields on right side of plots represent the compositional fields displayed on the corresponding left-side plots. Symbol color scheme is as in Fig. 4

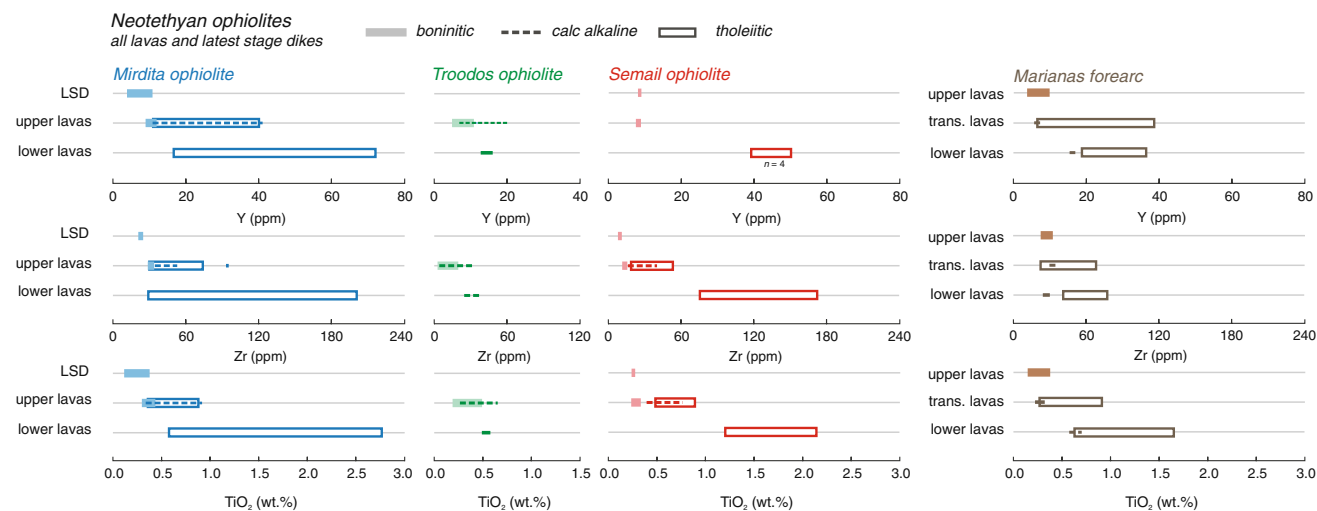
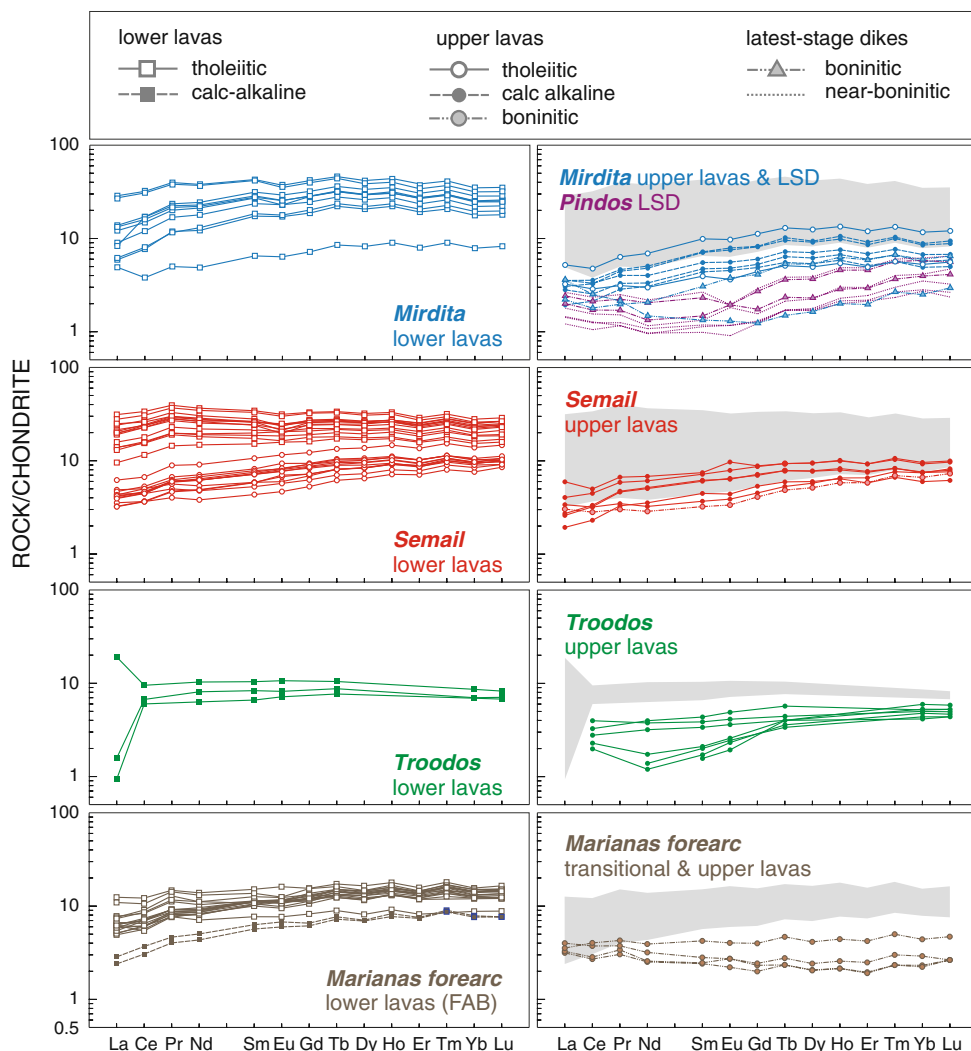


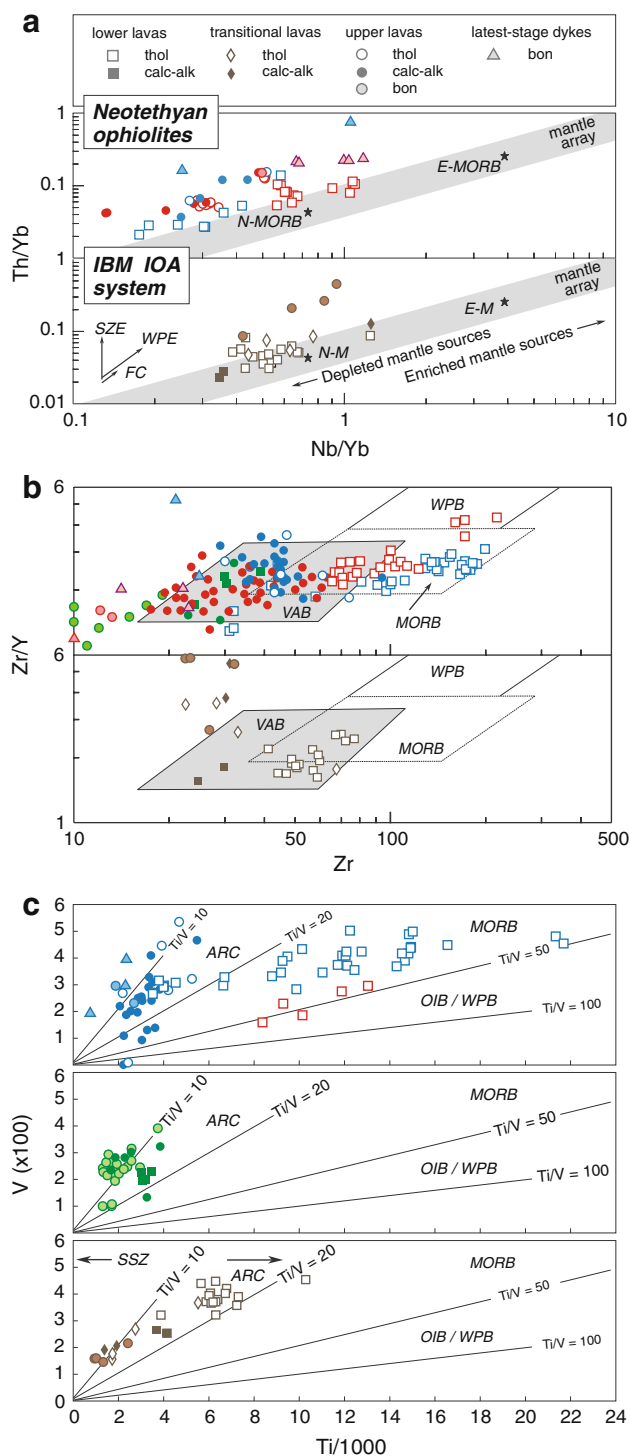
Fig. 7 Chemostratigraphic variation in TiO_2 (wt%), Zr (ppm) and Y (ppm) of lavas and latest stage dykes of the Mirdita, Pindos, Troodos, and Semail ophiolites and lavas of the Mariana forearc. Y axis

acronyms: LSD latest stage dykes; trans. lavas = transitional lavas. Symbol color scheme is as in Fig. 4

Fig. 8 Tectonomagmatic discrimination of lavas and latest stage dykes of Tethyan ophiolites and FAB and related rocks of the Mariana forearc on the basis of **a** Nb/Yb vs. Th/Yb (Pearce 2008), **b** Zr vs. Zr/Y (Pearce and Norry 1979), and **c** Ti/V (Shervais 1982). Note that in **a** N-, E-MORB, and OIB (oceanic island basalt, not indicated) compositions (Sun and McDonough 1989) plot along the mantle array (Pearce 1983). In **a**, vector SZE subduction zone enrichment; N-M, E-M normal, enriched mid-ocean ridge basalt (MORB); IOA intra-oceanic arc. In **b**, VAB volcanic arc basalt, WPB within-plate basalt. In **c**, MORB, OIB, and WPB as in **a** and **b**; SSZ supra-subduction zone. Symbols in **b** and **c** are as in **a** and color scheme for symbols is as in Fig. 4. As Oman data report V concentrations of only four samples, these are plotted together with Mirdita samples in **c**

lavas of the Mirdita and Semail ophiolites (Figs. 4, 5), whereas the overlying transitional basalts plot similar to both ophiolites' tholeiitic and calc-alkaline suites. A plot of MgO vs. TiO₂ (Fig. 5) effectively distinguishes Mariana FAB, transitional basalts, and boninites. Mariana FAB contains >0.5 wt% TiO₂ and plot within the field occupied by lower MORB-like Mirdita and Semail lavas. Conversely, Mariana forearc transitional basalts (average TiO₂ = 0.42 wt%) plot similarly to Mirdita and Semail upper lavas. Mariana forearc boninitic lavas plot similarly to late boninitic dykes of the Mirdita, Pindos, and Semail ophiolites.

On a Nb/Yb vs. Th/Yb plot, most Mariana FAB lie within or on the cusp of the mantle array indicating minor sediment-derived Th enrichment in their mantle source. In contrast, transitional Mariana forearc basalts and boninites manifest progressively greater Th enrichment (Fig. 8a). This evolution, reflecting progressive source depletion (lower HFSE concentrations) coupled with increasing source metasomatism (higher abundances of Th and LREE) is indistinguishable to that displayed by the well-characterized Tethyan ophiolites. The chemostratigraphic and temporal trend from early MORB-like/FAB to upper transitional and boninitic lavas is also apparent on the Zr vs. Zr/Y diagram (Fig. 8b). All Mariana FAB fall within the field occupied by lower tholeiitic lavas of the Mirdita and Semail ophiolites, whereas the transitional basalts and boninites generally plot near the fields defined by Tethyan ophiolite boninitic lavas and late dykes. Mariana FAB are similar to VAB based on Ti vs. V relationships, with arc-like Ti/V = 10–20, whereas all but two samples plot within the broad region defined by the lower tholeiitic lavas of the Mirdita ophiolite (Fig. 8c). The transitional basalts overlap the fields defined by upper ophiolite VAB and boninitic lavas, while the Mariana arc boninites plot entirely within the field of the upper ophiolite boninites. The similarity of SIR ophiolites to the Mariana forearc magmatic succession allows such ophiolites to be linked to nascent intra-oceanic forearc construction.



Which ophiolites do and do not follow the SIR and why?

When is an ophiolite not an ophiolite?

We reiterate that we use the term ophiolite to refer to an on-land remnant of ancient oceanic crust and upper mantle emplaced upon a former continental margin or other buoyant

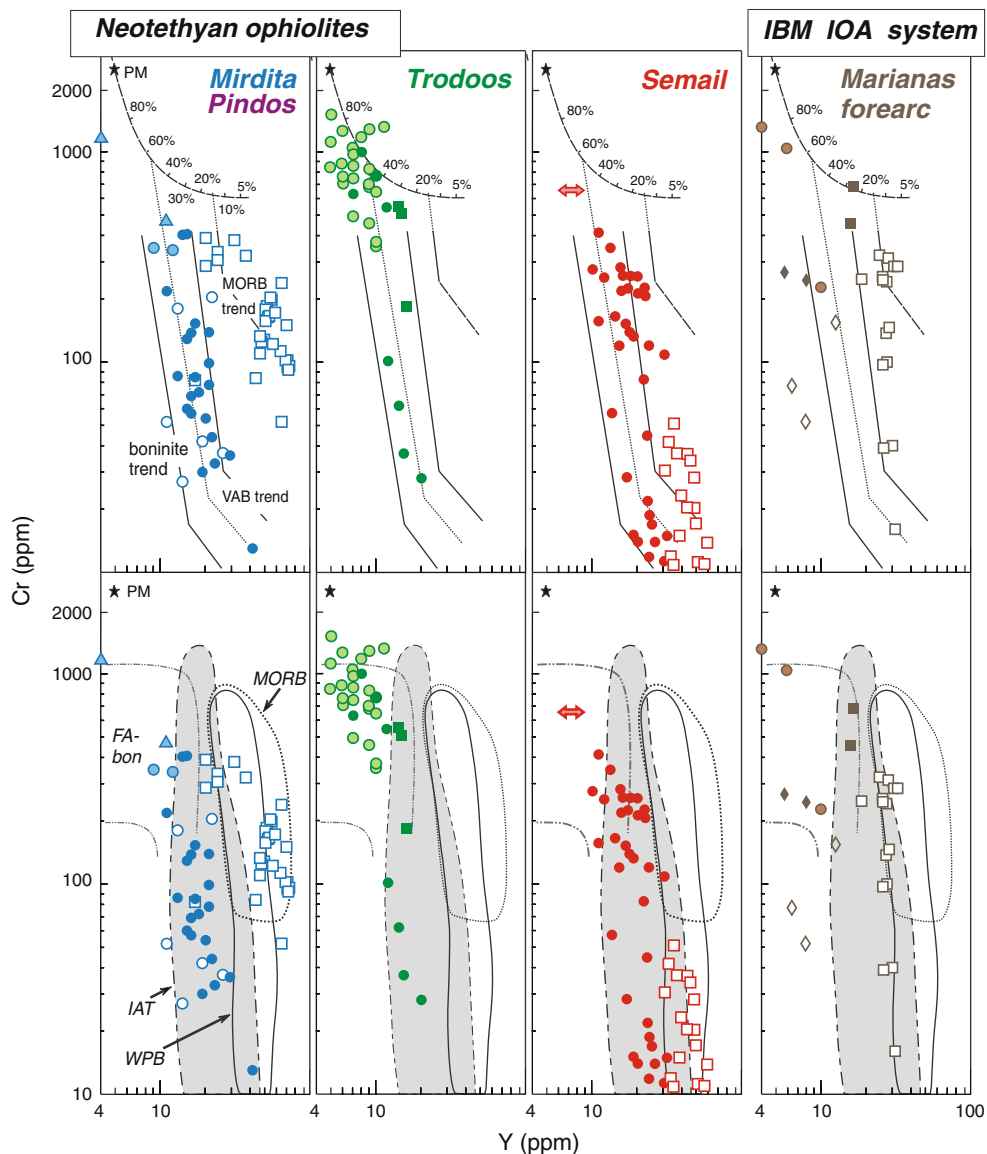


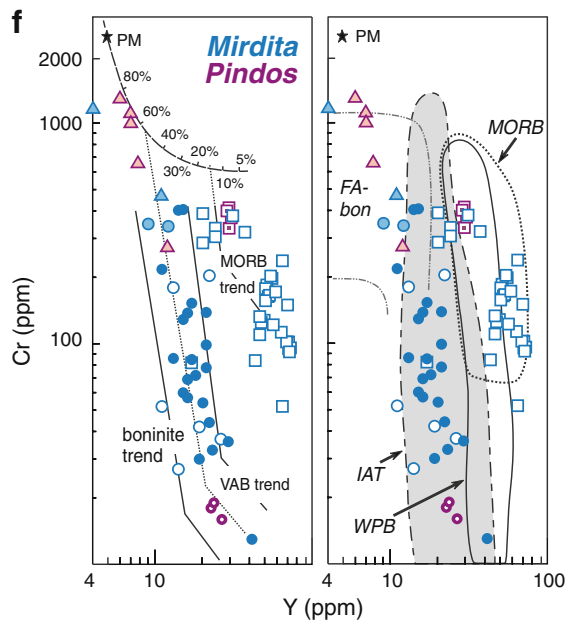
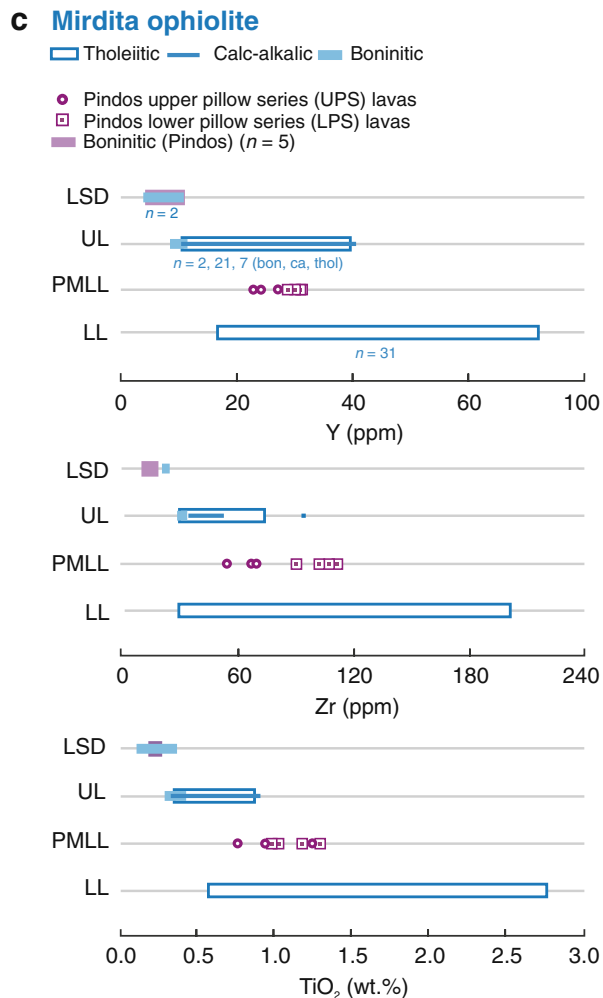
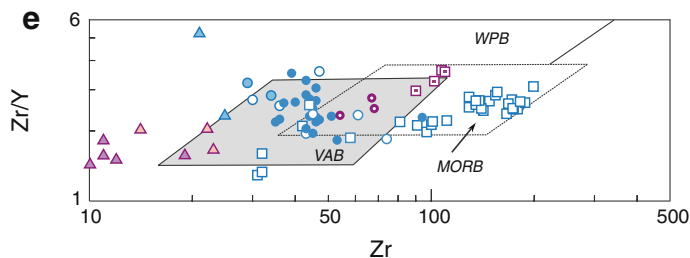
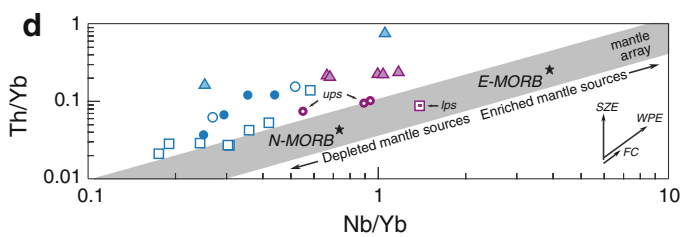
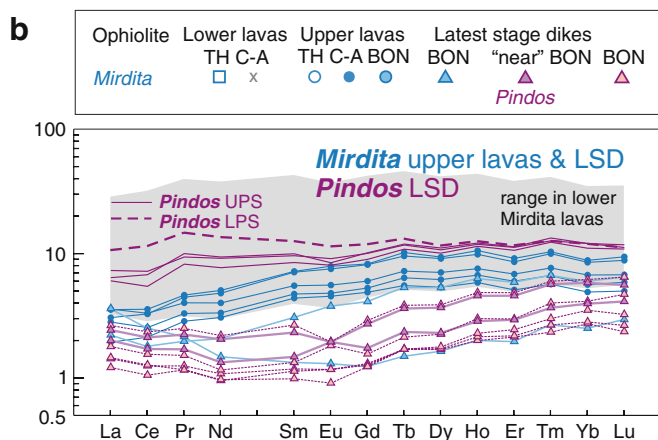
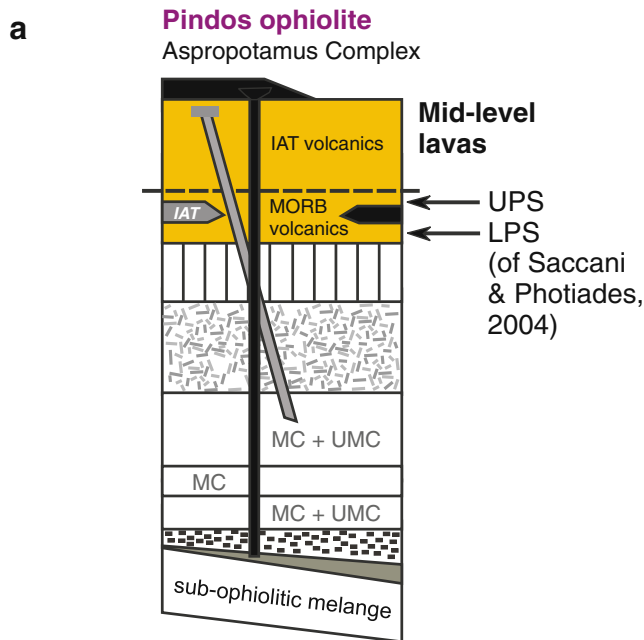
Fig. 9 Cr/Y discriminant plots of the Mirdita and Pindos, Troodos and Semail ophiolites, and the Marianas forearc. Plot is modified after Pearce (1983) and incremental batch melting calculations are from

Murton (1989). Symbols are as in Fig. 8 and color scheme is as in Fig. 4. IOA Intra-oceanic arc

tract as a result of a tectonic collision or underplating event prior to its incorporation into an orogenic belt. Both magmatic crust (mostly mafic) and residual mantle must be present. These must have been emplaced or gradually uplifted as a result of buoyant lithosphere being subducted beneath them. Emplacement was the result of forearc–continent collision in the case of allochthonous ophiolites, and in the case of autochthonous ophiolites, uplift was the result of sediments underplating the forearc. In the former scenario, collision and attempted but failed subduction of trailing continental lithosphere caused the subduction zone to fail. In both cases, isostatic rebound of depressed oceanic crust and

upper mantle caused emplacement/obduction or uplift of the proto-ophiolites. This is the mechanism by which the two main classes of ophiolites were emplaced.

Some tracts of MORB are described as ophiolites but are not emplaced or underplated in this fashion (e.g., those termed as ‘Macquarie type ophiolites’ by Dilek 2003, see below). This is an important point because it speaks to the rarity of ‘true’ MORB ophiolites in the geologic record and the mechanical difficulties in emplacing MORB or back-arc basin (BAB) lithosphere (Stern 2004). In the case of SIR ophiolites, their similarity to Mariana forearc indicates that these ophiolites are fossil forearcs.



◀ **Fig. 10** Detailed chemostratigraphic features of the Aspropotamus Complex of the Pindos ophiolite (Saccani and Photiades 2004) compared with that of the Mirdita ophiolite (Beccaluva et al. 2005; Dilek et al. 2008) including: **a** stratigraphy showing the relative locations of the Upper Pillow Series (UPS) and the Lower Pillow Series (LPS); **b** chondrite-normalized REE patterns (normalizing values from Nakamura 1974); **c** relative changes in HFSE concentrations between the LPS and UPS; **d** Nb/Yb vs Th/Yb systematics (Pearce 2008); **e** Zr vs Zr/Y systematics (Pearce and Norry 1979); and **f** Y vs Cr systematics (Pearce 1983; Murton 1989). Symbols in **d–f** are as in **b** and **c**. LSD in **b–d** latest stage dykes; in **c** *LL* lower lavas; *PMLL* Pindos mid-level lavas; *UL* upper lavas; fields in **e** and **f**: *MORB* mid-ocean ridge basalt; *VAB* volcanic arc basalt; *WPB* within-plate basalt. PM in **f** primitive mantle

Synopsis of ophiolite types that follow the SIR

Published ophiolite classifications usually discriminate SSZ ophiolites into two main types (Tethyan and Cordilleran) on the basis of their inferred mode of emplacement, the nature of the substrate upon which they were emplaced, and their relative intactness (Moores 1982; Moores et al. 2000; see also review of Beccaluva et al. 2004 and references therein). It is important to stress that these two main ophiolite types are considered by some as having formed via forearc extension upon and during SI (e.g., Shervais 2001; Stern 2004).

Tethyan ophiolites are largely coherent, uppermost oceanic mantle and crustal assemblages. Structural relations between the basal sections of Tethyan ophiolites and the continental basement upon which they rest are generally clear and represent a partially subducted continental margin-allochthonous thrust sheet (ophiolite) relationship. Emplacement is interpreted as having occurred above the same subduction zone above which the ophiolite was generated as a result of an intra-oceanic arc—continent collision. Ophiolite emplacement occurs as trailing buoyant continental material enters the trench, clogs the subduction zone, and thrusts forearc over the partially subducted continental margin.

According to this classification scheme, the SW Pacific belt of ophiolites that extends from Papua-New Guinea to the North Island of New Zealand can be considered ‘Tethyan-like’ as these complexes were emplaced upon the former eastern margin of the Australian Plate via intra-oceanic arc—continent collision shortly after their formation (Whattam et al. 2008; Whattam 2009 and references therein). It is important to note that lavas of SW Pacific ophiolites also exhibit a compositional bimodality with both MORB and SSZ affinities analogous to Tethyan ophiolites. Ambiguity in stratigraphic relations between the suites, however, has hindered determining the genetic relationship of the two suites (Whattam 2009). Similar to earlier interpretations of Tethyan ophiolite chemostratigraphy that invoked initial MOR formation followed by SI, a

long-standing paradigm for SW Pacific ophiolites maintains that the MORB-like suites, for example in the case of the New Caledonia ophiolite, represent BAB basalts (Cluzel et al. 2001) and the SSZ-like lavas represent those formed in concert with SI within the BAB. On the basis of geodynamic considerations, geochemical similarities between some ‘BAB’ and spatially related, unequivocal SSZ ophiolite basalts, and (limited) geochronological evidence, Whattam (2009) suggested instead that the MORB-like suites might represent ophiolite basement formed upon SI, i.e., that ophiolites of the SW Pacific region follow the SIR. Testing this idea requires better chemostratigraphic documentation; if this proves unfeasible, geochronological data at least is needed to determine the temporal and hence genetic relation between the MORB-like and the SSZ-like suites.

Cordilleran ophiolites include the Jurassic Coast Range and Josephine ophiolites of California (Shervais 1990) and arguably many situated in Central America and the circum-Caribbean region. In contrast to Tethyan ophiolites, many Cordilleran ophiolites occur as ‘stacked’ (commonly uppermost only) fragments of differing origins that appear to have been accreted to previous subduction complexes (i.e., island arc terranes) prior to final continental margin accretion. As a result, the relation of the basal section of many Cordilleran ophiolites with their associated continental basement is often unclear. Shervais (2001) used the term ‘accretionary uplift’ to describe the emplacement of many Cordilleran ophiolites, which entails gradual exhumation and exposure as a result of shallow underthrusting of hot, young, buoyant oceanic lithosphere beneath the precursor ophiolite or ophiolite fragments (see Fig. 2e of Shervais 2001).

Accreted oceanic terranes in and around the Caribbean region (Giunta et al. 2002) are Cretaceous in age and are classified as Cordilleran type by some (e.g., Beccaluva et al. 2005). This particular Cordilleran-ophiolite type comprises accreted terranes along the northern periphery of Cuba (e.g., Iturralde-Vinent 1989), southern and eastern Costa Rica and Panama (Hoernle et al. 2004; Wegner et al. 2011 and references therein) and along western Columbia and Venezuela (e.g., Kerr et al. 1997). Many of these mafic oceanic terranes are not called ophiolites by most researchers (however, see Giunta et al. 2002; Garcia-Casco et al. 2006) and were originally interpreted as uppermost sections of oceanic plateaux (e.g., Hoernle et al. 2002) with relatively minor amounts of other accreted oceanic terranes, e.g., oceanic islands and seamounts (e.g., Buchs et al. 2009, 2010). Recent detailed geochemical and stratigraphic studies of basement lavas in Panama and Costa Rica (Wörner et al. 2009; Buchs et al. 2010; Wegner et al. 2011), however, indicate a similar chemostratigraphic progression as SIR ophiolites, i.e., from lower MORB-like

to upper arc-like. In the case of these Caribbean ophiolites, the lower MORB-like sequence is interpreted as a thickened oceanic plateau as opposed to true MORB or BABB as in some interpretations of Tethyan and SW Pacific ophiolites. Continued multidisciplinary studies need to be conducted on Caribbean ophiolites, but the preliminary chemostratigraphic evidence suggests that these basement oceanic terranes also follow the SIR.

In summary, we consider that SW Pacific and Cordilleran ophiolites—including those of the Circum-Caribbean region—are as likely to follow the SIR and form during SI as are Tethyan ophiolites. Only further detailed studies will allow this supposition to be critically evaluated.

Non-SIR ‘ophiolites’

Not all emplaced or underplated oceanic terranes described in the literature as ophiolites follow the SIR. As applicability of this rule depends on the extent to which chemostratigraphic relations have been established and such relations in many ophiolites are ambiguous, its validity for other ophiolites will have to be assessed on a case-by-case basis by future studies. Moreover, ophiolite chemostratigraphic documentation is hindered by the fact that many ophiolites are highly dismembered and/or tectonized (e.g., SW Pacific ophiolites) and frequently incomplete (e.g., Cordilleran-type ophiolites that commonly comprise uppermost segments only).

Ligurian (or Alpine-type) ophiolites (Ishiwatari 1985) of the Alpine–Apennine belt occur in the western Alps and northern Apennines to the west of the classic Tethyan ophiolites of the eastern Mediterranean–Persian Gulf region (Fig. 1). Ligurian ophiolites are fundamentally different than Tethyan ophiolites described earlier as the former essentially consist of peridotite with subordinate gabbroic rocks that occur as discrete bodies and dykes intruding the peridotite; basalts are scarce and sheeted dykes are usually absent. These peridotite–mafic rock associations are interpreted as remnants of oceanic lithosphere of the Jurassic Ligurian (or western Tethys) basin that formed during incipient opening of Tethys (e.g., Rampone and Piccardo 2000 and references therein) and comprise two distinct suites of differing inferred paleogeographic location of formation and tectonic affinity within western Tethys. The External Ligurides are interpreted as subcontinental lithosphere peridotites that formed in a pericontinental setting (Marroni et al. 1998 and references therein), whereas the Internal Ligurides are linked to an intra-oceanic setting and comprise depleted peridotites and apparently much younger lavas and gabbros of exclusively MORB-affinity (Abbate et al. 1994 and references therein). Interestingly, field relationships and age determinations indicate that no mantle–crust (residua-

melt) relationship exists between the mantle peridotites and the crustal rocks. As the External Ligurides comprise subcontinental lithosphere, it is debatable as to whether these associated peridotite–mafic associations should be classified as ophiolites. Indeed, Rampone and Piccardo (2000) state that the Northern Apennine ophiolites cannot be interpreted as remnants of fossil mature oceanic lithosphere (i.e., ophiolites) but rather as lithologic associations that develop after continental breakup in response to the passive extension of continental lithosphere.

The Late Jurassic–Early Cretaceous Sarmiento and Tortuga oceanic complexes of southernmost South America are referred to collectively as the Rocas Verde ophiolites (C. Stern and deWit 2003) and encompass the Chilean-type ophiolite class of Dilek (2003). In terms of internal architecture, these ophiolites are the opposite of Ligurian types as they exhibit uppermost ophiolite-like assemblages of pillow lavas, sheeted feeder dykes, massive diabase, and gabbros (C. Stern and deWit 1980) but no peridotitic mantle section. Similar to gabbros and rare basalts of Ligurian-type ophiolites and the basal magmatic section of Tethyan SI-ophiolites, the associated mafic lavas and gabbros exhibit tholeiitic MORB-like affinities (Saunders et al. 1979; C. Stern 1980; C. Stern and deWit 2003). Chilean-type ophiolites share a common genetic origin with Ligurian types in that they appear to have a rifting origin; but in contrast to the latter, formation of Chilean-type ophiolites is attributed to rifting of an earlier-formed magmatic arc during backarc basin opening. The Rocas Verdes ophiolites are bounded to the east and west by continental crust and are interpreted to have formed by seafloor spreading that rifted the southwestern margin of Gondwana continental crust during incipient opening of the South Atlantic. These ophiolites are considered to be representative of the magmatic igneous component of backarc basin floor generated behind a magmatic arc (C. Stern and deWit 2003). These ophiolites are considered as more or less autochthonous in their present location.

The Macquarie ‘ophiolite’ constitutes the entire Macquarie Island, which is situated along the active Australia–Pacific plate boundary between New Zealand and Antarctica. It represents the only described example of a Macquarie-type ophiolite (classification scheme of Dilek 2003). This exposed oceanic terrane is unique as it represents a young (12–9 Ma) essentially autochthonous, in situ segment of a complete but dismembered segment of MOR crust (Sutherland 1995; Massell et al. 2000; Varne et al. 2000). As the Australia–Pacific boundary changed from an extensional regime to oblique compression circa 5 Ma, transpressional deformation uplifted the complex (Sutherland 1995; Varne et al. 2000). It is thus unique from other ophiolite types as it has not been incorporated into an orogenic belt. Similar to the Ligurian- and Chilean-type

ophiolites described earlier, the Macquarie oceanic complex shows no evidence of origin during SI.

Conclusions and implications for understanding subduction initiation

The subduction initiation rule links forearc lithosphere and most ophiolites as examples of the same phenomenon: what is produced by upwelling and progressively metasomatized asthenosphere when subduction begins. We now understand that the earliest stages of SI entail decompression melting of a fertile, lherzolitic, asthenospheric source to form early MORB-like suites as seen in the lowermost sections of Tethyan ophiolites and the IBM forearc and possibly in some ‘MORB-only’ ophiolites. These processes did not occur at mid-ocean ridges, but the lavas are nevertheless indistinguishable from those generated by seafloor spreading at true mid-ocean ridges. We further understand that if SI is not arrested in its early stage of development, continued mantle upwelling and concomitant development of the incipient subduction zone would progressively hydrate and metasomatize an increasingly depleted OPX-rich source; partial melting of this residue would then produce VAB-like lavas and possibly latest stage boninitic lavas and dykes. Understanding that most ophiolites are fragments of exhumed forearcs and that forearcs form during subduction initiation allows us to use ophiolites to explore how subduction zones form. Because forearc basement, even if not buried by sediments, is deeply submerged, it is difficult and expensive to study. With an appreciation that most ophiolites—those that follow the subduction initiation rule—are exhumed forearcs formed above a new subduction zone, we can more easily conduct the kinds of detailed studies that are needed to reconstruct the mantle and magmatic response to SI.

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