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Did the Troodos ophiolite of Cyprus form during subduction inception?

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Abstract

Understanding whether ophiolites formed during subduction inception or above long-lived subduction zones poses an outstanding challenge as modern examples of incipient subduction zones are rare. It is generally agreed that the Troodos ophiolite of Cyprus was formed at a spreading center above a subduction zone within the closing Neo-Tethys Ocean during the Late Cretaceous; beyond this, however, details of its geodynamic origin have been widely debated. To explore this problem, we examine further the analogy previously made between the Troodos ophiolite and the Mariana fore-arc, by here comparing extrusive rocks from the Troodos ophiolite to Pliocene-aged basalts from the southeastern Mariana fore-arc rifts (SEMFR), which formed by near-trench spreading above a highly dehydrating, mature subducted slab. The SEMFR basaltic glasses and olivine-hosted melt inclusions possess the highest markers of water-rich, slab-fluids (Rb/Th, Cs/Th, H₂O/Ce, Ba/Th) of any worldwide arc magmas, a signature that may be consistent with efficient slab dehydration within ~ 90 - 100 km from the trench. Troodos ophiolite lavas, which have preserved fresh glasses, recorded similar, elevated slab-fluid markers to those of the SEMFR glasses. Although geodynamic comparisons cannot be direct, we nevertheless propose that the chemical similarities in these slab-fluid markers support the formation of the Troodos ophiolite above a highly dehydrating, shallow subducted plate in a near-trench setting. Unlike the southern

Marianas, lack of juvenile arc volcanism and associated volcanoclastics, but presence of an extensive boninitic sheeted dyke complex with associated extrusive section, demonstrates that Troodos presumably developed by organized seafloor spreading in a near-trench setting, immediately following subduction inception of the Neo-Tethyan plate. As such, the chemical similarities between the SEMFR magmas and the Troodos ophiolite can only be used to provide constraints upon the geodynamic and the petrogenetic conditions of magma formation. Hence, deciphering precisely the original setting of ophiolites requires us to integrate thoroughly accurate geology and petrographic descriptions, along with comparison with modern analogues of infant subduction zones.

Keywords: Troodos ophiolite, Izu-Bonin-Marianas, southern Mariana fore-arc rifts, subduction initiation, near-trench spreading, slab fluids, supra-subduction zone ophiolites.

1- Introduction

Subduction, the sinking of oceanic plates into the interior of the Earth, has shaped the surface of our planet for millions of years by contributing to modern plate tectonics (Gao et al., 2004; Gerya et al., 2008; Lee et al., 2006; Rudnick, 1995) and thereby, to life sustainability (Berner and Caldeira, 1997; Lasaga et al., 1985; Lee et al., 2015; Walker et al., 1981). Reconstructing past subduction zones through time is essential to understand Earth's evolution. However, plate tectonic reconstruction mostly relies on relicts of the seafloor that have been preserved by being emplaced (obducted) onto continents (viz. ophiolites). It is important, therefore, to examine whether ophiolites formed above long-lived subduction zones, in mid-ocean ridge settings or during subduction inception.

Determining the precise origin of ophiolites has, however, proven challenging due to the apparent lack of modern analogs. Whereas their internal structure suggests formation by a

period of organized seafloor spreading, as at mid-ocean ridges, in the overwhelming majority of cases their magma compositions require the infiltration of water-rich fluids into their mantle sources, consistent – only – with an upper plate subduction zone setting. Such a conundrum may potentially be reconciled if ophiolites formed by seafloor spreading in highly extensional, near-trench environments at the earliest stage of subduction (Pearce et al., 1984; Pearce and Robinson, 2010; Stern, 2004; Stern and Bloomer, 1992) or directly in the fore-arcs of established, mature subduction zones (Ribeiro et al., 2013a; Ribeiro et al., 2015; Taylor et al., 1992; Woelki et al., 2019a). Nevertheless, the rarity of currently active spreading centers that initiate and function directly adjacent to the trench has raised questions about the geodynamic feasibility of such a scenario, as modern fore-arcs are generally underlain by a cold serpentinized mantle (Fryer et al., 1995; Hyndman and Peacock, 2003). As such, they are not expected to be the loci of extensive melt generation nor, therefore, sites of lithosphere formation by seafloor spreading above a sinking plate.

Potential support for the supra-subduction zone spreading model, however, derives from direct observations of fore-arc rifts in the Southeast Mariana Fore-arc Rift (SEMFR), where *in situ* near-trench extensional structures and associated magmatism formed above a highly dehydrating, subducting plate in Pliocene times within existing Eocene fore-arc basement (Martinez et al., 2014; Ribeiro et al., 2013a; Ribeiro et al., 2015; Ribeiro et al., 2013b). Although not associated with subduction inception, which occurred in the Eocene in the Izu-Bonin-Mariana (IBM; Ishizuka et al., 2018; Ishizuka et al., 2006; Ishizuka et al., 2011a; Ishizuka et al., 2011b; Reagan et al., 2019; Reagan et al., 2010; Reagan et al., 2017), the SEMFR magmas show that extension and magmatism – and hence, potentially, the generation of new ophiolite-type lithosphere – may be possible in a near-trench setting (Ribeiro et al., 2022; Ribeiro et al., 2013a; Ribeiro et al., 2015).

76 In this contribution, we examine the IBM – ophiolite analogy more closely, specifically
77 using the example of the Neo-Tethyan Troodos ophiolite of Cyprus. The original tectonic
78 setting of Troodos has remained widely debated, and remains so: alternatives proposed a
79 formation in the back-arc basin (Muenow et al., 1990; Regelous et al., 2014; Robinson et al.,
80 1983; Woelki et al., 2018), in the arc (Miyashiro, 1973) or in the fore-arc (Pearce, 1975; Taylor
81 et al., 1992; Woelki et al., 2019a) of a long-lived intra-oceanic subduction zone, or immediately
82 following subduction inception (Pearce and Robinson, 2010; Robertson and Hudson, 1975;
83 Robinson et al., 1983). Because fresh glass shards are preserved in the pillow rinds of the
84 Troodos ophiolite (e.g., Belgrano et al., 2021; Muenow et al., 1990; Rautenschlein et al., 1985;
85 Regelous et al., 2014; Robinson et al., 1983; Woelki et al., 2018), and hence original fluid-
86 mobile element concentrations likely preserved within them, we can place additional
87 constraints onto the original geodynamic setting of Troodos. For this, we compare and contrast
88 the compositions and the geodynamic settings of the SEMFR basaltic glasses and olivine-
89 hosted melt inclusions and of the IBM pre-arc magmas with the Troodos volcanic rocks, with
90 the aim of determining the original locus of magmatism in Troodos in Late Cretaceous. The
91 SEMFR magmas possess a distinct geochemical feature in slab-fluid markers (viz., the highest
92 Ba/Th, Cs/Th, Cs/Ba, Rb/Th, H₂O/Ce yet recorded in arc magmas), which we utilize to address
93 the question of whether the Troodos ophiolite formed by seafloor spreading above a mature
94 subduction zone or during subduction infancy. We find that such an analogy supports the
95 notion that spreading in Troodos most likely occurred directly in a near-trench, supra-
96 subduction environment at the earliest stages of a subduction zone. Geochemical differences
97 do exist between the IBM and Troodos convergent margins, and may result from differences
98 in mantle regimes, mantle flow, geodynamic setting, forcing mechanisms, the nature and
99 composition of the subduction inputs, and/or slab P-T paths; therefore, we deduce there is no
100 single, unique scenario for subduction inception.

101

102 **2- Geological background of the Troodos ophiolite**

103 Ophiolites are relicts of the oceanic lithosphere (i.e., oceanic crust and mantle) exposed at
104 the surface or emplaced onto continents. The Late Cretaceous Troodos ophiolite (~ 90 - 94
105 Myr) represents a complete record of the oceanic crust (viz. extrusive layer, sheeted dykes,
106 and mafic-ultramafic plutonic rocks, plus the uppermost lithospheric mantle underneath; Fig.
107 1) that formed within the Neo-Tethys Ocean (Gass, 1968). Occurrence of a ~100-km-wide
108 swarm of sub-parallel sheeted dykes, with associated basaltic pillow lavas, was taken to
109 resemble newly accreted oceanic crust formed at mid-ocean ridges, and to indicate formation
110 by *de facto* seafloor spreading (Gass, 1968; Moores and Vine, 1971). Reconciling the arc-like
111 geochemical signatures of the Troodos lavas, including occurrence of low-Si boninites (Fig.
112 2), with the physical evidence for organized seafloor spreading, demonstrate that the Troodos
113 ophiolite formed by seafloor spreading above a subduction zone (e.g., Miyashiro, 1973;
114 Pearce, 1975; Pearce et al., 1984; Pearce and Robinson, 2010; Taylor et al., 1992).

115 Troodos has played seminal role in understanding ophiolites, not only because it was the
116 first studied in detail, but also because it was one of the least deformed ophiolites during
117 emplacement. In contrast to many (e.g., Oman), it does not preserve a metamorphic
118 sole/thrust complex at its base, and its present-day position is likely relatively close to where
119 it formed within Neo-Tethys. Instead, in the latest Cretaceous, it became juxtaposed against
120 an early Mesozoic continental margin and an oceanic fragment (Mamonia Complex), during
121 which time Troodos was also rotated ~90° anticlockwise (Clube et al., 1985). It was only
122 much later uplifted to become emergent (Miocene to recent). The Troodos ophiolite also
123 possesses an organized, approximately N-S (to NW-SE), sheeted dyke complex of > 70 km
124 wide, with typically 100% dykes, which are evidence for seafloor spreading (Gass, 1968;
125 Kidd and Cann, 1974). Albeit with some scatter (e.g., Allerton and Vine, 1991), dyke

orientations are approximately perpendicular to the E-W 'Southern Troodos Transform Zone' (Gass et al., 1994; MacLeod and Murton, 1993, 1995), which separates the main Troodos sequence in the north from the 'Anti-Troodos' in the south (MacLeod, 1990) (Fig. 1). The Troodos volcanic rocks have traditionally been divided into 'lower pillow lavas' (plus underlying 'Basal Group' screens in sheeted dykes), which are composed of relatively evolved basaltic andesites, andesites, dacites, and rhyolites, closely succeeded by 'upper pillow lavas' that are relatively more primitive basaltic andesites and basalts (Pearce, 1975; Pearce and Robinson, 2010; Robinson et al., 1983), many of which can be categorised geochemically as low-silica boninites (e.g., Cameron, 1985; Pearce and Reagan, 2019; Pearce and Robinson, 2010) (Fig. 2). Both the upper and lower series are sometimes cogenetic; while in other places, the upper series are more depleted and more primitive than are the lower series. Geographically, most boninitic magmas are restricted to the Anti-Troodos regions (Cameron, 1985; Rogers et al., 1989; Taylor et al., 2022). Both series formed during spreading above a highly dehydrating subducting plate (Miyashiro, 1973; Pearce, 1975; Pearce and Robinson, 2010; Taylor et al., 1992). The petrology and the stratigraphy of the volcanic rocks that compose the bulk of the ophiolite are similar, but not identical to those observed in the IBM pre-arc crust, which developed during the early stages of the IBM subduction zone (Ishizuka et al., 2006; Pearce and Reagan, 2019; Pearce and Robinson, 2010; Reagan et al., 2019; Reagan et al., 2010). However, the Troodos ophiolite differs from the IBM pre-arc crust by lacking fore-arc basalts with a reduced subduction influence (also termed FABs in the literature), high-silica boninites, and any subsequent basalt to rhyolite successions that developed during arc infancy (Fig. 2) (Pearce and Reagan, 2019; Pearce and Robinson, 2010; Reagan et al., 2010; Robinson et al., 1983; Stern and Bloomer, 1992).

The rarity of modern analogs to subduction inception hinders our current understanding of Troodos ophiolite formation; and so its origin has remained widely debated for decades.

The fact that relatively fresh boninitic glasses and olivine-hosted melt inclusions from Troodos are generally more enriched in highly incompatible elements (Ba, Cs, Rb) than are back-arc basalts (Hu et al., 2021; Regelous et al., 2014; Woelki et al., 2019a; Woelki et al., 2018), back-arc boninites and mid-ocean ridge basalts (MORBs), strongly suggests that they likely overlaid a shallower part of the subducted slab than commonly found in the back-arc region (Pearce and Robinson, 2010; Woelki et al., 2019a). To reconcile these paradoxical observations, the Troodos ophiolite has been proposed to form by ‘pre-arc’ (i.e., before the onset of any arc magmatism) spreading either above an infant subduction zone (Pearce et al., 1984; Pearce and Robinson, 2010; Robinson et al., 1983; Taylor et al., 2022), or in the fore-arc of a long-lived subduction zone, such as the SE Mariana fore-arc rift (Woelki et al., 2019a). In this manuscript, we use the term ‘pre-arc’ crust, instead of the term ‘proto-arc’ often found elsewhere (e.g., Ishizuka et al., 2011a; Reagan et al., 2019; Reagan et al., 2017; Ribeiro et al., 2022; Shervais et al., 2019), to describe rocks that were generated before the development of a magmatic arc, for consistency with Pearce and Robinson (2010), albeit noting that in the case of Troodos the magmatic system was terminated before any such ‘arc volcanism’ ever formed (see Section 5.1 below).

3- Data compilation and filtering

We compiled a dataset for the Troodos ophiolite ($n = 667$), which includes fresh glass shards, olivine-hosted melt inclusions and bulk rocks, from 10 published sources (Supplementary Materials Table S1). For comparison, we used the pre-compiled datasets of Ribeiro et al. (2022) from the Southern Mariana fore-arc and IBM pre-arc crust. Samples in Table S1 were filtered for freshness (assuming $\text{LOI} < 2 \text{ wt\%}$) and a total sum of oxides of $100 \pm 2 \text{ wt\%}$. Fresh glasses (i.e., glass shards and olivine-hosted melt inclusions) were selected where available to minimize secondary alteration processes. Where trace element

ratios were used, our dataset was carefully screened to only retain basaltic ($\text{SiO}_2 \leq 56$ wt%; as in Pearce et al. (2005)) and boninitic compositions (as reported in the literature and by following the classification of Pearce and Reagan (2019), and highlighted in Fig. 2B - C). This was done to minimize the effect of crystal fractionation, ensuring that some mineral phases (e.g., amphibole, rutile, titanium oxides, ...) did not modify the incompatible element ratios of interest upon crystallization. Such a thorough screening allows us to ensure that elemental ratios may reliably track subduction and mantle processes (Pearce et al., 2005).

Elements of interest (Ba, Rb, Th, H_2O , ...) were also plotted against elements that are believed to remain relatively immobile during alteration and degassing to ensure further that the composition of the elements of interest reliably track the composition of the slab fluids that infiltrated their mantle source. Preservation of the fractionation trends supports the notion that the Troodos magmas were little affected by alteration and hydrothermal processes (Fig. S1). Correlation between H_2O and Rb (Fig. S2) further demonstrates that the Troodos glass shards and olivine-hosted melt inclusions likely preserved their pre-eruptive water content without suffering extensive water degassing.

For the purposes of reconstructing the geodynamic setting of Troodos, we focus on fingerprinting slab fluids in the dataset as a whole: deconvolving spatial and temporal variations (e.g., Taylor et al., 2022) is beyond the scope of this manuscript. Using the entire dataset provides a more robust basis for geodynamic interpretations, and avoids issues relating to unreported stratigraphic information or sample location as well as the use of distinct sample classification schemes. As such, any uncertainties related to sample location and/or classification do not alter our results nor our interpretations, despite the complexities of the volcanic stratigraphy of Troodos.

The complete filtered dataset is reported in Table S1. References and details can be found therein and in the supplementary material.

4- Results: Troodos magma composition

4.1- Major element composition

The Troodos volcanic sequence normally exhibits a two-fold field division, which generally, although not always, corresponds also to a geochemical (and/or metamorphic) division (e.g., Gass and Smewing, 1973; Taylor, 1990). The lower pillow lavas (including a 'Basal Group' transition into sheeted dykes below) are normally more evolved, composed of low-K, tholeiitic basalt andesites to dacites ($50 \text{ wt}\% < \text{SiO}_2 < 72 \text{ wt}\%$, $\text{K}_2\text{O} < 1 \text{ wt}\%$) (Fig. 2A, 3). Overlying upper pillow lavas tend to be more primitive and, according to the definition of Pearce and Reagan (2019), include boninites ($\text{H}_2\text{O} = 2.07 \pm 0.32 \text{ wt}\%$) as well as tholeiitic basalts ($\text{H}_2\text{O} = 2.41 \pm 0.12 \text{ wt}\%$) (Fig. 2 - 3) (Pearce and Reagan, 2019; Pearce and Robinson, 2010). Many of these upper series volcanics are olivine-phyric, some of which phenocrysts may enclose fresh melt inclusions (Portnyagin et al., 1997; Sobolev and Chaussidon, 1996). The tholeiitic basalts possess low potassium contents ($\text{SiO}_2 < 56 \text{ wt}\%$, $\text{K}_2\text{O} < 1 \text{ wt}\%$) (Fig. 2A) and average water contents of $2.11 \pm 0.47 \text{ wt}\%$ (Supplementary Table S1) (Pearce and Robinson, 2010; Sobolev and Chaussidon, 1996; Woelki et al., 2019a). The Troodos boninites possess low SiO_2 contents ($< 57 \text{ wt}\%$), low TiO_2 contents ($< 0.5 \text{ wt}\%$), and relatively high MgO contents ($\sim 7 - 11 \text{ wt}\%$), hence plot within the compositional field of low-silica boninites of Pearce and Reagan (2019) (Fig. 2B-C). In contrast to the IBM pre-arc (Coulthard et al., 2021; Pearce and Reagan, 2019; Reagan et al., 2019; Reagan et al., 2010; Shervais et al., 2019), high-silica boninites which are believed to mark the onset of IBM arc volcanism (Reagan et al., 2019; Reagan et al., 2010), are not present in Troodos. Another key feature of the Troodos ophiolite is the lack of a calc-alkaline magmatic series (Fig. 3), which usually characterizes arc volcanic rocks from long-lived subduction zones (Gill, 1981; Pearce and Robinson, 2010).

The Troodos upper and lower volcanic series generally overlap the compositional range of the SEMFR basaltic glasses and associated olivine-hosted melt inclusions (Ribeiro et al., 2015; Ribeiro et al., 2013b), as well as that of the IBM LSB, which formed during subduction inception (Fig. 2) (Coulthard et al., 2021; Pearce and Reagan, 2019; Reagan et al., 2019; Reagan et al., 2010; Shervais et al., 2019). The low TiO₂ content of the Troodos low-silica boninites (LSB) (Fig. 2B) reveals a strongly depleted, residual mantle source, as also observed during the early IBM stages and in the SEMFR (Pearce and Reagan, 2019; Reagan et al., 2017; Ribeiro et al., 2015). The low K₂O content of the Troodos upper and lower series also overlaps the composition of the SEMFR magmas and of the IBM LSB (Fig. 2A).

4.2 – Trace element contents

The Troodos upper and lower series are both enriched in fluid-mobile elements (Rb, Ba, Cs, Th, Sr, H₂O, Pb) and depleted in high field strength elements (HFSE), such as Nb, Ta, Ti and Zr, consistent with a supra-subduction zone setting (Fig. 4) (e.g., Miyashiro, 1973; Pearce et al., 1984; Pearce and Robinson, 2010; Robinson et al., 1983; Taylor et al., 2022; Taylor et al., 1992; Woelki et al., 2019b). The Troodos lower basalts display similar chondrite-normalised trace element patterns to the those of NW SEMFR basalts, which are relatively flat towards the heavy rare Earth elements (HREE). By contrast, the Troodos upper boninites display similar patterns to the IBM LSB, specifically in fluid-mobile elements and in HREE (Fig. 4). The trace element patterns of the SEMFR olivine-hosted melt inclusions are generally much less enriched in some fluid-mobile elements (e.g., U, Th, Pb, Sr), and more depleted in HFSE and in HREE, compared with the Troodos boninites. Hence, our newly compiled dataset (Table S1) suggests that Troodos boninites from the upper series more closely resemble the IBM pre-arc LSB in terms of major and trace element contents

(Fig. 2, 4). By contrast, they are generally much more depleted in trace elements compared with the Lau Basin back-arc boninites (Fig. 4C), implying distinct petrogenetic conditions.

The enrichment in fluid-mobile elements of the Troodos upper and lower magmas (Fig. 4), together with their higher water content (~ 2 wt%) compared with MORBs (Portnyagin et al., 1997; Sobolev and Chaussidon, 1996), reflects the infiltration of slab fluids (both as water-rich slab fluids and slab melt) into the asthenospheric mantle source, requiring that the Troodos oceanic crust developed above a dehydrating (and perhaps melting), subducted plate (Miyashiro, 1973; Pearce et al., 1984; Pearce and Robinson, 2010; Robinson et al., 1983; Taylor et al., 2022; Taylor et al., 1992). Therefore, the enrichments in fluid-mobile elements and in water demonstrate that the Troodos oceanic crust was generated by spreading in an intra-oceanic subduction setting (Gass et al., 1975; Miyashiro, 1973, 1975; Pearce and Robinson, 2010; Robinson et al., 1983; Taylor et al., 2022; Taylor et al., 1992).

4.3 – Markers of slab dehydration and slab melting

Slab dehydration and slab melting can be tracked using chemical proxies in subduction zone magmas, provided that the magmas did not crystallize mineral phases such as biotite, titanium oxides, amphibole, garnet and/or muscovite, which fractionate such elemental ratios upon magma cooling (Elliott et al., 1997; Pearce et al., 2005). These slab-fluid markers represent a record of the water-rich slab fluids (Rb/Th, Cs/Th, H₂O/Ce, Cs/Ba) and hydrous slab melts, either derived from the subducted sediments (Th/Nb, La/Sm) or from the oceanic crust in the amphibolite facies (Hf/Sm, Zr/Sm), that infiltrated the mantle source of the magmas and triggered mantle melting (Elliott et al., 1997; Johnson and Plank, 1999; Manning, 2004; Pearce et al., 1984; Pearce et al., 2005; Pearce et al., 1992). Using elemental ratios has the main advantage of seeing through the geochemical effects of fractionation and melting (Pearce et al., 2005), so such ratios may track a reliable slab fluid signature in the

magmas (Kogiso et al., 1997; McCulloch and Gamble, 1991). The Troodos tholeiitic basalts and low-silica boninites possess similar markers in slab dehydration ($\text{Ba/Th} = 58 - 270$, $\text{Rb/Th} = 13 - 158$, $\text{Cs/Th} = 0.33 - 11.8$, $\text{H}_2\text{O/Ce} = 3,934 - 33,868$) to the SEMFR glasses and IBM pre-arc boninites (Fig. 5). While the compositions of the two Troodos series generally overlap, the tholeiitic basalts are generally more enriched in Th/Nb (Fig. 5A). In contrast, the upper boninites are more enriched in Rb/Th and $\text{H}_2\text{O/Ce}$ (Fig. 5B), and some of them are lowered in Th/Nb (i.e., $\text{Th/Nb} \sim 0.10$) relative to the tholeiitic basalts (i.e., dark blue circles with a white outline which plot slightly above the MORB compositional field in Fig. 5A) (Taylor et al., 2022). The elevated Th/Nb, La/Sm and Hf/Sm (Fig. 5A - 6) in both Troodos magma series further indicate that melting of subducted sediments and the amphibolitized oceanic crust of the subducted Neo-Tethyan slab occurred (Taylor et al., 2022).

5- Discussion

Despite evidence in support of a subduction setting, debate persists as to whether the Troodos ophiolite formed at the onset of subduction (Pearce et al., 1984; Pearce and Robinson, 2010), or in a mature and relatively stable convergent margin (e.g., Flower and Levine, 1987; Miyashiro, 1973; Regelous et al., 2014; Woelki et al., 2018). Because boninites are not restricted to the pre-arc crust that developed at the onset of a subduction zone, but may also be erupted in arcs and back-arc basins (e.g., Cooper et al., 2010; Resing et al., 2011), the original geodynamic setting of the Troodos ophiolite has remained as widely debated today as it was half a century ago (e.g., Gass et al., 1975; Hynes, 1975; Miyashiro, 1973; Pearce, 1975; Pearce et al., 1984; Pearce and Robinson, 2010; Regelous et al., 2014; Woelki et al., 2019a; Woelki et al., 2019b; Woelki et al., 2018). In the following sections we discuss the regional geological constraints upon Troodos formation, and how they impact upon the more recent models derived from geochemistry alone, and implications, therefore, for the original geodynamic setting of

the ophiolite. Then, we explore key constraints (i.e., inferred paleo-slab depth and distance to the paleo-trench) in the context of the formation of the Troodos ophiolite using the chemical fingerprint of near-trench magmas and the geodynamic setting of the SEMFR. Lastly, we explore the sources of the slab fluids captured by the ophiolite to better comprehend its petrogenesis in Late Cretaceous time.

5.1 - Regional geological constraints upon formation of the Troodos ophiolite

It has been proposed, based almost entirely on geochemical arguments, that the Troodos ophiolite formed during splitting and/or spreading of the fore-arc crust above a mature subduction zone, such as the SEMFR (Woelki et al., 2019a). Geological constraints from Troodos and nearby Neo-Tethyan terranes have not, however, generally been considered in these models. These constraints may be summarised as follows:

(1) Presence of a sheeted dyke complex ~100 km across-strike width in Troodos (Fig. 1B), associated with plutonic crust below and extrusive section above, implies organised seafloor spreading and creation of new oceanic lithosphere in response to sustained extension over a substantial period of time (e.g., Gass, 1968; Gass et al., 1975), probably several millions of years. This point is not weakened by more recent studies that have revealed a more complex internal spreading structure than previously supposed (Allerton and Vine, 1991; Varga and Moores, 1985).

(2) The Troodos extrusive section, with its relatively regular and uniform lower and upper pillow lava sequences (e.g., Robinson et al., 1983), is virtually devoid of any syn-volcanic inter-lava sediment (Fig. 1B). That it was completely free from any externally-derived sediment input, despite forming a relatively flat and smooth seafloor, is striking. The only intra-volcanic sediments are local ferromanganoan sediments spatially associated with hydrothermal venting, and within the Arakapas Fault Belt along the southern margin of the

Troodos ophiolite, which was a fault-bounded seafloor trough directly associated with ocean-floor transform faulting, locally-derived volcanic debris flows are interbedded with boninitic lavas (Gass et al., 1994; MacLeod, 1990; Simonian and Gass, 1978). In marked contrast, even 'sediment-starved' modern back-arc basins and fore-arcs are blanketed by near-contemporaneous sediments derived from adjacent subaerial or submarine arc volcanoes (e.g., Parson et al., 1994), as volcanoclastics can travel up to 1000 km away from their source (e.g., Kutterolf et al., 2018); hence, the complete absence of any such arc-derived pyroclastic or volcanoclastic sediments, or any exotic continental-derived sediments during eruption of the Troodos extrusive sequence is strong evidence that none could have been present. This lack of external detrital inputs from other, potentially continental, sources is also difficult to reconcile in those models that invoke spreading occurring in very deep water settings (> 4 km; Belgrano et al., 2021). It is noteworthy that the branch of Neo-Tethys in which Troodos and other contemporary supra-subduction zone ophiolites (e.g., Hatay/Kizildagh; Lytwyn and Casey, 1993; Şimşek et al., 2023) were formed is thought to have been small and interspersed with rifted micro-continental blocks derived from northern Gondwanaland (e.g., Robertson et al., 2012).

(3) There is no known geological evidence in the Eastern Mediterranean region for any volcanic arc, whether continental or intra-oceanic, of comparable age to Troodos (~90 - 94 Myr; Morag et al., 2020; Mukasa and Ludden, 1987). Given its relative thickness and buoyancy in mature and long-lived arcs (≥ 20 km), felsic arc crust, if it had developed in Troodos, is unlikely to have been obliterated completely, nor its volcanic products. The first evidence for potential arc volcanism of any sort in the vicinity of Cyprus is also far too young to be a candidate for such an arc. This potential material is found within the Kannaviou Formation, of Campanian-Maastrichtian age (Robertson, 1977), a sequence of predominantly bentonite clays derived from the alteration of silicic ash and other fine volcanoclastic

materials (≤ 750 m thick) deposited on top of Troodos lavas, umbers (i.e., ferromanganoan hydrothermal sediments) and deep-water, low-energy radiolarian shales on the SW margin of the Troodos ophiolite only (Chen and Robertson, 2019; Robertson, 1977). Zircon ages of no older than ~ 80 Myr show that this highly localized, continental arc volcanism in the Kannaviou Formation post-dated the cessation of any magmatic activity in the Troodos ophiolite by at least 10 Myr (Chen and Robertson, 2019). Possible candidate sources for the Kannaviou ash of the appropriate composition and age have been found locally within the Kyrenia Range of present-day northern Cyprus (Chen et al., 2022), and attributed either to granitic plutons in southern Turkey or else to local minor magmatism along the margins of the developing Troodos microplate (Chen et al., 2022). This 'Troodos microplate' (Clube et al., 1985) was inferred in order to explain the 90° anticlockwise rotation that affected the entire ophiolite very rapidly in the late Campanian to Maastrichtian period, at the exact same time the SW margin of the Troodos basement was juxtaposed against the fragmented early Mesozoic continental margin and deep marine successions of the Mamonia Complex of SW Cyprus (e.g., Clube and Robertson, 1986); also the exact same time the Kannaviou Formation volcanic ash was deposited along the suture between Troodos and Mamonia terranes in SW Cyprus. Note that claims by Osozawa et al. (2012) of boninitic magmatism persisting in Troodos until 75 Myr or even 55 Myr are based upon an erroneous interpretation of lava-sediment relationships, and are incorrect.

Taken together, the detailed local and regional geological evidences summarised above, built up from decades of study in Cyprus and neighbouring areas of the Eastern Mediterranean, provide key constraints that must be reconciled in any model for the origin of boninitic and other volcanism in the Troodos ophiolite, and acknowledge the significant differences in the geodynamic setting with respect to the IBM system.

5.2 - Did the Troodos ophiolite form by near-trench spreading above a mature subduction zone, similar to the SEMFR?

Despite many geochemical similarities between the Troodos ophiolite and the SEMFR magmas (Fig. 2, 4, 5) (Ribeiro et al., 2018; Woelki et al., 2019a), some significant geodynamic differences do nevertheless exist. For instance, the Southern Mariana is characterized by the occurrence of a juvenile volcanic arc (the Fina-Nagu Volcanic Chain) that began to develop less than 5 Myr ago (Brounce et al., 2016; Ribeiro et al., 2019; Stern et al., 2013). The Southern Mariana arc erupted basaltic to felsic, calc-alkaline magmas with an arc-like geochemical fingerprint (Ribeiro et al., 2019; Stern et al., 2013). Such a stratigraphic sequence is definitely absent in Troodos (Miyashiro, 1973; Pearce et al., 1984; Pearce and Robinson, 2010; Taylor, 1990) and never been reported elsewhere in the region (e.g., Robertson et al., 2012). The petrology and stratigraphy of the Troodos volcanics most closely resemble (albeit are not identical to) that observed in the IBM pre-arc crust, notably to the IBM low-Si boninites (Fig. 2-4) (Pearce and Reagan, 2019; Pearce and Robinson, 2010). Although the SEMFR olivine-hosted melt inclusions share similar features to the IBM pre-arc low-silica boninites (Ribeiro et al., 2022), boninites have not been sampled yet in the Southern Mariana as volcanic rocks (Ribeiro et al., 2013a; Ribeiro et al., 2015).

Because markers of mantle enrichment-depletion (e.g., Nb/Yb, TiO₂/Y) and slab fluids (e.g., Ba/Th, Rb/Th, Th/Nb, Hf/Sm, Ba/Nb) mostly reveal mantle and subduction processes (Ishizuka et al., 2020; Pearce and Robinson, 2010; Ribeiro, 2022; Straub et al., 2015; Taylor et al., 2022), they only provide some constraints into petrogenetic conditions (e.g., adiabatic decompression vs. fluid-assisted mantle melting, slab fluid composition). They cannot, however, in themselves permit discrimination between mature vs. incipient subduction zones. However, mantle refertilization may occur during magma petrogenesis, so that markers of mantle enrichment-depletion may not help in discriminating the original tectonic setting of

ophiolites; and so only markers of the slab-fluids may be reliably utilized. Indeed, the SEMFR
magmas possess some similar geochemical features in slab-fluid markers to those of the IBM
pre-arc crust, notably their olivine-hosted melt inclusions are similar to the IBM pre-arc low-
silica boninites (Fig. 2, 4B, 5), despite being emplaced above a mature subduction zone
(Ribeiro et al., 2022). The similarities in geochemical features between the SEMFR magmas
and the IBM pre-arc boninites may thus be characteristic of near-trench magmas, regardless of
whether they were formed during subduction inception or in the fore-arc of a mature subduction
zone (Pearce and Robinson, 2010; Ribeiro et al., 2022).

One key observation in long-lived convergent margins is the development of a mature
volcanic arc front that has erupted tholeiitic to calc-alkaline basalts to rhyolites, lava flows and
associated volcanoclastics (Fig. 3), which possess a clear arc fingerprint in markers of the slab
fluids (Ba/Th, Ba/Nb, Th/Nb ...) (Gill, 1981; Ishizuka et al., 2006; Ishizuka et al., 2011b;
Pearce et al., 2005; Stern, 2002; Stern et al., 2003; Straub, 2003; Straub et al., 2015). The fact
that the Troodos low-silica boninites display similar major and trace element contents, and
notably similar slab-fluid markers (Ba/Th, Rb/Th, Cs/Th, Hf/Sm, La/Sm) to the IBM pre-arc
low-silica boninites (Pearce and Robinson, 2010) (Fig. 2 - 7) implies that they likely formed
during similar petrogenetic conditions (Pearce and Reagan, 2019; Pearce and Robinson, 2010).
Lastly, the absence of any high-Si boninites in Troodos, which marks the onset of arc
magmatism in IBM (Coulthard et al., 2021; Reagan et al., 2019; Shervais et al., 2019; Shervais
et al., 2021), further demonstrates that fluid-assisted mantle melting, and thereby the onset of
any arc volcanism, was probably never reached in Troodos, precluding its formation in a long-
lived and relatively stable convergent margin (Pearce et al., 1984; Pearce and Robinson, 2010).

Such observations concur with the notion that Troodos likely emplaced during near-trench
spreading above the shallow part of the highly dehydrating nascent, subducted Neo-Tethyan
plate in Late Cretaceous (Pearce et al., 1984; Pearce and Robinson, 2010). The ophiolite rapidly

aborted (likely within a few millions of years) before the onset of arc magmatism and any associated arc volcanic edifices (Pearce et al., 1984; Pearce and Robinson, 2010). Regional constraints (Section 5.1 above) suggest that curtailment of the Neo-Tethyan subduction/supra-subduction spreading system, including Troodos and neighbouring ophiolites, was most probably a consequence of the collision of the Arabian margin with the trench (e.g., Clube and Robertson, 1986; Robertson et al., 2012).

5.3 - Chemical characteristics of near-trench magmas: Implications for the petrogenesis of the Troodos ophiolite

Although related to a mature subduction zone, the development of a new basaltic crust within 90 kilometers from the trench in the SEMFR has the potential to provide critical insights into how spreading and formation of new oceanic crust may occur just above the shallow part of a dehydrating slab, where cold conditions usually prevail and favor mantle serpentinization (Hyndman and Peacock, 2003). In this section, we use further the geochemical and geodynamic characteristics of the SEMFR magmas to place new constraints onto magma petrogenesis in Troodos.

The similarities in geochemical features between the SEMFR magmas and the IBM pre-arc low-Si boninites imply that their enrichments in markers of slab dehydration (Fig. 5) and low K₂O contents (Fig. 2A) may be ascribed to a near-trench setting both during subduction inception and in the fore-arc of a long-lived subduction zones (Pearce and Robinson, 2010; Ribeiro et al., 2022). We therefore propose that such similarities can be further utilized to discriminate between near-trench environments, relative to arc and back-arc settings, but not for incipient vs. mature subduction zones. For instance, low K₂O content, along with high markers of slab dehydration (Rb/Th, Ba/Th, Cs/Ba, Cs/Th, H₂O/Ce) in the IBM pre-arc boninites and the SEMFR olivine-hosted melt inclusions (Fig. 2A, Fig. 5)

may represent diagnostic features of near-trench magmas (Pearce and Robinson, 2010; Ribeiro et al., 2015). Such high markers of the water-rich slab fluids in the near-trench magmas, compared with worldwide arc magmas ($\text{Rb/Th} \leq 111$, $\text{Cs/Th} \leq 4$, $\text{H}_2\text{O/Ce} \leq 10,612$) (Ribeiro et al., 2015), imply extensive slab dehydration close to (< 100 km) the trench (Maunder et al., 2020; Pearce and Robinson, 2010; Reagan et al., 2019; Ribeiro, 2022; Ribeiro et al., 2022; Ribeiro et al., 2015).

Because subducted K-rich mineral phases (e.g., lawsonite) break down beneath the arc and the back-arc basin, subduction zone magmas are progressively enriched in potassium with increasing slab depth and increasing distance from the trench (Dickinson, 1975; Kimura and Stern, 2008; Pearce and Robinson, 2010). Therefore, near-trench magmas are expected to have low K_2O content (< 1 wt%) (Pearce and Robinson, 2010), along with high ratios in water-rich slab fluid markers (Rb/Th , Ba/Th , Cs/Ba , Cs/Th , $\text{H}_2\text{O/Ce}$). The enrichment in such slab-fluid markers and the low K_2O content of the Troodos ophiolite is thus consistent with its formation by near-trench spreading. Using further the actual geodynamic setting of the SEMFR, we can place some additional constraints onto the paleo-location of the Troodos ophiolite in the Late Cretaceous. For example, the low K_2O content and the high Rb/Th ratios of the Troodos magmas (Fig. 2A, 5) suggest that it likely overlaid the shallow part of the nascent subducted slab (presumably at less than ~ 90 km depth to the slab), which dehydrated extensively within, perhaps, $\sim 90 - 100$ km from the trench (Fig. 7) (Ribeiro et al., 2018). Arc magmas from the mature IBM subduction zone are, instead, more enriched in K_2O , but have lower Rb/Th , which is consistent with their formation above a deeper portion of the subducted slab (~ 100 km depth) that dehydrated less relative to the near-trench magmas (Fig. 2A, 5).

Island arc volcanoes from worldwide subduction zones are also known to have preserved their location at a slab depth of roughly 112 ± 19 km (Tatsumi, 1986), or 124 ± 38

km (Gill, 1981), or 105 km (Syracuse and Abers, 2006) for millions of years. Such a relatively steady location for mature arc volcanoes suggests that the Troodos ophiolite likely overlaid the nascent, subducted Neo-Tethyan slab at less than $\sim 100 - 120$ km depth. Our estimates of paleo-trench distance and paleo-slab depth, however, assume a similar slab P-T path in Troodos to that observed today underneath the SEMFR (Ribeiro et al., 2013b), as the actual P-T path of the slab that subducted beneath Troodos is unknown. A shallower slab P-T path (i.e., slab with a smaller dip) in Troodos would imply that the near-trench magmas could have formed further away from the trench. By contrast, a deeper slab P-T path (i.e., slab with a higher dip than in the SEMFR) would result in near-trench magmas that developed much closer to the trench (Fig. 7) (Ribeiro, 2022). However, most subduction zones have been proposed to initiate with a warm slab P-T path, which cools over time (Agard et al., 2020; Agard et al., 2016; Soret et al., 2022). As such, it is likely that the incipient Neo-Tethys subducted slab was warmer than the Pacific plate subducting today underneath the SEMFR.

5.4 - Origin of the slab fluids during subduction inception in Troodos

To place additional constraints onto Troodos ophiolite's formation and evolution, here we examine the sources of the slab fluids that were captured by the pre-arc magmas as subduction initiated in the late Cretaceous. Pb-Sr-Nd isotopic ratios can provide key constraints onto the subduction and mantle sources of magmas. Because Pb and Sr are fluid-mobile elements that are sensitive to the slab fluids, their radiogenic isotopes can be used to infer which part of the subducted slab the aqueous fluids and the slab melts are derived from. By contrast, Nd radiogenic isotopes provide constraints onto the mantle source of the magmas (Fig. 8 - 9). Although the composition of the nascent Neo-Tethyan slab that was subducting underneath Troodos is unknown, in a similar fashion to Taylor et al. (2022) and

Fonseca et al. (2017), we used the isotopic composition of the drilled sediments from the Eastern Mediterranean Sea (Klaver et al., 2015) and of the Hawasina ophiolite (Oman) (Chauvet et al., 2011), which are believed to be appropriate representatives respectively of the sediments and of the underlying oceanic crust from the subducted Neo-Tethys Ocean. They are hence considered likely to be the closest match to the composition of the Neo-Tethys plate, whose incipient subduction in the mid to late Cretaceous led to the formation of the Troodos ophiolite. The asthenospheric mantle flowing underneath Troodos is likely to have the Pb-Sr-Nd isotopic composition of MORB-like depleted mantle (DMM), as also proposed by Taylor et al. (2022) (i.e., $^{143}\text{Nd}/^{144}\text{Nd} = 0.5129$; $^{206}\text{Pb}/^{204}\text{Pb} = 18.33$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.48$; $^{208}\text{Pb}/^{204}\text{Pb} = 37.93$; $^{87}\text{Sr}/^{86}\text{Sr} = 0.70300$) (Fig. 8). Compositions of the end-member are detailed in supplementary Table S2.

Nd-Sr isotopic composition of the Troodos magmas show that the water-rich slab fluids are mostly released from dehydrating the subducted serpentinized mantle (Fig. 8A). These water-rich slab fluids interacted with the DMM-like asthenospheric mantle to trigger mantle melting in Troodos. The $^{86}\text{Sr}/^{87}\text{Sr}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ isotopic compositions plotted against Ba/Th of the Troodos pre-arc magmas suggest that the water-rich slab fluids were mostly released from dehydrating the subducted sediments (~20%) and the subducted serpentinized mantle (~80%) (Fig. 8 - 9). The Troodos pre-arc magmas captured up to 3 to 20% of this water-rich slab fluid. The Th/Nb ratios plotted against Pb isotopic ratios (Fig. 9C) demonstrate further that the Troodos magmas also captured up to 20% of sediment melt upon their genesis. In the $^{207}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams (Fig. 8C - 9D), some of the Troodos pre-arc magmas plot along a distinct mixing line which overlaps the compositional fields of the IBM magmas. This more radiogenic Pb isotopic compositions, along with lowered Th/Nb in some of the Troodos pre-arc magmas (which is probably due to Nb enrichment in boninites: Rogers et al., 1989; Taylor et al., 2022; Fig. 9C),

reveals melt enrichment, potentially due to seamount subduction as proposed by Taylor et al. (2022) (Fig. 10).

The compositional variations in Pb-Sr radiogenic isotopes, coupled with the slab-fluid markers Ba/Th and Th/Nb clearly demonstrate that deserpentinization of the subducted mantle influenced dehydration and melting of the overlying crust in the amphibolite facies and sediments (Fig. 6, 8 - 9) to produce the Troodos pre-arc magmas. The incipient Neo-Tethyan subducted plate hence began to dehydrate and melt as the slab began foundering. A certain fraction of the Troodos magmas potentially captured the slab crustal melts released in Taylor et al.'s (2022) seamount subduction model (Fig. 8 - 10). By contrast, in IBM, the incipient subducted Pacific plate began to dehydrate within $\sim 1 - 2$ Myr following the onset of subduction, so that the first basalts that erupted in the IBM pre-arc crust (i.e., FABs) captured only relatively little to no slab fluids during their petrogenesis (Coulthard et al., 2021; Reagan et al., 2010; Reagan et al., 2017; Shervais et al., 2019). Such chemical differences between Troodos and IBM could reveal sediment accretion at the onset of the IBM (Li et al., 2019; Ribeiro et al., 2022); while the sediments from the Neo-Tethyan plate could be readily subducted in Troodos. These differences may also be consistent with a warmer slab surface temperature, seamount subduction (Taylor et al., 2022), and/or a return toroidal flow of asthenospheric mantle in Troodos (Pearce and Robinson, 2010); and so further investigations are required. Despite the superficial resemblance of Troodos to the IBM, we emphasise that each subduction zone system must be carefully examined on a case by case basis in order to better comprehend the subduction and mantle processes that prevailed over its lifetime, and hence to better understand the generic range of processes operating at convergent margins systems.

6- Conclusions

Magma series in the Troodos ophiolite record a distinctive subduction signal characterized by strong enrichments in fluid-mobile elements (Cs, Rb, Ba, Th, U, Pb) compared with MORBs and worldwide arc magmas, and demonstrating its supra-subduction origin (Pearce, 1975; Pearce et al., 1984). The similarities in markers of the water-rich slab fluids (Rb/Th, Ba/Th, Cs/Ba, Cs/Th, H₂O/Ce) between the Troodos ophiolite, the SEMFR magmas and the IBM pre-arc boninites, along with their low K₂O contents (< 1 wt%; Fig. 2), imply that the ophiolite formed by near-trench spreading above a highly dehydrating, subducted slab (i.e., within ~100 km from the trench). The lack of coeval arc rocks (i.e., basaltic to felsic, calc-alkaline rocks that usually erupt during arc volcanism), volcanoclastics and associated volcanic edifices clearly demonstrate that the Troodos ophiolite formed by seafloor spreading during or immediately following subduction inception, long before any arc magmatism initiated (Pearce et al., 1984; Pearce and Robinson, 2010; Robinson et al., 1983). The first evidence for any potential arc magmatic activity is more than 10 Myr after seafloor spreading and crust formation ceased, and that activity anyway appears geodynamically unrelated. Such geological observations thus preclude the formation of Troodos in the fore-arc or in the back-arc basin of a long-lived subduction zone, but much more likely during subduction inception.

Nd-Pb-Sr radiogenic isotopes coupled with slab-fluid markers further show that deserpentinization of the subducted lithospheric mantle likely modulated rapid dehydration and melting of the overlying sediments, as well as melting of the amphibolitized oceanic crust of the nascent Neo-Tethyan subducted plate. If worldwide subduction zones maintain an arc location at ~ 100 - 120 km depth to the slab, regardless their slab thermal state (Gill, 1981; Tatsumi, 1986), we can reasonably argue that the paleo-depth of the Neo-Tethyan subducted plate in Troodos was likely less than 100 km in the late Cretaceous. Lastly, we emphasize the importance of the careful integration of thorough geological and petrological observations (both regional and local) with precise geochemical interpretations to infer the

original geodynamic setting of ophiolites, as geochemistry alone can only provide some pieces of the puzzle.

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 937

938 Figure captions

939 **Fig. 1: Location maps of the Troodos ophiolite of Cyprus.** A) Location map of Cyprus.
 940 The Troodos ophiolite of Cyprus is shown in red. B) Simplified geological map of the 92-
 941 Myr-old Troodos ophiolite after (Martin et al., 2020), with location of the samples examined
 942 in this study. C) Inset map of Cyprus showing Troodos in red.

943
 944 **Fig. 2: Geochemical features of the Troodos ophiolite magmas.** A) SiO₂ (wt%) vs. K₂O
 945 (wt%) classification diagram (Peccerillo and Taylor, 1976). B) MgO vs. TiO₂ diagrams used
 946 to characterize boninites. C) MgO (wt%) vs. SiO₂ (wt%) diagram of Pearce and Reagan
 947 (2019) used to discriminate boninites from subduction zone magmas. The Troodos boninites
 948 plot within the compositional field of the low-silica boninites. Troodos magmas are compared
 949 with the SEMFR magmas and the IBM pre-arc magmas. Samples are only filtered for
 950 freshness (LOI < 2 wt%) and a total sum of oxides of 100 ± 2 wt% in all diagrams. FABs:
 951 fore-arc basalt, HSB: high-silica boninites, LSB: low-silica boninites, HMA: high-
 952 magnesium andesites, bas. andesites: basaltic andesites.

953
 954 **Fig. 3: Tholeiitic vs calc-alkaline discriminating AFM diagram (Irvine and Baragar,**
 955 **1971).** The Troodos upper and lower magmatic series plot within the tholeiitic compositional
 956 field, demonstrating the absence of calc-alkaline series in Troodos (Pearce and Robinson,
 957 2010). The thin black line delineates the boundary between tholeiitic and calc-alkaline
 958 magmas. The IBM arc magmas (grey symbols), compiled by Ribeiro et al. (2022), are plotted
 959 for comparison.

960
 961 **Fig. 4: Averaged trace element patterns of the Troodos lower and upper series.**
 962 Comparison between (A) the SEMFR basaltic glasses to the Troodos lower basalts, (B) the
 963 SEMFR olivine-hosted melt inclusions (OLMI) and the Troodos upper boninites, and (C) the
 964 IBM pre-arc boninites and the Troodos boninites. Trace elements are normalized to the
 965 depleted mantle source of MORBs (DMM) (Salters and Stracke, 2004). The SEMFR magmas
 966 were divided into SW and NE sections, as in Ribeiro et al. (2013b), for a thorough
 967 comparison with the Troodos magmas. The SW SEMFR basalts possess an arc-like
 968 subduction signal, compared with the NE SEMFR magmas. OLMI: olivine-hosted melt
 969 inclusions, LSB: low-silica boninites, HSB: high-silica boninites.

970
 971 **Fig. 5: Composition of the slab fluids released in Troodos.** A) Th/Nb vs. Nb/Yb, B) Ba/Th
 972 and C) Cs/Ba vs. Rb/Th diagrams, after Pearce et al. (2005). The Troodos magmas are
 973 strongly enriched in slab-fluid markers (Rb/Th, Cs/Ba and Ba/Th) and to a lesser extent in
 974 Th/Nb (a proxy used to track sediment melting) (Johnson and Plank, 1999; Pearce et al.,
 975 2005), indicating that they captured water-rich slab fluids and the sediment melts
 976 respectively. We also plotted the compositional fields of the Mariana back-arc basin basalts
 977 (BABBs) (Ribeiro et al., 2022) and of the mid-ocean ridge basalts (MORBs) (Jenner and
 978 O'Neill, 2012) for comparison. The Lau Basin boninites display BABB-like slab-fluid
 979 markers, which is consistent with their formation behind the volcanic arc front, as they
 980 captured the deeper slab fluids which are generally much less enriched in fluid-mobile,
 981 incompatible elements (Pearce et al., 2005). As such, the strong enrichment in markers of
 982 slab dehydration in the Troodos magmas is inconsistent with its formation in a back-arc
 983 setting. Instead, high ratios in Ba/Th, Rb/Th, Cs/Th and Cs/Ba are more consistent with
 984 formation during near-trench spreading either in the fore-arc of a long-lived subduction zone,
 985 as the SEMFR, or during subduction inception, as the IBM pre-arc boninites. FABs: fore-arc

basalt, HSB: high-silica boninites, LSB: low-silica boninites, MORBs: mid-ocean ridge basalts, BABBs, back-arc basin basalts.

Fig. 6: Slab melting in the amphibolite facies. Hf/Sm vs. La/Sm diagram (Pearce et al., 1992) used to track melting of the slab crust in the amphibolite facies. The slight enrichment in Hf/Sm in the Troodos pre-arc magmas, as compared to the mid-ocean ridge basalts (MORBs), suggests that the subducted, amphibolitized crust melted during subduction inception of the Neo-Tethyan plate, but perhaps to a lesser extent than in the IBM pre-arc crust.

Fig. 7: Inferring the distance to the paleo-trench in Troodos. A) H₂O/Ce and B) Rb/Th vs. trench distance diagrams showing that the magmas that formed within the vicinity of the trench display the highest H₂O/Ce and Rb/Th compared with arc and back-arc magmas, thus demonstrating a decrease in the water-rich slab fluids away from the trench (Ribeiro, 2022; Ribeiro et al., 2022; Ribeiro et al., 2015). Because the investigated near-trench magmas systematically display the highest ratios, these can be used as diagnostic features of the near-trench magmas. Therefore, we can use these characteristics and the actual location of the SEMFR to infer the distance to the Troodos paleo-trench during the Late Cretaceous. See text for details. We used the averaged composition and slab depth of the SEMFR magmas of Ribeiro et al. (2015) to assess the SEMFR-like paleo-slab depth; and the slab depth of Matthew-Hunter of Ribeiro (2022) to assess the depth of a warmer paleo-slab.

Fig. 8: Pb-Sr-Nd isotopic composition of the Troodos ophiolite. A) ¹⁴³Nd/¹⁴⁴Nd vs. ⁸⁷Sr/⁸⁶Sr; B) ⁸⁷Sr/⁸⁶Sr vs. ²⁰⁶Pb/²⁰⁴Pb, and C) ²⁰⁶Pb/²⁰⁴Pb vs. ²⁰⁷Pb/²⁰⁴Pb diagrams used to track the mantle and subduction sources in the Troodos upper and lower series. We used the Pb-Sr-Nd isotopic composition of the Neo-Tethyan sediments of Klaver et al. (2015) and Fonseca et al. (2017), and of the Neo-Tethyan oceanic crust of Chauvet et al. (2011) and Taylor et al. (2022). We also used published isotopic composition (Cannaò et al., 2015; Delacour et al., 2008; Scambelluri et al., 2001) for the subducted serpentinized mantle. Details regarding the end-members and the mixing calculations for IBM can be found in Ribeiro et al. (2022). Sed.: sediments, serp.: subducted serpentinized mantle, AOC: altered oceanic crust.

Fig. 9: Tracking the sources of the slab fluids in Troodos. A) Ba/Th vs. ²⁰⁶Pb/²⁰⁴Pb and B) Ba/Th vs. ⁸⁷Sr/⁸⁶Sr diagrams showing the sources of the water-rich slab fluids. C) Th/Nb vs. ²⁰⁶Pb/²⁰⁴Pb diagram showing the enrichment in sediment melts. D) ²⁰⁶Pb/²⁰⁴Pb vs. ²⁰⁸Pb/²⁰⁶Pb diagram. The subducted serpentinized mantle from the Neo-Tethyan plate likely dehydrated first to trigger dehydration and melting of the overlying oceanic crust and sediments. We used published compositions for the serpentinized mantle, the sediments and the oceanic crust subducting underneath Troodos (Cannaò et al., 2015; Chauvet et al., 2011; Fonseca et al., 2017; Klaver et al., 2015) in our mixing calculations. Compositions of the end-members and the slab fluids for IBM and SEMFR, as well as mixing considerations, are detailed in Ribeiro et al. (2022). AOC: altered oceanic crust. The black start represents the estimated mantle composition both for Troodos and IBM.

Fig. 10: Paleo-reconstruction of the Neo-Tethyan Troodos ophiolite in Late Cretaceous (Pearce et al., 1984; Pearce and Robinson, 2010). A) Paleo-geographic reconstruction of the Eurasia-Africa-Arabia plate boundary in Late Cretaceous time, modified after Pearce and Robinson (2010) and Robertson et al. (2012). B) Sketch illustrating the processes that occurred in Troodos during the Late Cretaceous. During subduction inception, extension and

near-trench spreading of the upper lithosphere allows the pre-arc asthenosphere to flux in and melt. The nascent subducted Neo-Tethyan slab began to dehydrate and melt as soon as it began descending, so large fluxes of water-rich fluids were released within, perhaps, 90 km from the paleo-trench. Lower basalts and upper low-silica boninites were subsequently produced in Troodos. The slab fluids were likely released from dehydrating the subducted mantle, which modulated dehydration and melting of the altered oceanic crust (AOC) in the amphibolite facies and the overlying sediments from the nascent, Neo-Tethyan subducting plate. The Troodos subduction zone aborted shortly, before the onset of any arc magmatism.

Supplementary material

Supplementary text that contains details about data filtering and references used for data compilation.

Table S1: Compiled dataset for major and trace element composition of the fresh glass shards and olivine-hosted melt inclusions from the Troodos ophiolite.

Table S2: Composition of the end-members (mantle source, subducted sediment, oceanic crust and serpentinized mantle) used for the mixing calculations for the Troodos magmas.

Figure 1

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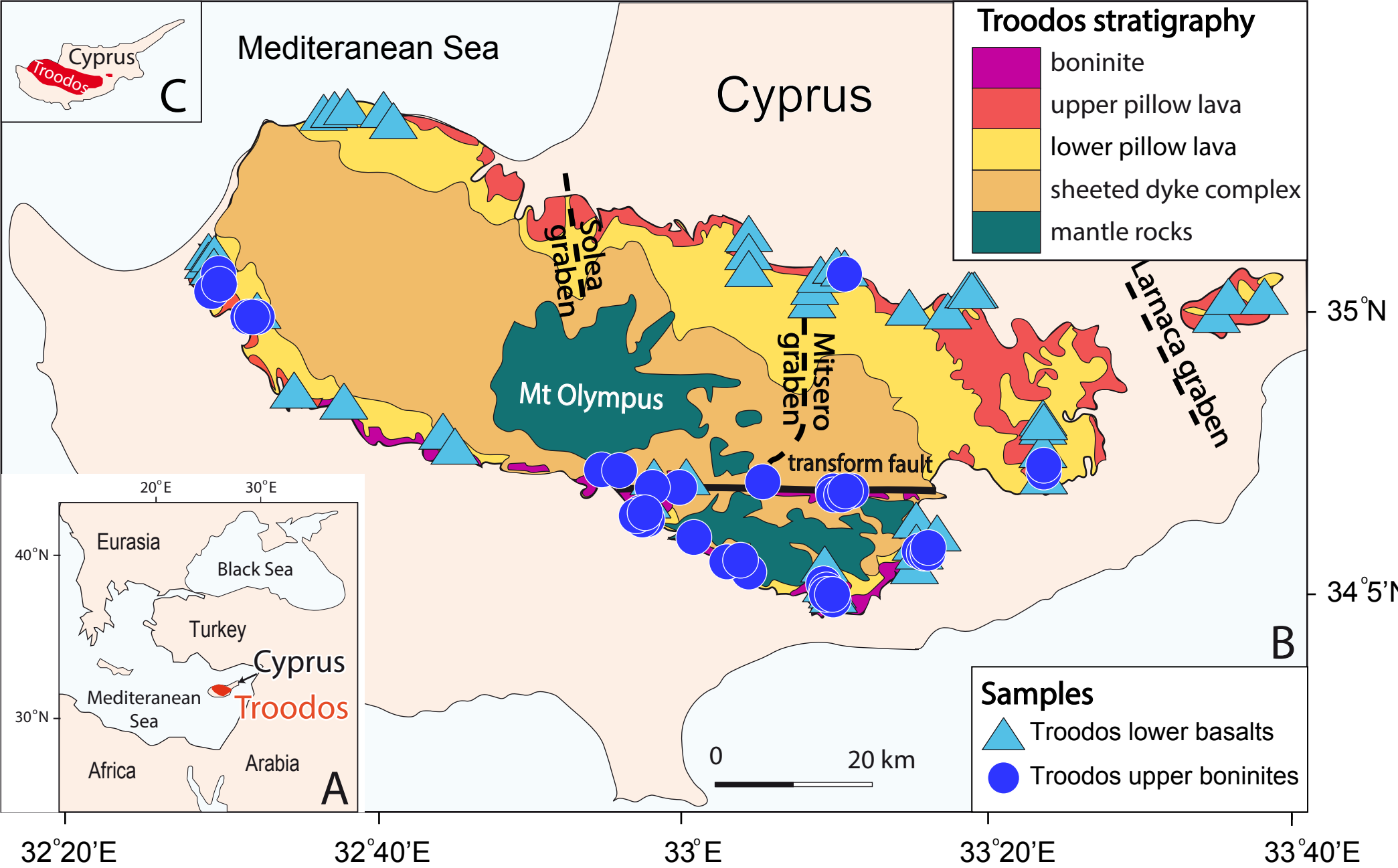


Figure 2

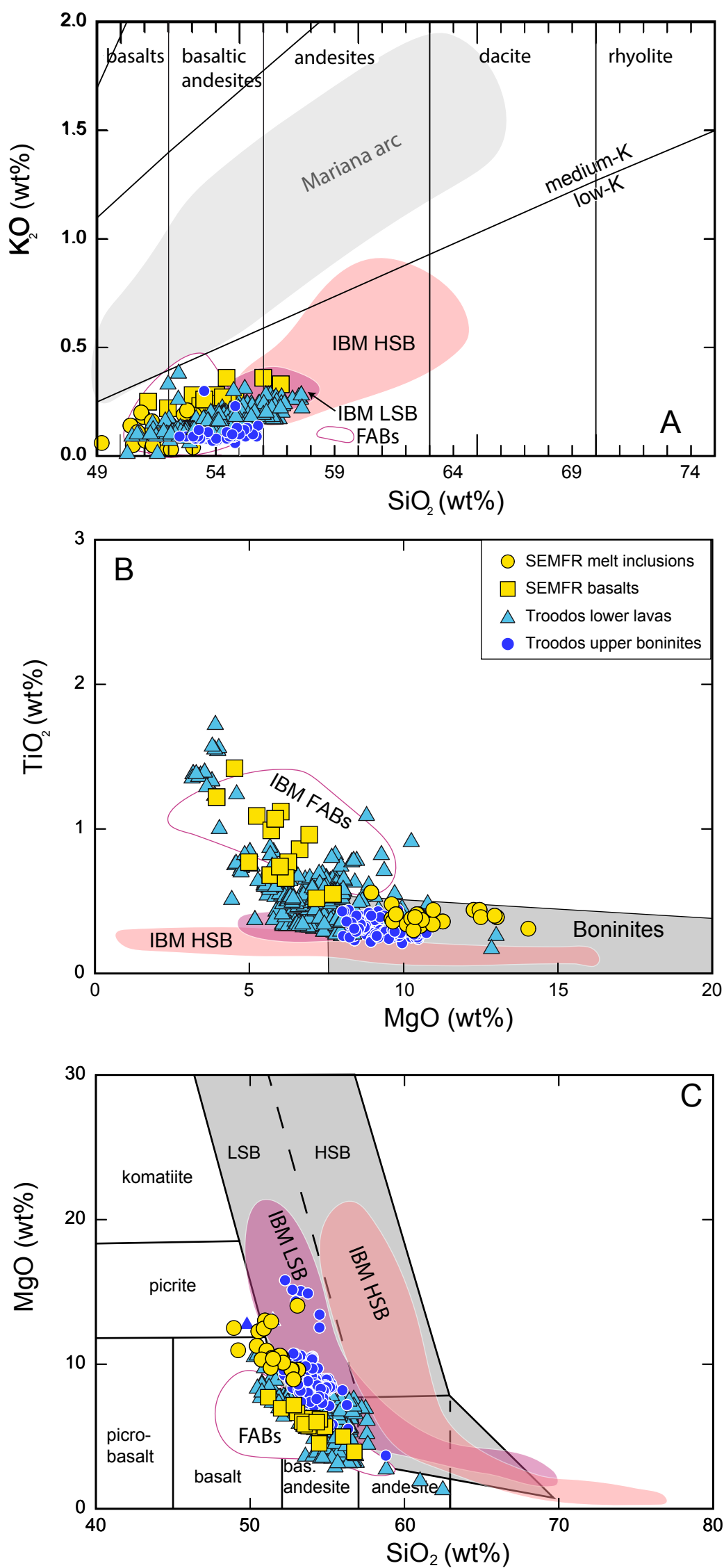
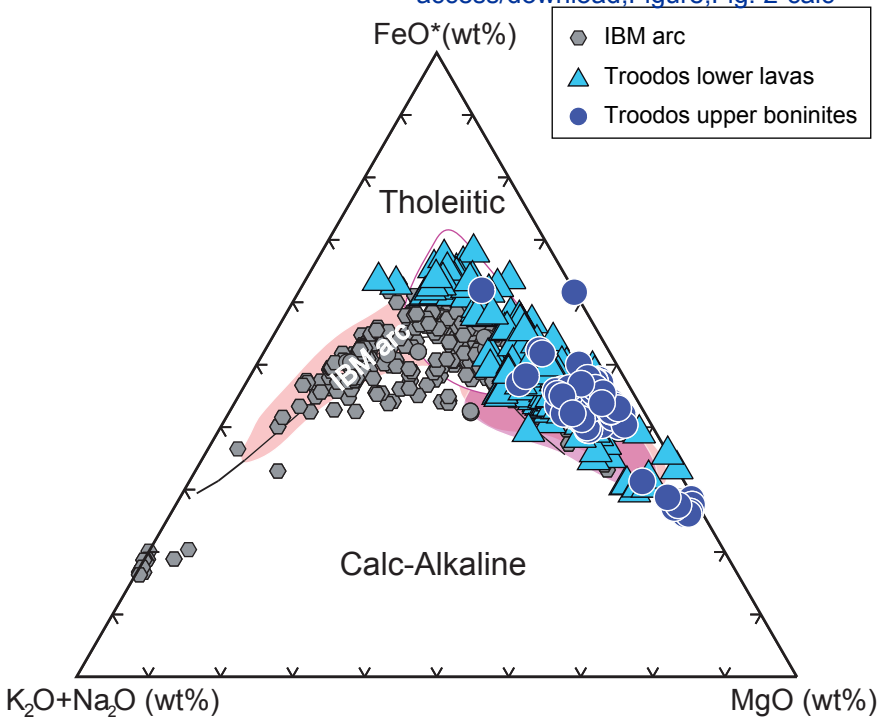
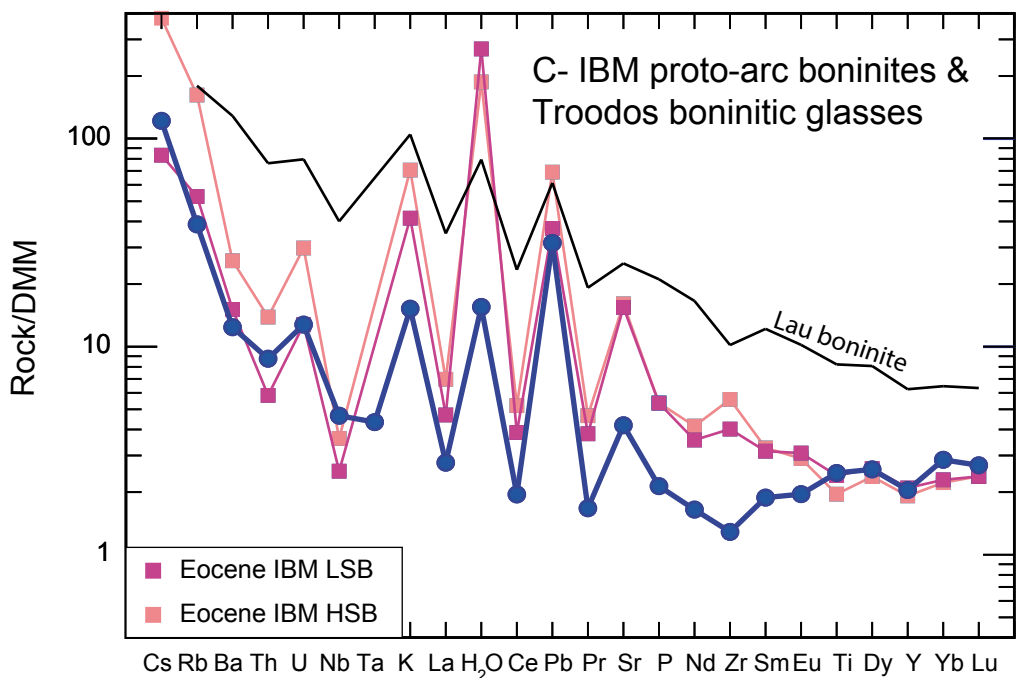
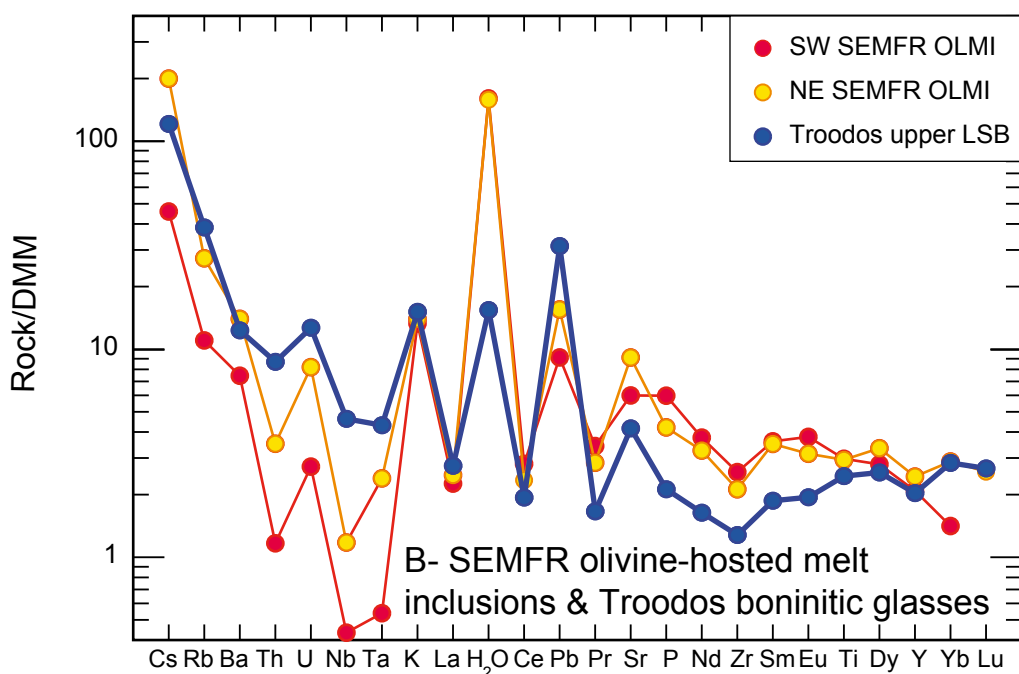
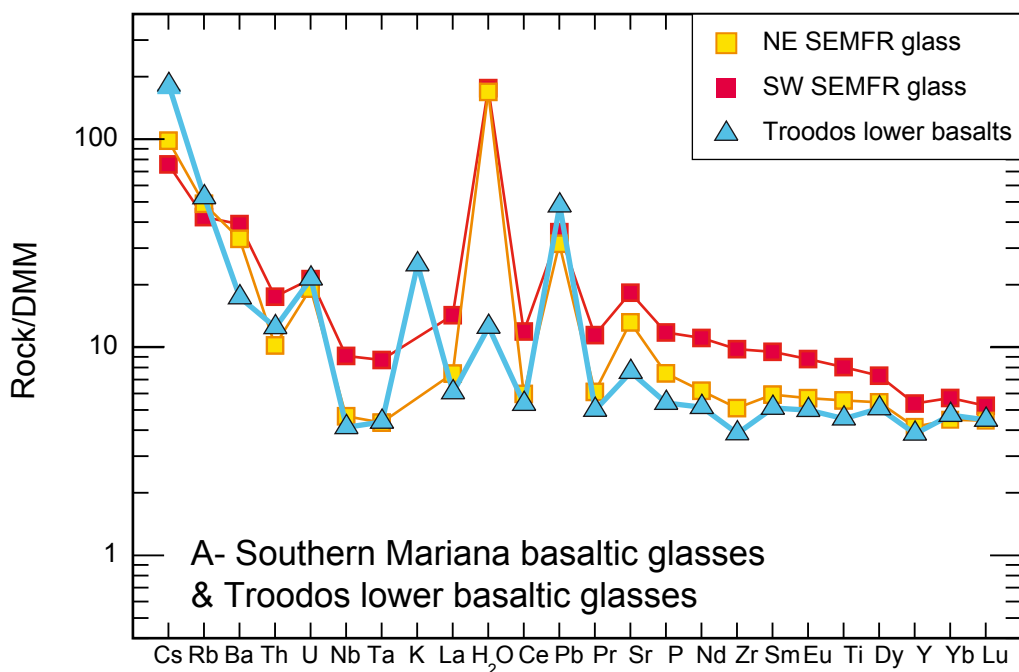
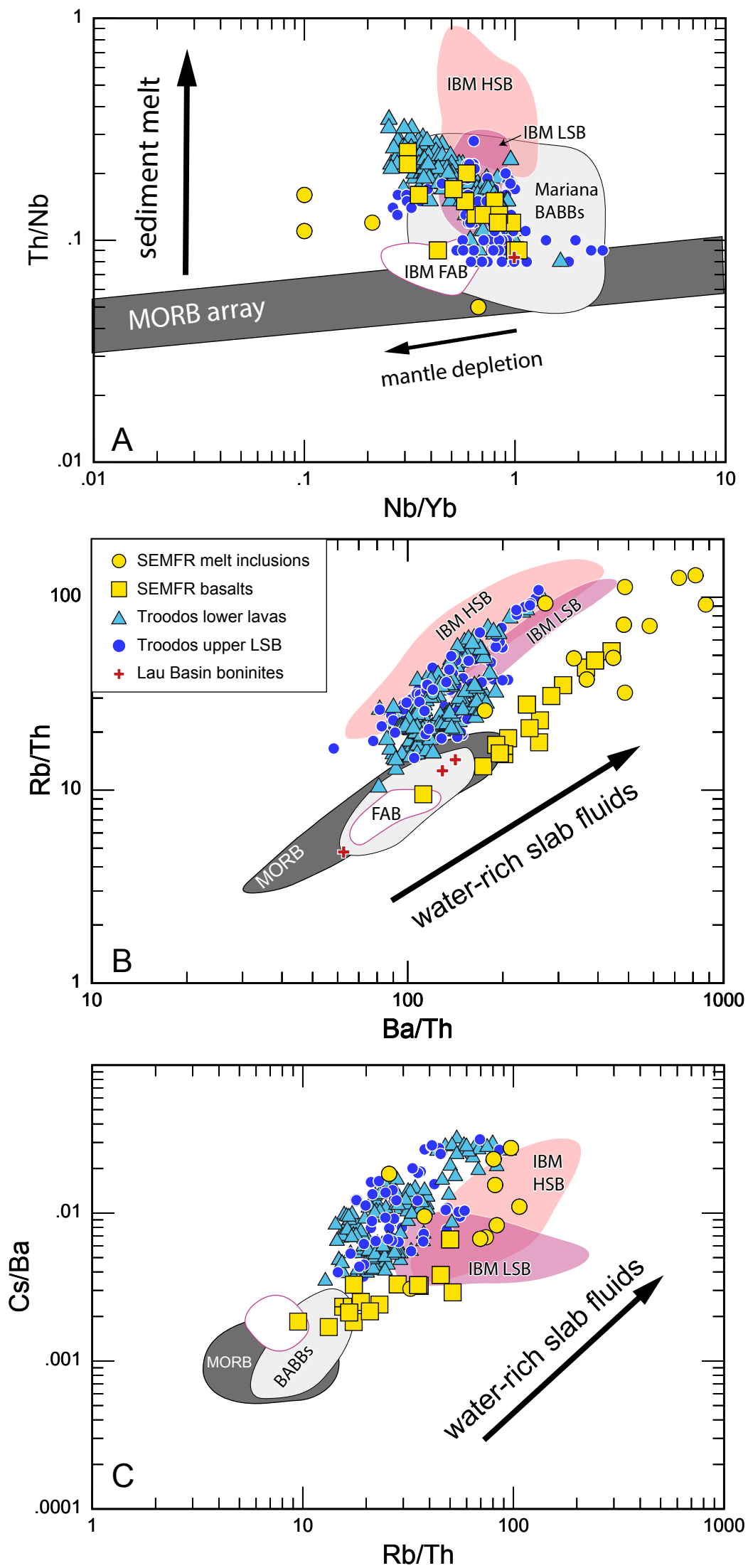
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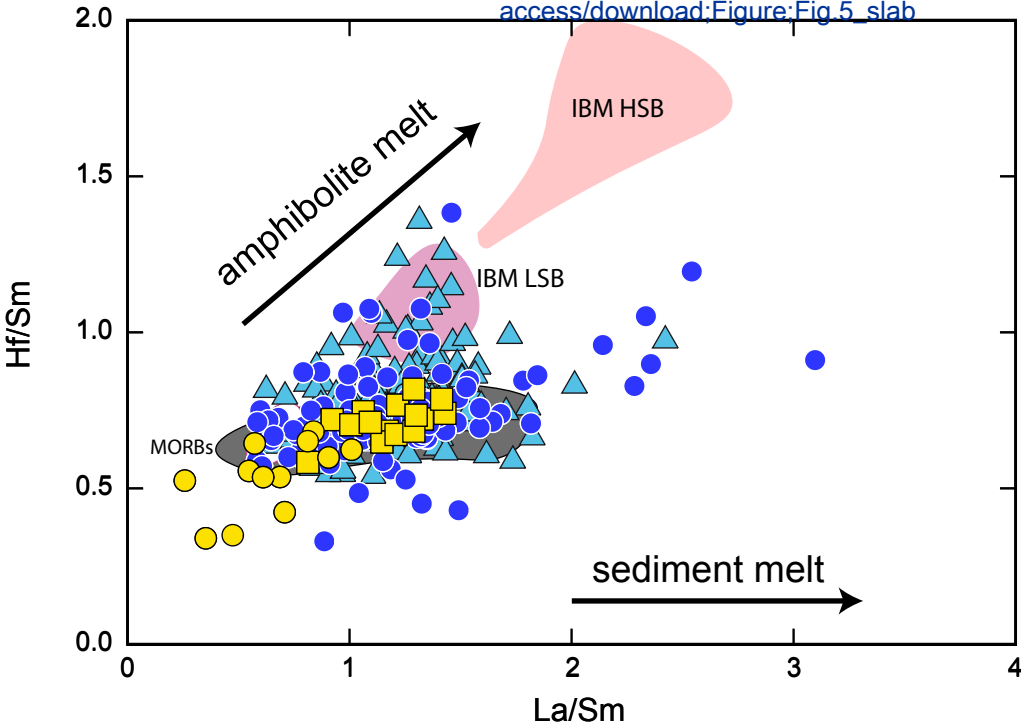
Figure 3

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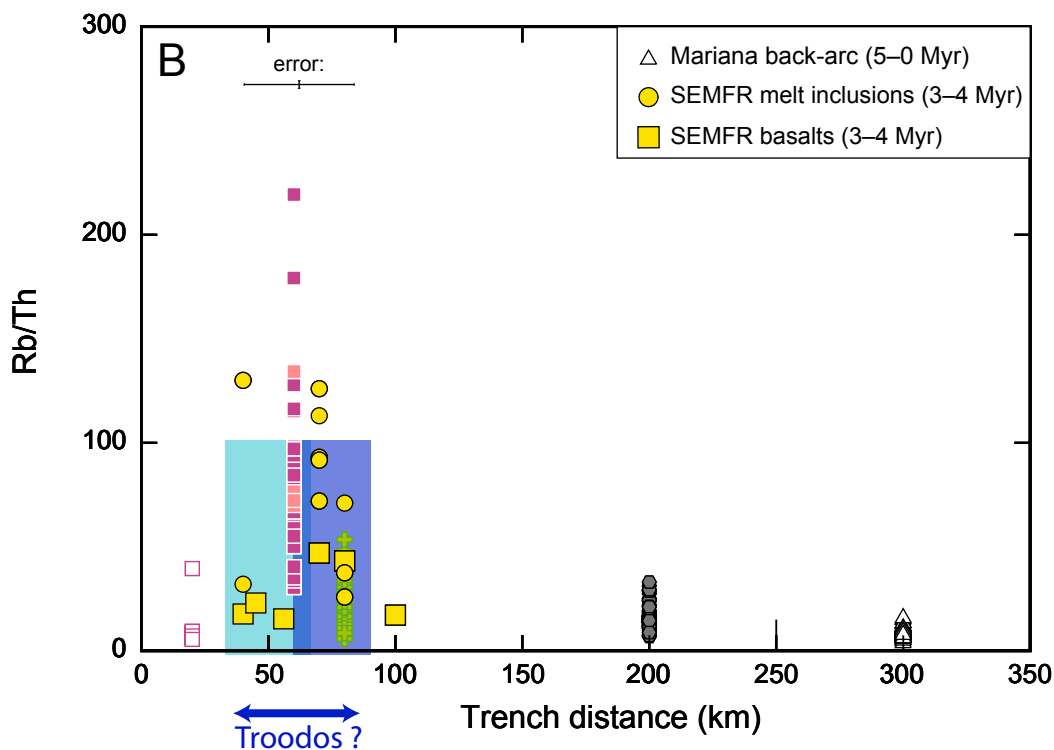
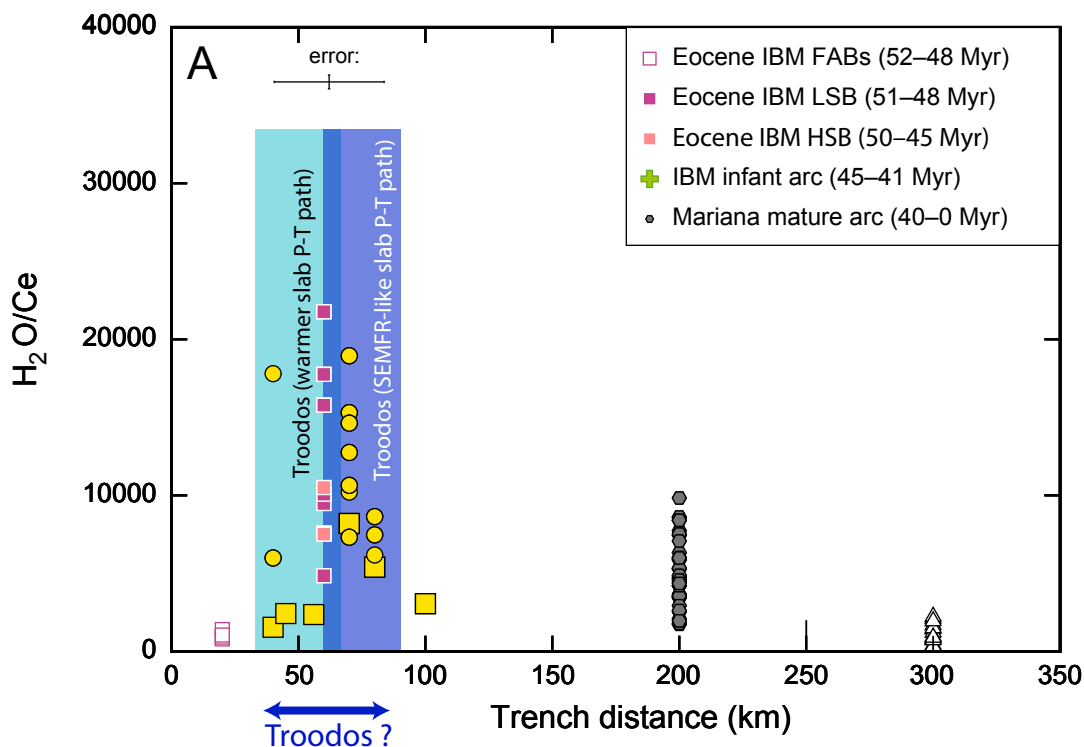
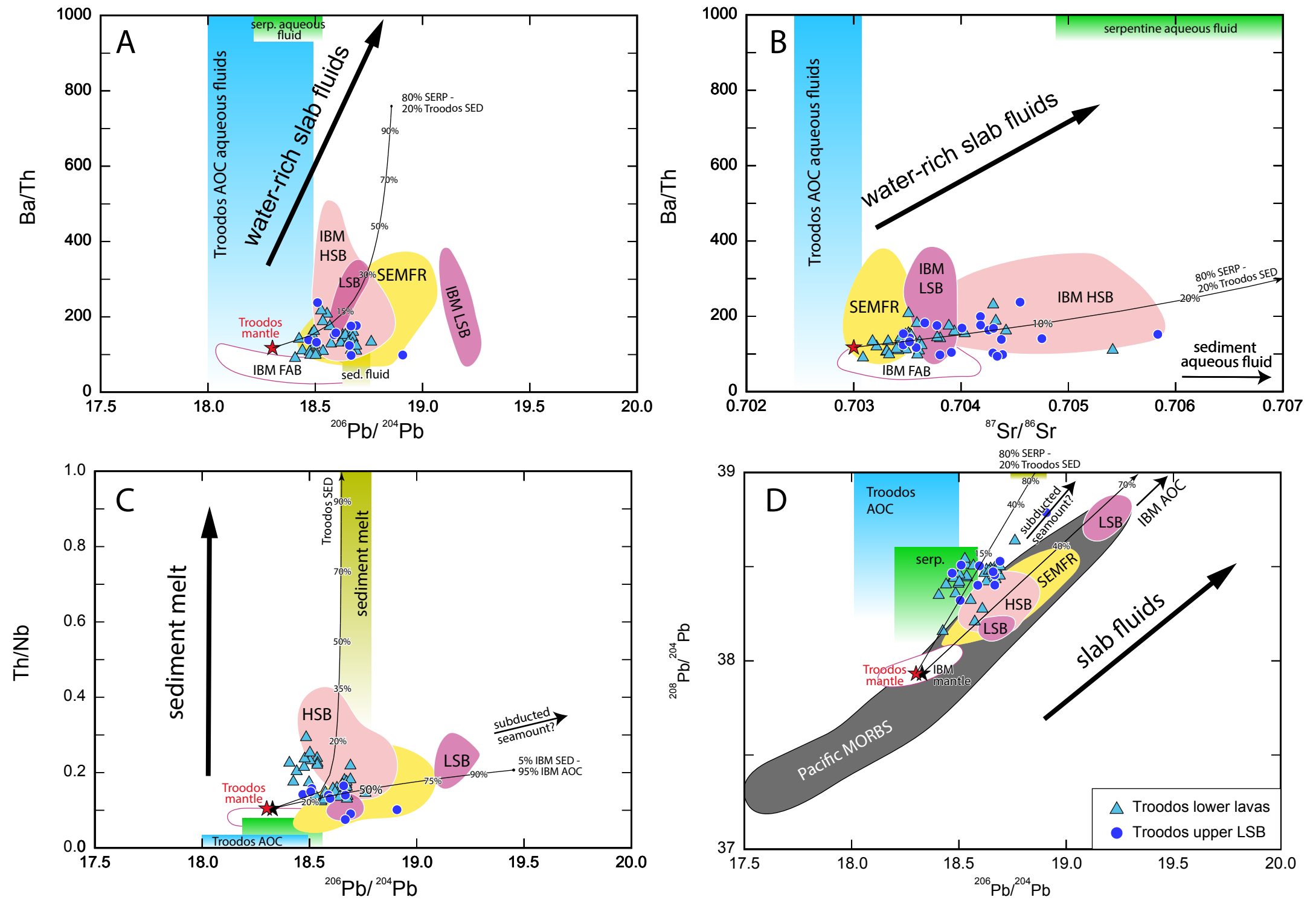


Figure 8

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