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Oligo-miocene subduction-related volcanism of the loyalty and three Kings ridges, SW Pacific: A precursor to Tonga-Kermadec arc

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Abstract :

The SW Pacific region contains several ridges and basins that are inferred to represent pre-Quaternary volcanic arcs and back-arc basins. The geology of these features is less well characterized than that of the active Tonga-Kermadec and Vanuatu arcs. We report new major and trace element, and Pb, Hf, Sr and Nd isotope data for 27 lavas dredged from the Loyalty and Three Kings ridges during the 2015 VESPA cruise of R/V l'Atalante. Low-K basalts were dredged from the seabed deeper than 3300 m, and high-K to shoshonitic suites from shallower ridge crests at 2000–3300 m. The samples are mainly basalts, with lesser trachybasalts, basaltic andesites, trachyandesites andesites, dacites, and one granite (anhydrous SiO2 and K2O + Na2O range from ~47 to 64 and 1.5 to 11 wt% respectively). Trace element patterns allow discrimination of three geochemical signatures, identified as i) depleted, ii) transitional and iii) enriched, based on their light to heavy rare earth element (REE) ratios (with La/Sm ranging from 0.4 to 8). Depleted and transitional samples are basalts, featuring REE concentrations similar to MORB, but with high field strength element and large ion lithophile element contents, typical of back-arc basin basalts. The most enriched samples are basaltic andesites, andesites, trachyandesites and trachytes with island arc magma trace element signatures. Pb isotope ranges are limited (208Pb/204Pb ~38 to 39.8, 207Pb/204Pb ~15.51 to 15.64 and 206Pb/~17.9 to 20.1), while Hf isotopes display more diverse compositions (εHf ranging from +7.7 to +14). Both Nd (εNd = 2.8–9.3) and Sr (87Sr/86Sr = 0.7026–0.7048) isotopes are correlated with Hf data. Trace element and isotopic compositions can be explained in terms of mixing between three distinct geochemical endmembers in the mantle resembling DMM, HIMU and EM-2 sources. Our study confirms voluminous subduction-related magmatism on the Loyalty and Three Kings ridges, mostly of Late Oligocene – Early Miocene age. The issue of polarity of subduction to generate these rocks remains open, but the composition-space-time distribution of the igneous rocks can be explained in the context of SW Pacific geodynamics using a west-dipping Pacific slab model.

Highlights

► Late Oligocene–Miocene subduction-related magmatism on the Loyalty and Three Kings ridges.

Keywords : Zealandia, Loyalty Ridge, Three Kings Ridge, Igneous rocks, Geochemistry, Subduction

1. Introduction

The 95% submerged continent of Zealandia (Fig. 1A, Mortimer et al., 2017, 2020a) forms the western backstop to a region of active and inactive arcs and back-arc basins in the southwest Pacific. The region has been volcanically active for more than 100 m.y. and hundreds of rift, hotspot, subduction and intraplate volcanoes have erupted across the region. Subduction is currently active along the New Hebrides, and Tonga-Kermadec trenches. Associated back-arc basins are the Havre, Lau and North Fiji basins (Fig. 1A; Crawford et al. 2003; Collot et al., 2020). The tectonics, kinematics and petrology of these features have been intensely studied, and processes and history are very well characterized at the regional scale over the last 10 Ma (e.g. Pelletier et al., 1998; Crawford et al., 2003). Less well studied is the older subduction record of the southwest Pacific which is inferred to have started sometime in the Eocene or possibly the Late Cretaceous (e.g. Crawford et al., 2003; Schellart et al., 2006; Matthews et al., 2015; Collot et al., 2020). The eastward retreat of the Tonga-Kermadec trench has allowed the geological records of remnant submarine arcs and unclosed back-arc basins to be preserved, except where they have been subducted in southwestward Vanuatu subduction zone (Fig. 1A).

Continental crust of north-eastern Zealandia underlies the Norfolk and Loyalty Ridges ((e.g., Schellart et al. 2006; Mortimer et al. 2017; Collot et al., 2020). These ridges lie at c. 1000-1500 water depths and contrast with the back-arc basin oceanic crust of the South Fiji and Norfolk basins which lies at 3000-4000 m water depth (Fig. 1). The Loyalty and Three Kings Ridges are inferred to be the site of Cenozoic arc volcanism (Crawford et al., 2003; Schellart et al., 2006; Maurizot et al., 2020a). However, only a few rock samples have been recovered from these ridges in reconnaissance (Mortimer et al. 1998, 2007 2018) so their origin and nature are open to debate. Uncertainty about the nature and age of the Loyalty and Three Kings Ridges results in first order ambiguities concerning tectonic models of the geological evolution of the Cenozoic southwest Pacific and, especially, the number, longevity, location and polarity of subduction zones (see review by Collot et al., 2020).

The present study was designed to obtain volcanic rock samples from the Loyalty and Three Kings ridges in order to to fill SW Pacific geology's largest knowledge gap. By retrieving and analyzing a large number of samples, our aim was to ground truth the age range and polarity of subduction, and hence try to reconcile and test the variety of Paleogene southwest Pacific tectonic models. In May-June 2015 the VESPA (Volcanic Evolution of South Pacific Arcs) cruise of R/V *l'Atalante*, surveyed and dredged rocks from along the Norfolk, Loyalty and Three Kings ridges and their adjacent basins (Mortimer and Patriat, 2016). In total, useful igneous and sedimentary rock samples were obtained from 36 out of 43 dredge sites (Fig. 1B). In this paper, we present geochemical and isotopic data from the igneous rocks (mainly lavas) in order to : (1) document the petrologic nature of volcanism on the Loyalty and Three Kings ridges; (2) explore upper mantle composition and dynamics under this region; (3) use this information to test models of the subduction history and more generally the geodynamics of the SW Pacific during the Cenozoic.

This paper follows on from earlier reconnaissance petrology and dating studies of pre-Quaternary SW Pacific dredge and onland samples (Mortimer et al., 1998, 2007, 2014, 2018; Bernardel et al., 2002; Meffre et al., 2002; Booden et al. 2011; Timm et al., 2019). It is a companion paper to other outputs from the VESPA cruise (Patriat et al., 2018; Gans et al., 2022, submitted; Collot et al., in preparation).

2. Geological setting

The entire study area of the Three Kings and Loyalty ridges is underwater. The closest parts of Zealandia that are above sea level are New Caledonia and New Zealand. Despite being 1500 km apart, these countries have several continental geological features in common. These include thick crust, a basement of pre-Late Cretaceous accreted terranes, Late Cretaceous to Miocene terrigenous-calcareous sedimentary basins, and ophiolitic and sedimentary allochthons emplaced as northeast-verging nappes (Isaac et al., 1994; Maurizot et al., 2020b). Some notable differences are (1) New Caledonia has only a sparse record of arc magmatism in the form of Eocene dikes and two small Oligocene plutons but northern New Zealand has several well-developed Early Miocene to Holocene subduction-related volcanic-plutonic arc systems; (2) New Caledonia has a Paleogene blueschist-eclogite facies metamorphic core whereas New Zealand lacks high pressure metamorphic rocks; (3) the mantle-derived Peridotite Nappe of New Caledonia was emplaced between c. 34 and 27 Ma. In contrast, the Northland Allochthon was emplaced at 22-25 Ma and is dominated by a metavolcanic thrust sheet (Isaac et al., 1994; Maurizot et al., 2020b).

Zealandia, along with Australia and Antarctica, was formerly part of the southern supercontinent of Gondwana. Subduction-related magmatism persisted along Gondwana's Pacific-facing margin until at least 110 Ma after which it started to separate from Gondwana (Mortimer et al., 2017).

Sometime in the Paleocene or Eocene, a renewed episode of subduction is thought to have commenced (Cluzel et al., 2006; 2012; ; Maurizot et al., 2020c). Numerous alternative geodynamic models have been proposed to explain the initiation and development of this younger SW Pacific subduction (see Matthews et al., 2015; Collot et al., 2020 for reviews). As outlined above, the Loyalty and Three Kings ridges are inferred to be remnant arcs of this older Paleogene subduction. Eocene arc lavas are also found in Tonga and Fiji (Bloomer et al., 1995, , Meffre et al., 2012). The two ridges are interpreted to have once been co-linear, having subsequently been separated by the c. 400 km sinistral strike slip fault called the Cook Fracture Zone (Sdrolias et al., 2004; Herzer et al., 2011). Using the orientation of the present-day Loyalty and Three Kings ridges as a reference, one class of SW Pacific tectonic models proposes that an east-dipping subduction zone initiated sometime in the Paleocene to Early Eocene (e.g. Crawford et al., 2003; Cluzel et al., 2001, 2006; Schellart et al., 2006; Whattam et al., 2006; Schellart, 2007). Subduction became collision by the arrival of the Norfolk Ridge in the trench in the Late Eocene, resulting in an arc-continent collision that culminated in the obduction of the overriding forearc (see review by Maurizot et al., 2020a). The transition in space and time of the subduction flip to the present-day west-dipping Pacific slab subduction is not a focus of these models which mainly address events associated with the emplacement of the New Caledonia Peridotite Nappe.

In a contrasting class of models, a west-dipping subduction initiated in the Eocene beneath the Loyalty-Three Kings ridge, and evolved via episodic Pacific trench retreat to the present-day Tonga-Kermadec subduction (e.g. Malpas et al., 1992; Mortimer et al., 1998; 2007; Sutherland et al., 2010;). A commonality in both classes of model is that the Norfolk Ridge is assumed to be the easternmost continental part of Zealandia, and the Loyalty-Three Kings Ridge the position of a Paleogene volcanic arc. An attempt to reconcile the contrasting tectonic models was presented by Herzer et al. (2011) who invoked an older east-dipping slab that became truncated by the west-dipping Pacific slab as a triple junction spreading center migrated south.

Samples from the submarine SW Pacific ridges and basins recovered prior to the VESPA cruise have been insufficient to test between the two general classes of model. Knowledge of the geology of the Loyalty and Three Kings Ridges is particularly important in this regard but, instead, there is a large data gap. On the Three Kings Ridge, Mortimer et al., (1998, 2007) recovered Late Oligocene and Early Miocene andesites and shoshonites and Bernardel et al. (2002) reported a 37 Ma old boninite lava and serpentinite.

The basement of the Loyalty Ridge is even more poorly sampled and its origin and nature, while prominently mentioned in the literature are almost completely unsupported by actual rock samples. The Loyalty Islands that emerge from the ridge are essentially composed of Mio-Pleistocene uplifted carbonate reefs; two Late Miocene basaltic intraplate intrusions are reported on Maré Island (Maurizot et al., 2020c and references therein). Elsewhere along the ridge, several Oligocene-Miocene intraplate basalts have been sampled (Monzier et al., 1989; Mortimer et al., 2014). Because of its possible spatial link with the D'Entrecasteaux Ridge located far north, where Eocene subduction-related lavas have been sampled (Baker et al., 1994; Mortimer et al., 2014), and in order to match with the geological interpretation of the Grande Terre of New Caledonia, the Loyalty Ridge is often considered as an Eocene arc (Cluzel et al., 2001, Crawford et al., 2003, Schellart et al., 2006, Matthews et al., 2012 Maurizot et al. 2020c). However, no Eocene arc lavas have ever been obtained.

3. Sampling strategy

In order to test the above SW Pacific tectonic models we focused the sampling effort of the 2015 VESPA cruise on the topographic highs of the Loyalty and Three Kings ridges, and the intervening Cook Fracture Zone and South Fiji Basin seafloor (Fig. 1). Based on experience from past expeditions, we anticipated issues with blanketing sediments, limestone caps and/or ferromanganese crusts. Therefore, prior to dredging, we made shallow seismic profiles and multibeam bathymetry surveys across the area. Sampling was deliberately made in a relatively dense (for the area) dredging grid over north-south and east-west baselines. Additionally, we took advantage of the steep scarps of the Cook Fracture Zone and Cagou Trough to sample deep into the deepest parts of the two ridges (Fig. 1). The fracture zone and trough walls enabled targeted dredging over ~2500 m vertical height difference. To maximise sample recovery, our dredge sites were preferentially made on steep rocky slopes.

4. Petrographic and geochemical results

4.1. Petrographic features and lava classification

The dredged igneous rocks are mainly basalts, with lesser trachybasalts, basaltic andesites, trachyandesites andesites, dacites, and one granite. Basalts range from aphyric to sparsely olivine, plagioclase and clinopyroxene-phyric to occasionally moderately plagioclase-phyric. The other lavas are generally plagioclase-phyric and biotite is a prominent phenocryst in trachyandesites and dacites. Some basalts are vesicular and have amygdaloidal infillings of zeolite, carbonate and phosphatic sediment. Many samples with a formerly glassy groundmass show moderate to extensive secondary alteration (seafloor weathering) to orange-brown clay minerals (Fig. S6).

Wherever possible, only the freshest parts of dredge samples were analysed (see supplementary File 1 for detail). Despite this, elevated loss on ignition (LOI) values (e.g. up to >10 wt% for sample DR07Ci) are present in our dataset. As such, we are circumspect in our geochemical interpretation and try and place more emphasis on using concentrations and ratios of rare earth elements (REEs) and high field strength elements (HFSEs) rather than large ion lithophile elements (LILEs). The least altered samples (LOI< 4 wt%) were classified according to their position in a total alkali-silica plot (Le Bas et al., 1986; Fig 2A). Their chemical compositions confirm the wide petrographic range, and include alkaline and subalkaline suites (confirmed by variation in relatively immobile element ratios e.g. Nb/Y; not shown).

One of the first things apparent from our entire dataset is that samples dredged from the deeper parts of the area e.g. South Fiji Basin, Cook Fracture Zone (blue symbols in all figures) are basaltic. In contrast, samples dredged from the shallower levels of the Loyalty and Three Kings ridges (yellow symbols in all figures) are more petrologically evolved and are typically andesitic or trachytic. This difference is also reflected in K_2O

and other LILE contents. In the deep basaltic lavas (SiO_2<49 wt%, MgO~7.4) K_2O is typically low at 0.1 wt%, they are low-K tholeiites. In the shallower, intermediate composition lavas (SiO_2 <57 wt%, MgO 1.1- 5.4 wt%), K_2O ranges as high as 7 wt% and many are classed as high-K and shoshonitic in the SiO_2 vs K_2O diagram of Peccerillo and Taylor (1976) (Fig.2B). Primary high K_2O contents of these dredged VESPA lavas are supported by the presence of biotite phenocrysts (Fig. S6).

4.2. Trace element concentrations

Trace element concentrations are reported in table S1, and shown on the multi-element diagrams in Fig. 3. Based on REE patterns (Fig. 3 A-C) at least three distinct groups can be distinguished, here called depleted (Fig. 3A), transitional (Fig. 3B) and enriched (Fig. 3C) according to their light to heavy REE ratios, with La/Sm ranging from 0.4 to 8.

The samples most depleted in light REEs are two basalts from VESPA dredge 39 (depth ~ 3900 m) in the Cook Fracture Zone (Fig. 1, 3A and blue symbols on all geochemical diagrams). They have SiO_2 ~48.5 wt%, MgO ~7 wt%. They display REE concentrations similar to those found in normal mid-ocean ridge basalts (N-MORBs) with La contents similar to primitive mantle (McDonough and Sun, 1995) and Lu concentrations of about 4x primitive mantle. Nevertheless, their HFSE concentrations appear slightly low compared to REE contents with Nb/Yb=0.17-0.19 and LILEs display higher concentrations than in N-MORB (with, for instance, Ba/Yb ranging from 3.6 to 10.7) suggesting that these signature are more typical of back-arc basin basalts (BABB) rather than typical open ocean N-MORBs (Pearce and Stern, 2006). However, most of these indicators (e.g., Ba, Rb concentrations) can easily be affected by alteration and it is in turn difficult to assess with certainty if these samples correspond to BABB or to normal-MORB suites.

Most basalts and basaltic andesites display flat, undepleted REE patterns (Fig. 3B). These lavas have REE contents ranging from 3 to >10 times primitive mantle, depending on extent of fractionation, but nonetheless have remarkably constant REE relative abundances. In the context of our dataset, we refer to these as transitional basalts, but do not use this term to imply any alkaline character (as shown in Fig. 2A most of the lavas are subalkaline). Most of these basalts also have HFSE depletions and LILE enrichments relative to other incompatible elements, features which are typical of subduction related fluid enrichments and therefore of arc lavas, and/or continental-crust-contaminated intraplate basalts (Li et al., 2015; Mortimer et al., 2018). The trace element signatures in these lavas are very similar to those reported for samples FAUST2 D3, collected along the CFZ and analysed by Bernardel et al (2002) (see supplementary figure S1). On a Th/Yb vs Nb/Yb diagram (Fig.3E) of Pearce (2008) all of these lavas lie in the field of back-arc basalts (as delimited by Li et al, 2015). All samples with these geochemical characteristics were dredged from 3300-4800 m water depth along the Cook Fracture Zone scarp (Fig. 1).

Basaltic andesites, andesites, trachyandesites and trachytes dredged at shallow-water depth have the most incompatible element enriched compositions (Fig. 3C). Their REE contents range over an order of magnitude (La= 10 to 100x chondrite) and are characterized by strong enrichments in the most incompatible LREE compared to HREE (La/Yb ranging from 3 to 16). As with the transitional samples in Fig 3B, this group of enriched lavas display chemical characteristics typical of subduction processes, such as HFSE depletions and LILE enrichments as well as similar HREE contents (Yb ranging from 2-10x chondrite. The main difference between the trace element signatures of this and the other groups of samples is in the degree of light REE enrichments relative to intermediate and heavy REE concentrations, with La/Sm ranging from 1 and 3.1 for the basalts (Fig. 3B) on the one hand, and from 2.3 to 4.9 for the more evolved samples (Fig. 3C). These differences in REE spectra slopes cannot readily be accounted for by crystal fractionation of the basalts (which would lead to parallel patterns), but instead may indicate different degrees of partial melting, a more incompatible element enriched source (for the LREE enriched lavas), or a combination of both. On the Th/Yb vs Nb/Yb diagram (Fig.3E) of Pearce (2008), these samples lie in the field of island arc basalts.

4.3. Pb, Hf, Nd and Sr isotopes

The Pb, Hf, Nd and Sr of the samples are reported in Table S1. The Pb isotope ratios of our entire VESPA dataset cover a relatively restricted range, with $^{208}Pb/^{204}Pb$ ranging from 38 to 39.8, $^{207}Pb/^{204}Pb$ ranging from 15.51 to 15.64 and $^{206}Pb/^{204}Pb$ ranging from 17.9 to 20.1. They plot systematically above the North Hemisphere Reference Line of Hart (1984) on Fig. 4, so within typical Indian rather than Pacific MORB fields (Crawford et al., 1995). Some possible mixing trends between end-members can be seen in our dataset. In particular there seems to be an array between depleted MORB mantle (DMM) and more enriched compositions (Fig. 5). The small number of samples and limited range of compositions affect confidence in this trend. Additionally there is another trend, mainly shown by the incompatible element enriched lavas (yellow symbols on all figures) pointing towards an EM2 end-member (Hart et al., 1992) (Fig. 5). A principal component analysis calculated on the Pb isotope data reveals the existence of only two significant principal components (the first one accounting for ~76% of the total variability, and the second for ~23%, Fig. S3). This result affirms the qualitative interpretation that the diversity of isotopic compositions observed in the VESPA dataset can be accounted for by the mixing of no more than three components along two arrays.

Hf isotopes range from typically depleted (N-MORB-like) signatures ($^{176}Hf/^{177}Hf$= 0.28317, ε_{Hf} =+14) to enriched (Ocean Island Basalt-like) compositions ($^{176}Hf/^{177}Hf$= 0.28299, ε_{Hf}=+7.7). The comparison of Hf isotopes with Pb isotopes (Figs. 4B, 5), reveals a sharper geochemical portrayal than Pb isotopes alone. A clear distinction can be made between the depleted (DR39) and transitional groups on the one hand and the enriched group on the other hand (Figs. 4Bis and 5).

The exact same features can be seen using Nd and Sr isotopes, although we note the vulnerability of submarine basalts to weathering, despite the leaching in our sample preparation. The VESPA lavas have $^{143}Nd/^{144}Nd$=0.5128-0.5131, ε_{Nd}= 2.8-9.3 and $^{87}Sr/^{86}Sr$= 0.79026-0.7048, both of which are correlated with Hf data (Fig. 5).

5. Discussion

5.1 Mantle source compositions and conditions of melting

The three distinct trace element signature groups recognized on Fig. 3 (depleted, transitional and enriched in incompatible elements) can theoretically be accounted for by different amounts of melting, fractionation, source compositions or a combination of all three. Nevertheless, the wide range in trace element concentrations and ratios (e.g. La/Sm ranging 0.3 to >8) makes it very unlikely that the parent melts of all samples shared a common mantle source.

Both the depleted and the transitional tholeiitic basalt groups (blue symbols), have HFSE depletions and LILE enrichments suggesting that these magmas were likely produced by the decompression melting of the moderately fluid-enriched upper mantle, which is a common feature of both back-arc basin basalts (BABBs) (e.g. Pearce and Stern, 2006), forearc basalts (FABs) (e.g. Reagan et al., 2010; Falloon et al 2014), Fijian early arc basalts (Todd et al. 2012) and SW Pacific rear-arc basalts from the Colville Ridge (Timm et al. 2019). The main geochemical distinctions proposed for BABB and FAB are based on the relative abundances of REE and vanadium; FABs typically feature higher REE/V than BABBs. A wide overlap exists between these populations, and our Loyalty-Three Kings tholeiites all lie within this broad compositional range (Supplementary Fig. S.2.) but, overall, show more affinity with rear-arc and back-arc basin basalts. The incompatible element-enriched group (yellow symbols) show a wide range in normalised anhydrous SiO_2 (51-65 wt%), MgO (1-7 wt%)_and Cr (1-360 ppm) but defy attempts to apply depth of melting geobarometers and interpretation via simple modelling of melting and fractional crystallization processes. Clearly, their chemistry is more typical of hydrous flux-melting products than the depleted and transitional lavas (Fig. 3) and could therefore be accounted for by the building of an arc at 25-22 Ma..

The variability and clustering of Pb, Hf, Nd and Sr isotopic compositions confirm that different mantle sources melted to generate the depleted, transitional and enriched lavas. One isotopic component overlaps those of Pacific and Indian N-MORB (grey and green fields on Fig. 4 and 5) and can therefore be interpreted as normal depleted ambient upper mantle. The two depleted BABB-like samples DR39A and B appear to be the "purest" carriers of this signature (Fig. 5) and can be compared with approximately coeval adjacent South Fiji Basin basalts (Todd et al. 2011). The trend defined by these two samples together with all the transitional group possibly points toward more enriched compositions (especially in Pb-Hf space), which, speculatively, could be the second component of the mixture (the purple trend on Fig. 5). This tendency is a relatively common feature of SW Pacific volcanic rocks (see for example the grey area representing Pacific MORB on Fig.5) and is referred here as an "enriched-Pacific-MORB" (EPM) component. It has, for instance, been well documented in intraplate, intracontinental volcanism of Zealandia (e.g. Timm et al., 2010). The ubiquity of this signature within the SW Pacific suggests that the DMM-EPM trend, also possibly shown by our samples, probably reflects the melting of the naturally heterogeneous upper mantle beneath the SW Pacific and Zealandia. The Miocene Northland Arc is anchored in Zealandia continental crust and a wide variety of basalts, andesites, dacites and rhyolites are reported from several volcanic centres (Isaac et al. 1994). Unfortunately, only Sr and Nd isotopic data are available for these rocks (Booden et al., 2011) so they are of limited use in characterising the Miocene continental mantle wedge under Zealandia.

The third geochemical component revealed on Figures 4 and 5 (pink trend on Fig. 5), has Pb isotopic compositions similar to those of the DMM-EPM mixture described above (blue trend on Fig.5). It is therefore mostly defined using Sr, Hf and Nd isotopes (Fig. 4 and 5) and is represented by the most geochemically enriched (intermediate to felsic) samples, shown as yellow diamonds in all figures. Its unradiogenic Hf and Nd, and its radiogenic Sr signatures can be interpreted in two different ways. First, it could simply reflect the effect of crustal contamination on mantle melts. This possibility is supported by a broad correlation existing between isotope signatures and Ce/Pb and Nb/U ratios (Fig. S4), which are classic proxies for continental crust contamination (Hofmann et al., 1986; Rudnick and Fountain, 1996). Nevertheless, in samples defining the trend (pink band, yellow diamonds on Fig. 5), cover the same range as most of those, featured by the basaltic samples belonging to the previous trend (DMM-EPM, blue circles. purple band) and no clear correlation can be established between isotopes and major elements such as SiO_2 and Al_2O_3. Moreover, if Ce/Pb and Nb/U are particularly low in continental crust material (Rudnick and Fountain, 1995) compared to MORB (Gale et al., 2015), they can be just as low in arc related melts, as illustrated in Fig. S5 (Gale et al. 2015; Turner and Langmuir, 2015; Yang et al., 2021). It is in turn difficult to assert that these geochemical signatures are strictly due to crustal contamination. In any case, the continental crust under the TKR and LR is likely to be relatively young (Jurassic to Cretaceous) and relatively low $^{87}Sr/^{86}Sr$, and high bulk $^{143}Nd/^{144}Nd$, as such reported for the Waipapa Terrane accretionary wedge (Adams and Maas, 2004). Therefore, the signal of such contamination would be subtle. The second simple explanation, for the pink band EM2 isotopic trend, would be the addition of variable amounts of subducted sediments to the mantle wedge, as has been documented for other subduction zones worldwide and in the SW Pacific by Timm et al.

(2019) and Mortimer et al. (2022).

5.3 Chronology

On Fig. 6, crystallization ages are compared with geography, Hf isotopes and La/Sm ratios in order to explore across-arc trends, involvement of mantle sources and degree of geochemical enrichment with time. The vast majority of sampled and dated lavas from the Loyalty and Three Kings ridges fall in a relatively narrow range of ~25 to ~22 Ma i.e. latest Oligocene to earliest Miocene. The age range of the three different geochemical groups overlap with depleted basalts ~23 and ~22 Ma, transitional basalts ~25 to 22 Ma, and enriched lavas ~25 to 22 Ma. Thus, there is no clear geochemical change with age, nor with east-west distance (Fig. 6). However, as previously noted, there is a geochemical change with current water depth, with depleted and intermediate basalts occurring at deep levels and enriched lavas at shallow levels. The overlapping ages do not necessarily refute a crude correspondence of water depth with stratigraphy but attest to the rapidity of build-up of the volcanic piles and operation of different petrogenetic processes in the short 25 to ~22 Ma time interval.

Two tholeiitic basalts in our dataset (VESPA DR25A and DR25C), collected within a single dredge at 3850 meters deep along the east side of the Cagou Trough, stand out as being substantially older than 25-21 Ma. Despite being dated at 36 and 38 Ma, these DR25 basalts are geochemically indistinguishable from the more numerous 25-21 Ma transitional basalts.

5.3 Geodynamic interpretation

Our study area of the Loyalty and Three Kings ridges is approximately halfway between New Caledonia and New Zealand. As such our geochemical results provide useful ground truthing and have several important implications for the tectonic development of the SW Pacific region (Fig. 7). The main interpretations that can be made are: Documentation of a major pulse of subduction-related magmatism that has built up the arcs of the Loyalty and Three Kings ridges in the Late Oligocene to Early Miocene. This confirms the formerly-joined ridges as a single volcanic arc and is at odds with existing geodynamic models which assumed the subduction zone and arc were far to the east in Early Miocene (e.g. Crawford et al., 2003; Schellart et al., 2006; Whattam et al., 2006; Meffre et al., 2012). Late Oligocene-Early Miocene arc volcanism, previously documented on the Three Kings Ridge (Mortimer et al., 1998, 2007) is now shown to be present on the Loyalty Ridge and so must be incorporated into the post-obduction history of New Caledonia.

The Loyalty-Three Kings ridge lavas are dominated by basalts. Geochemically, compositions overlap with reference suites of back-arc basin basalts and low-K arc tholeiites. Our extensive vertical and lateral sampling from the crests to the bases of the Loyalty and Three Kings ridges, documents the major presence of subducted-related basalts. Basaltic andesites and andesites are rare (and rhyolite is absent) in our data set whereas these are relatively common rock types in other volcanic arcs. It is difficult to unambiguously assign an independent tectonic setting of eruption to the Loyalty-Three Kings basalts on a sample-by-sample geochemical basis but, overall, an arc setting is preferred because of the buildup of a linear volcanic ridge. The Cook Fracture Zone may represent a 'leaky transform' style of volcanism in a disrupted arc setting akin to that on the Northland Plateau (Mortimer et al., 2007). Trachyandesites and trachytes are exposed on the topmost crests of the Loyalty-Three Kings Ridge. They show shoshonitic affinities.

The across-strike width of co-eval subduction-related volcanism is possibly wider in the Loyalty-Three Kings Ridge than in other SW Pacific arcs such as the Lau-Colville and Tonga-Kermadec ridge systems. In part this may be due to more broad or diffuse volcanism expected at a continental margin, and in part due to syn- or post-magmatic extension e.g. in the Cagou Trough and Kwênyii Basin (Mortimer et al., 2007, 2020c; Patriat et al., 2018). Two granite plutons in New Caledonia of 24 and 27 Ma age (Cluzel et al., 2005; Paquette and Cluzel, 2007) display geochemical characteristics similar to our EM2 trend lavas (towards EM-2). It is therefore possible that they are petrogenetically related.

Four pre-Late Oligocene subduction-related volcanic rocks have now been dredged from the Three Kings Ridge and range in age from ~38-32 Ma (Bernardel et al., 2002; Mortimer et al., 2007; this study). These pre-Late Oligocene lavas represent a very small minority in our data set and they have all been recovered on the westernmost side of the Three Kings Ridge. Rocks of this age may reasonably be inferred to be also present on the westernmost edge of the Loyalty ridge, i.e. on the Félicité Ridge. However, the only area along the strike of the Loyalty arc where Eocene rocks have been recovered and dated is the D'Entrecasteaux Ridge, some 1000 km NW of our study area (Baker et al., 1994; Mortimer et al., 2014).

Mantle sources for the Loyalty-Three Kings arc lavas were heterogeneous. Lavas lie on trends between DMM, an "enriched-Pacific-MORB" and a EM2-like component. This is an expected mix of mantle types in the SW Pacific oceanic region adjacent to the Zealandia continent. Together with the Indian/Gondwana nature of the DMM component and EM-2 / Zealandia continental component, it may provide tentative evidence for persistent west-dipping subduction, occurring in Oligocene-Miocene time under the Loyalty-Three Kings ridge, before retreating under the Lau-Colville, and Tonga-Kermadec ridges.

Collectively, these new constraints lead us to propose a revised tectono-petrogenetic evolution model of the SW Pacific as shown in Figure 7: the Eocene subduction, initiated around 56 Ma, ended with the obduction of the Peridotite Nappe in New Caledonia during the Late Eocene-Early Oligocene (Cluzel et al., 2001; Maurizot et al., 2020a). We cannot comment with any confidence about the subduction polarity of this Eocene subduction because lavas of this age are rare. But in our view, all the Paleogene magmatism within the Poya Terrane (including our DR25 samples), plausibly fits as BABB, or FAB related to a west-dipping subduction along the eastern edge of Zealandia. Accordingly, Figure 7A shows the end of the Eocene subduction stage with a west-dipping slab, which is in agreement with the long duration of the Paleogene magmatic activity within the Poya Terrane (more than 10 My, Cluzel et al., 2017 and references therein) and a flake tectonic interpretation of ophiolite obduction (Malpas et al. 1992). Nevertheless, subduction flips during this time interval are also viable. Whatever the polarity, an important new information brought by our study is that the main magmatic phase attesting of the building of an arc along the LR and TKR happened after this stage of obduction and is therefore clearly distinct from the Eocene subduction.

Obduction was followed by a period of post-orogenic extension (Lagabrielle et al., 2005; Patriat et al., 2018) accompanied by sparse magmatism as indicated by the 32 Ma Early Oligocene lava on Three Kings Ridge (Mortimer et al., 2007), the New Caledonia granites (Cluzel et al., 2005; Paquette et al., 2007) and the Northland supra-subduction zone ophiolites of this age (Whattam et al., 2006). These scattered suites are related in time but not necessarily in petrogenesis. At this time, the supra subduction margin was composed of an obducted oceanic lithosphere stretched and fractured by normal faults (Patriat et al., 2018) lying over the similarly stretched and thinned eastern continental margin of Zealandia (Fig. 7B).

At around 25 Ma, thick piles of lava of different compositions erupted in and around the LR and TKR (Fig. 7C). A variety of igneous processes operated. Subduction at the eastern edge of the Zealandian thinned margin induced a phase of decompression melting of the normal Pacific upper mantle (our so-called transitional lavas and an isotopic DMM-EPM trend). Simultaneously, steepening of the slab accompanied its eastward rollback, and induced a significant increase of the slab derived fluid into the wedge, leading to the generation of magmas from EM2-like geochemically enriched material (our so-called enriched lavas and isotopic trend towards EM2). This flux melting led to the eruption of what are now the shallow water parts of the Loyalty and Three Kings ridges. Steepening of the slab and increase of the slab derived fluid input into the wedge explains the shoshonitic compositions as are observed e.g. in the Aeolian arc (Morrison, 1980). Alternatively and/or additionally, the shoshonites can also be related to rollback-related extension of the arc (Mortimer et al. 2007, 2022).

After migration of arc-related volcanism away from LR and TKR, the eastward roll-back of the Pacific slab and associated trench retreat, accelerated (Fig. 7D). This may have induced further extension in New Caledonia in the Miocene (e.g. Sevin et al. 2020). The decompression melting of the depleted DR39 BABBs may have taken place at this time, along with rapid generation of oceanic crust in the Norfolk and South Fiji basins, accompanied by sinistral movement on the Cook Fracture Zone (Herzer et al., 2011). The arc later stabilised further east, along the Lau-Colville Ridge (Timm et al., 2019) and, subsequently, the Tonga-Kermadec Ridge.

6. Conclusions

Results of new analyses of lava samples collected along and across the Three Kings and Loyalty ridges during the 2015 VESPA expedition provide a unique and informative geochemical-space-time perspective on the magmatic and tectonic evolution of the SW Pacific. Almost all dredged lavas are subduction-related and erupted between 25 and 22 Ma, although two lavas are of ~ 38-36 Ma age. Their trace element and isotopic compositions can be explained in terms of three distinct geochemical end-members in the mantle sources (DMM, enriched-Pacific-MORB and EM-2 like) and two different melting processes (decompression melting producing tholeiitic magmas and flux melting producing high-K magmas).

The main conclusions arising from this study of SW Pacific lavas is that subduction-related magmatism is confirmed on the Loyalty Ridge and this observation must be incorporated into tectonic models of New Caledonia obduction. There is a strong correlation between geochemical grouping and present-day water depth, with low-K tholeiitic basalts dredged in deep water and high-K to shoshonitic lavas from shallower ridge crests. The Loyalty-Three Kings arc was most active in the Late Oligocene to Early Miocene. The issue of polarity of subduction remains open, but the composition and distribution of the VESPA igneous rocks can be explained using a west-dipping subduction model since Eocene time.

Data Availability Statement

Supplementary data files that support the findings of this study are openly available https://www.seanoe.org/data/00789/90050/. General information about the VESPA cruise can be found in the SISMER repository at http://doi.org/10.17600/15001100.

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Figure captions

Fig. 1. A. Study area in the SW Pacific Ocean. LR: Loyalty ridge, TKR: Three King's ridge, NR: Norfolk Ridge, BG: Bougainville Guyot. **B.** Dredge sample location map and major bathymetric features of ridge and basins. The symbol colour code is established by geochemical signatures as justified in Figs. 3-5: Blue circles=tholeiitic basalts and basaltic andesites, yellow hexagons=incompatible element-enriched lavas. **C.** Sample location depths projected onto two NW-SE seismic profiles across the Loyalty and Three Kings ridges (from Mortimer and Patriat, 2016).

Fig. 2. Major element compositions of Loyalty and Three Kings ridge area lavas plotted on an anhydrous basis. **A.** total alkali – silica plot (Le Bas et al., 1986). **B.** K_2O vs SiO_2 plot (Peccerillo and Taylor, 1976). The symbol colour code is established by geochemical signatures as justified in Figs. 3-5: Blue circles=tholeiitic basalts and basaltic andesites, yellow hexagons=incompatible element-enriched lavas.

Fig 3. A-D: Multi-element normalised plots of samples from Loyalty and Three Kings ridge area. **A-C.** Rare-earth element (REE) patterns normalized to CI Chondrite (McDonough and Sun, 1995). **D.** Multielement plot of all samples normalized to primitive mantle values (McDonough and Sun, 1995). **A.** the two most depleted BABB-like tholeiitic samples DR39A and DR39. **B.** transitional tholeiitic basalts (blue circles). **C**. incompatible trace element-enriched samples (yellow hexagons). For reference, the transitional compositions are shown as thin blue lines in panels A and C. **E.** Th/Yb vs Nb/Yb diagram of Pearce (2008). Fields of back-arc basalts (BABB) ans Island arc basalts (IAB) are those of Li et al. (2015).

Fig. 4. A. Pb isotopic composition of VESPA samples, most of the samples lie above the North Hemisphere Reference Line (NHRL, Hart, 1984).; **B.** ε_{Hf} and Sr isotopes vs ε_{Nd}. The dotted black line represents the mantle array of Vervoort et al (1999). The green areas represent MORB from the South West Indian ridge and the grey areas MORB from the Pacific (The data were downloaded from the PetDB Database (www.earthchem.org/petdb on 16 August, 2022, using the following parameters: feature name = SPREADING CENTER/ EAST PACIFIC RIDGE, PACIFIC-NAZCA RIDGE, PACIFIC IZANAGI RIDGE, PACIFIC-ANTARCTIC RIDGE, SOUTHWEST INDIAN RIDGE and rock classification= « basalt.”). The blue dotted lines identify the Indian/Pacific Mantles limits as defined by Pearce et al. (1999) and Pearce et al. (2007).

Fig.5: Hf, Nd and Sr isotope ratios vs $^{206}Pb/^{204}Pb$. In the left column, VESPA samples are compared with various other reference sets. Two isotopic trends shown by purple and pink bands, are less well defined with Sr isotopes, possibly due to the sensitivity of this system to sea water alteration. The enriched-Pacific-MORB trend crosscuts the EM2 trend at one extremity, suggesting a pseudo binary mixing pattern (e.g. Douglas and Schilling, 2000). C.F.Z. = Cook Fracture Zone, TKR.=Three Kings Ridge. The green and grey areas correspond to SW Indian and Pacific MORB respectively (see Fig. 4 for references). The purple fields represent Kermadec Subducting Sediments (Todd et al, 2010). Red circles are South Fiji basin basalts (Mortimer et al., 1998; Todd et al., 2011) and blue circles are Kermadec basalts (Todd et al., 2010).

Fig 6. A. Variation in sample longitude, Hf isotope ratios and La/Sm ratios with age. **B.** Variations in sample Hf isotope ratios and La/Sm ratios with sample depth. See Fig. 4 for symbols. With one exception, all enriched samples were collected at shallower depths than tholeiitic samples. N.R.=Norfolk Ridge, L.R.=Loyalty Ridge, T.K.R.=Three Kings Ridge. Norfolk Ridge samples from Mortimer et al. (2021).

Fig. 7. Speculative geodynamic reconstruction to explain the development of the Loyalty and Three Kings ridges along the eastern Zealandian margin. Our data demonstrate the building of the Loyalty-Three Kings Ridge is achieved by arc volcanism over a very short (3 Myr) Late Oligocene-Early Miocene period of time (24-22 Ma, panel C). See details in the text. **A.** Late Eocene-Early Oligocene jamming of the Eocene subduction zone (Maurizot et al, 2020a). Subdued or no volcanic activity accompanying collision and obduction. **B.** Post-orogenic extension and resumption of subduction. Extension induces thinning of the previously thickened lithosphere at the same time as emplacement of the Oligocene granitoids of New Caledonia. **C.** Maturing subduction and trench rollback result in decompression melting of the normal Pacific upper mantle to produce low-K

tholeiites. Later, there is mature arc formation. As the retreating Pacific slab steepens, there is a significant increase of slab derived fluid input into the wedge, which produces the high-K to shoshonitic lavas. The topographic ridges/arcs are built during this phase. **D.** Cessation of volcanism at Loyalty-Three Kings ridges. Slab retreats rapidly driving arc volcanism east of the Loyalty-Three Kings Ridge. The arc later stabilises along the Lau-Colville Ridge and, eventually the Kermadec-Tonga Ridge. NC: New Caledonia, L3KR: Loyalty-Three Kings Ridge, LCR: Lau-Colville Ridge, SFB: South Fiji Basin**.**

Fig. 1

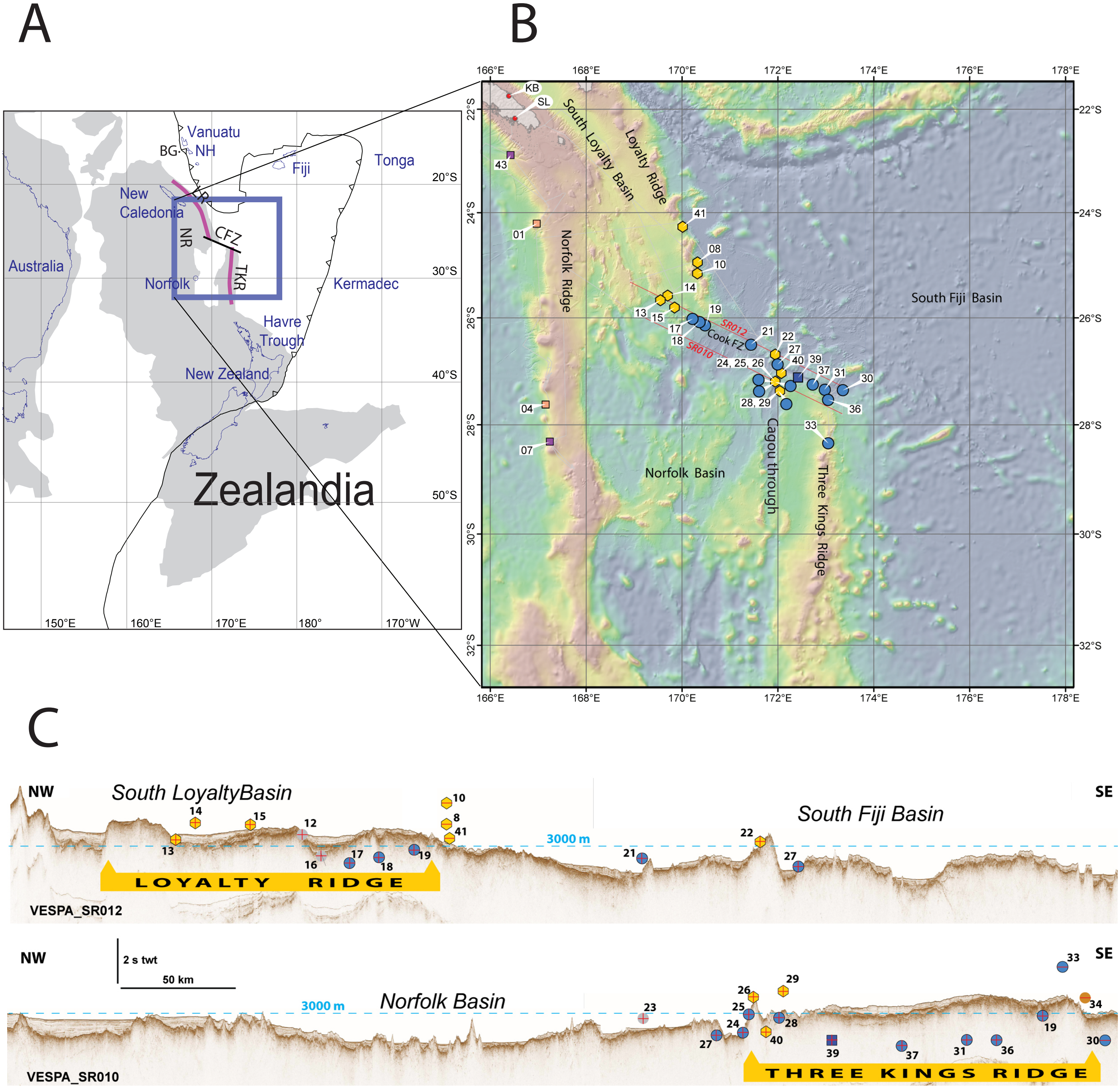

A
B
C
Vanuatu
NH
BG
Fiji
Tonga
New Caledonia
Australia
Norfolk
NR
CFZ
TKR
Kermadec
Havre Trough
New Zealand
Zealandia
150°E
160°E
170°E
180°
170°W
20°S
30°S
40°S
50°S
KB
SL
South Loyalty Basin
Loyalty Ridge
Norfolk Ridge
Norfolk Basin
Cagou through
Three Kings Ridge
South Fiji Basin
Cook FZ
SR012
SR010
166°E
168°E
170°E
172°E
174°E
176°E
178°E
22°S
24°S
26°S
28°S
30°S
32°S
NW
SE
South LoyaltyBasin
South Fiji Basin
3000 m
LOYALTY RIDGE
VESPA_SR012
2 s twt
50 km
Norfolk Basin
THREE KINGS RIDGE
VESPA_SR010

Fig. 2

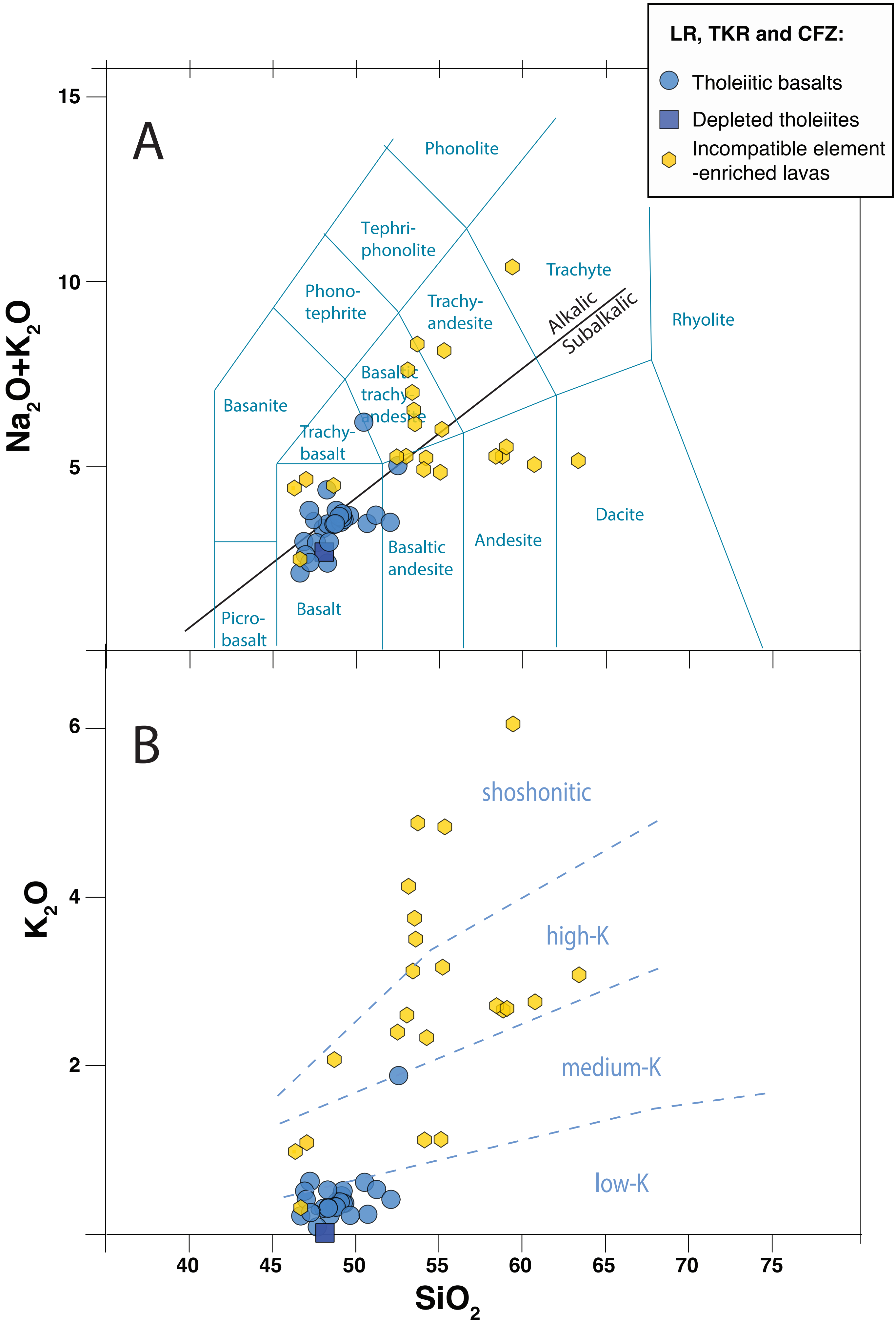
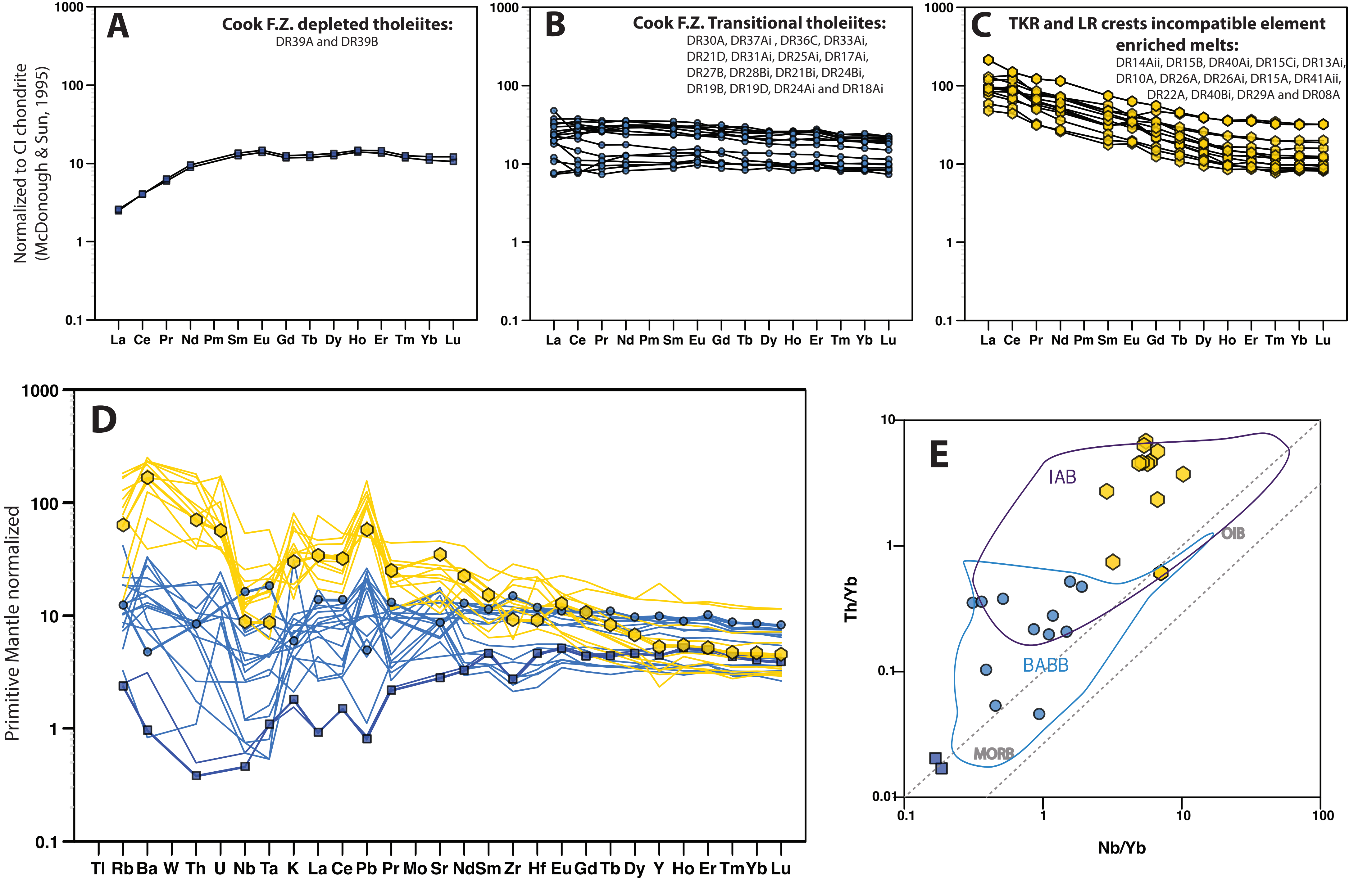

LR, TKR and CFZ:
Tholeiitic basalts
Depleted tholeiites
Incompatible element -enriched lavas
A
Phonolite
Tephri-phonolite
Phono-tephrite
Trachyte
Trachy-andesite
Basaltic trachy-andesite
Basanite
Trachy-basalt
Alkalic
Subalkalic
Rhyolite
Dacite
Andesite
Basaltic andesite
Basalt
Picro-basalt
15
10
5
Na_2O+K_2O
B
shoshonitic
high-K
medium-K
low-K
6
4
2
K_2O
40
45
50
55
60
65
70
75
SiO_2

Fig. 3



A
Cook F.Z. depleted tholeiites:
DR39A and DR39B
B
Cook F.Z. Transitional tholeiites:
DR30A, DR37Ai , DR36C, DR33Ai,
DR21D, DR31Ai, DR25Ai, DR17Ai,
DR27B, DR28Bi, DR21Bi, DR24Bi,
DR19B, DR19D, DR24Ai and DR18Ai
C
TKR and LR crests incompatible element enriched melts:
DR14Aii, DR15B, DR40Ai, DR15Ci, DR13Ai,
DR10A, DR26A, DR26Ai, DR15A, DR41Aii,
DR22A, DR40Bi, DR29A and DR08A
Normalized to CI chondrite (McDonough & Sun, 1995)
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
D
Primitive Mantle normalized
Tl Rb Ba W Th U Nb Ta K La Ce Pb Pr Mo Sr Nd Sm Zr Hf Eu Gd Tb Dy Y Ho Er Tm Yb Lu
E
IAB
OIB
BABB
MORB
Th/Yb
Nb/Yb

Fig.4

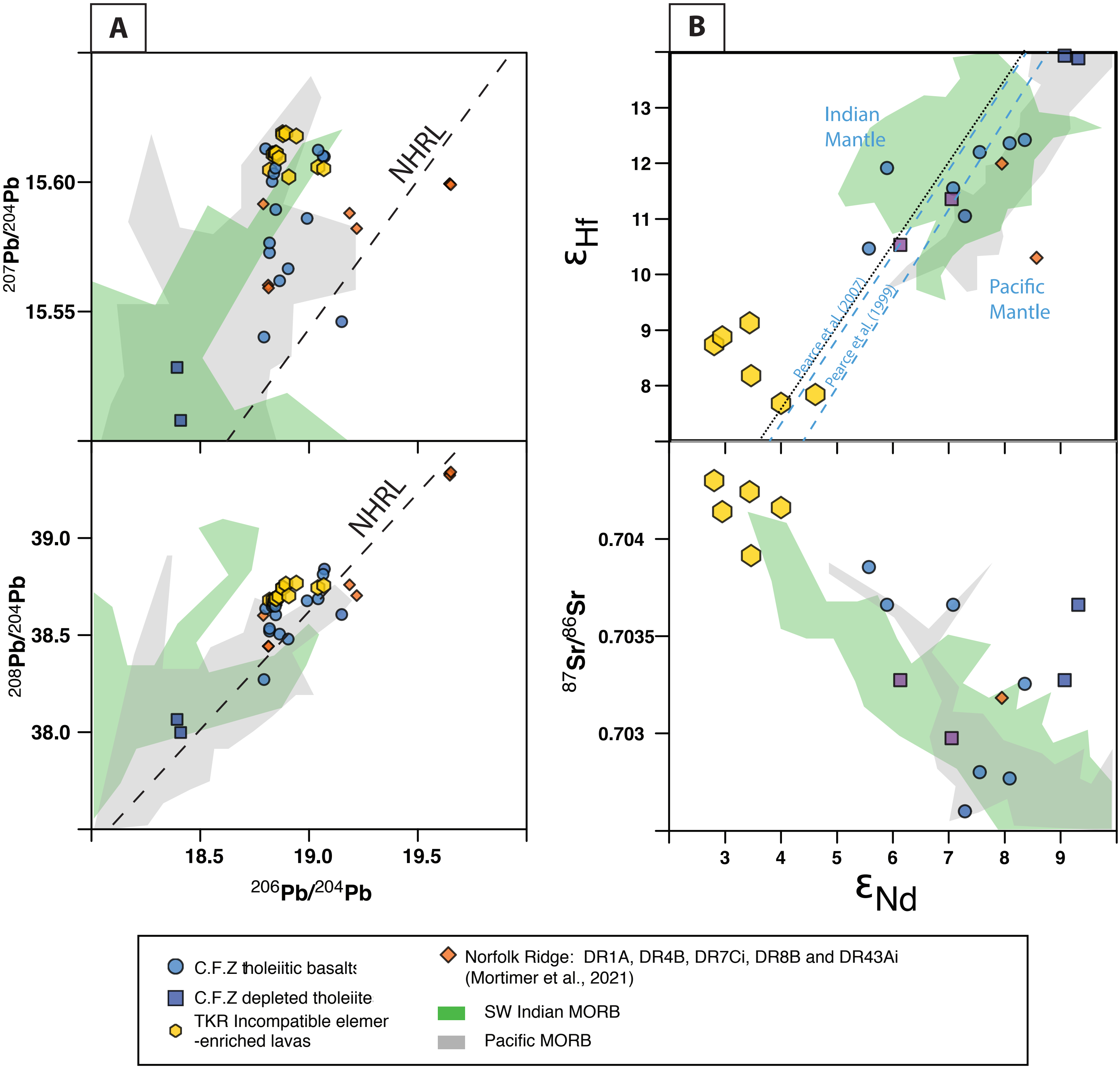
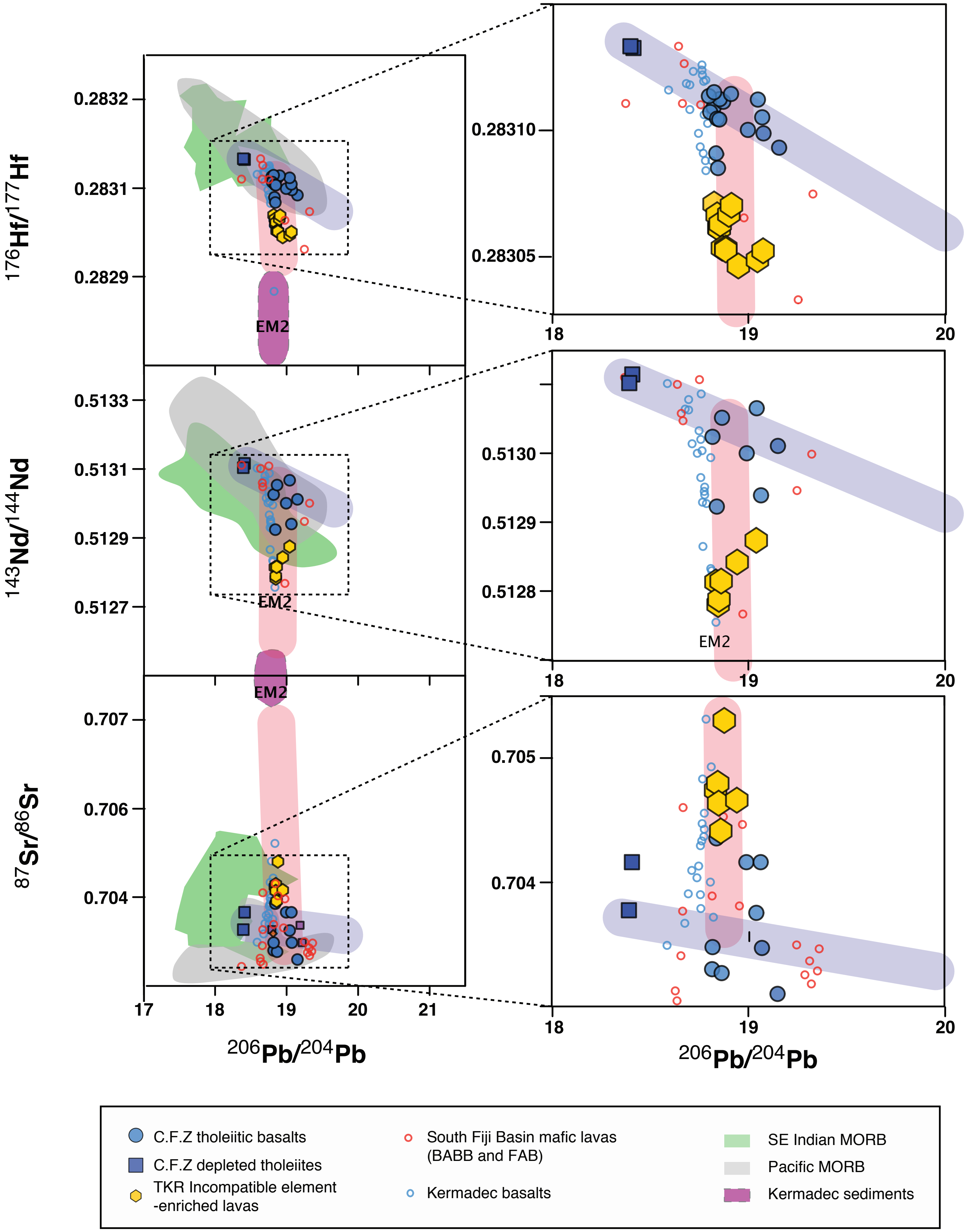
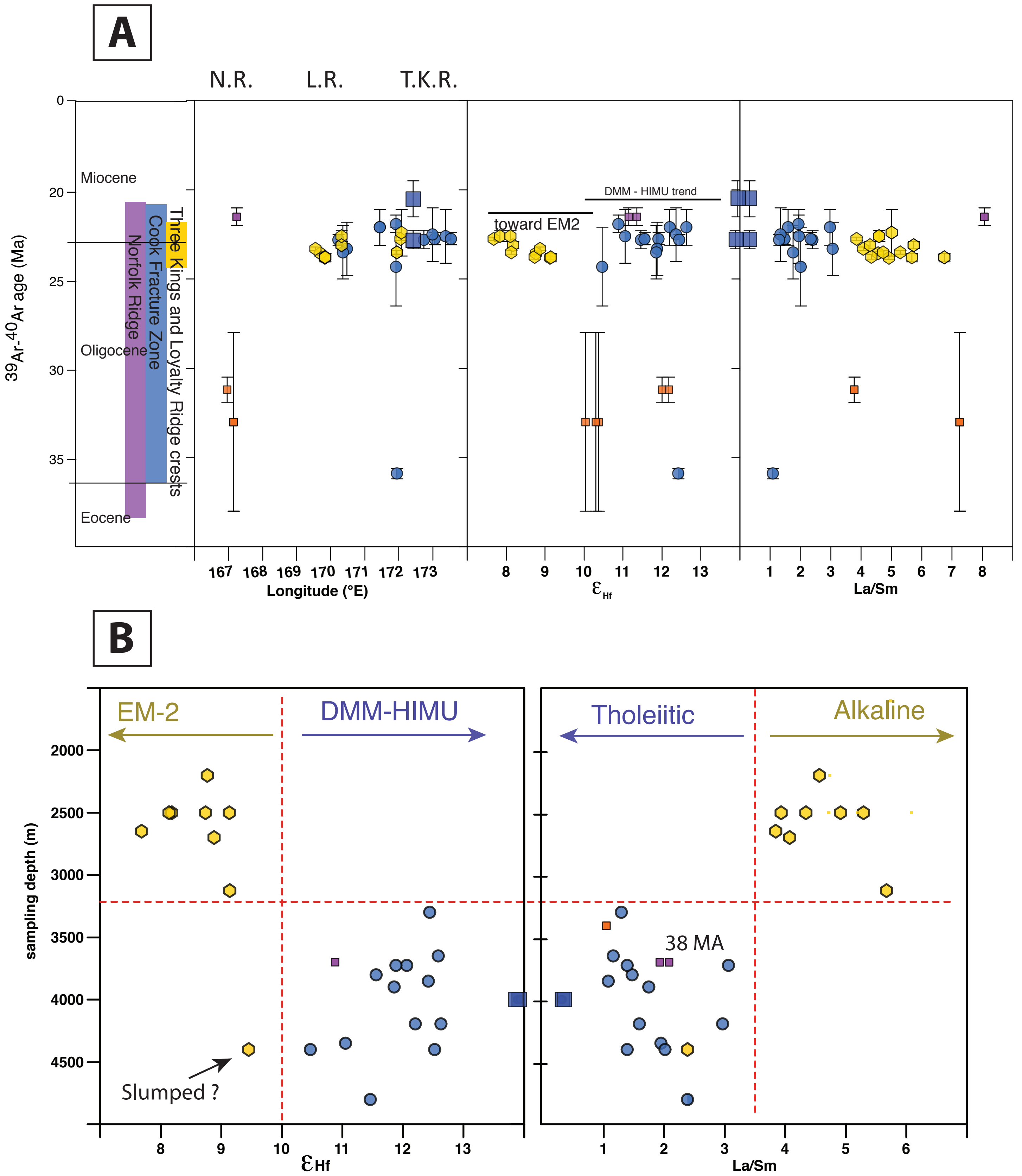

A
B
NHRL
NHRL
15.60
15.55
39.0
38.5
38.0
18.5
19.0
19.5
207Pb/204Pb
208Pb/204Pb
206Pb/204Pb
13
12
11
10
9
8
εHf
Indian Mantle
Pacific Mantle
Pearce et al (2007)
Pearce et al (1999)
0.704
0.7035
0.703
87Sr/86Sr
3
4
5
6
7
8
9
εNd
C.F.Z tholeiitic basalts
C.F.Z depleted tholeiite
TKR Incompatible elemer
-enriched lavas
Norfolk Ridge: DR1A, DR4B, DR7Ci, DR8B and DR43Ai
(Mortimer et al., 2021)
SW Indian MORB
Pacific MORB

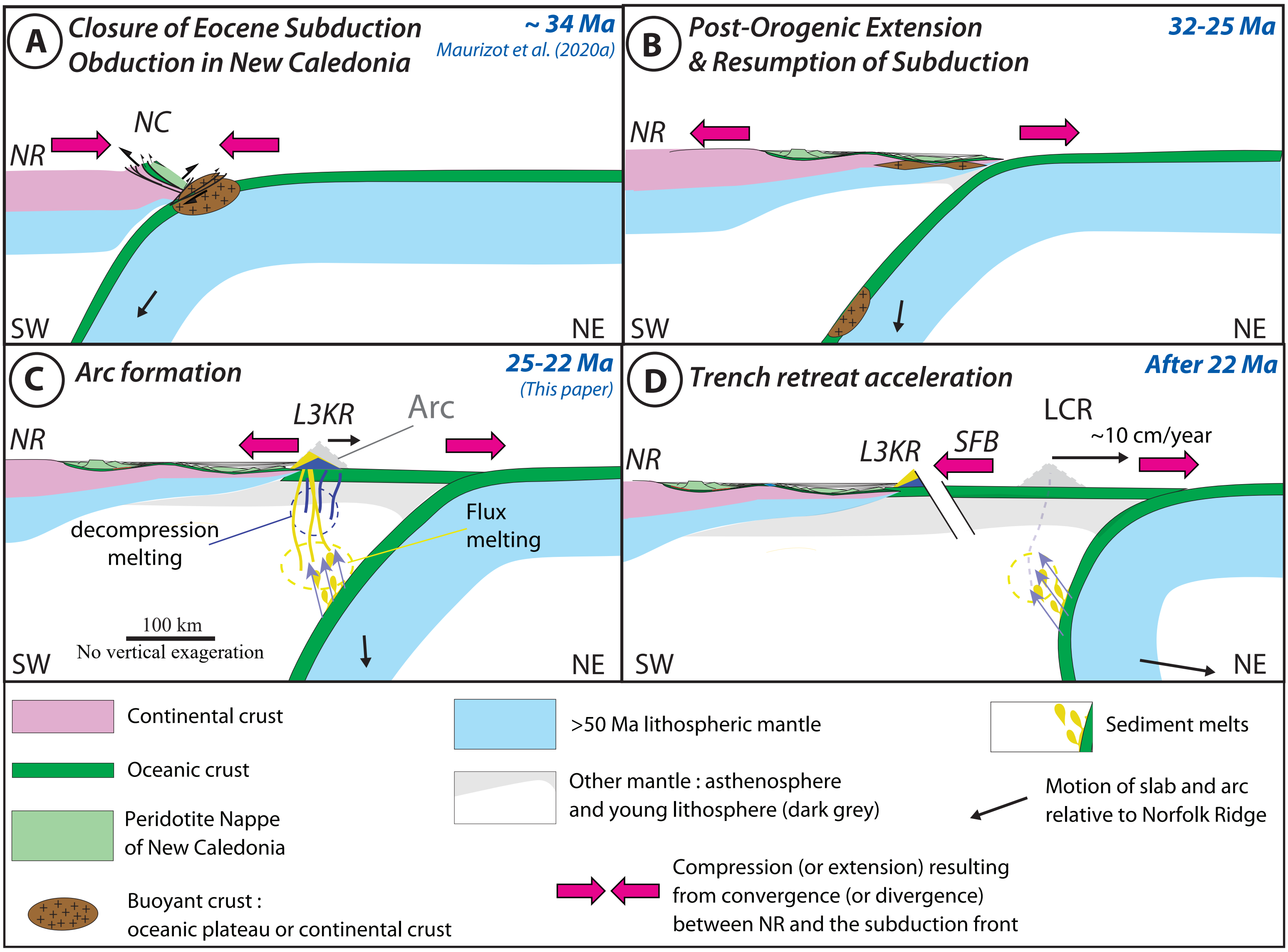
Fig. 5



$^{176}Hf/^{177}Hf$
0.2832
0.2831
0.2829
EM2
0.28310
0.28305
$^{143}Nd/^{144}Nd$
0.5133
0.5131
0.5129
0.5127
0.5130
0.5129
0.5128
$^{87}Sr/^{86}Sr$
0.707
0.706
0.704
0.705
17
18
19
20
21
$^{206}Pb/^{204}Pb$
C.F.Z tholeiitic basalts
C.F.Z depleted tholeiites
TKR Incompatible element -enriched lavas
South Fiji Basin mafic lavas (BABB and FAB)
Kermadec basalts
SE Indian MORB
Pacific MORB
Kermadec sediments

FIGURE 6


A
N.R.
L.R.
T.K.R.
39Ar-40Ar age (Ma)
Miocene
Oligocene
Eocene
Three Kings and Loyalty Ridge crests
Cook Fracture Zone
Norfolk Ridge
toward EM2
DMM - HIMU trend
Longitude (°E)
εHf
La/Sm
B
EM-2
DMM-HIMU
Tholeiitic
Alkaline
sampling depth (m)
38 MA
Slumped ?
εHf
La/Sm


A
Closure of Eocene Subduction
Obduction in New Caledonia
~ 34 Ma
Maurizot et al. (2020a)
NC
NR
SW
NE
B
Post-Orogenic Extension
& Resumption of Subduction
32-25 Ma
NR
SW
NE
C
Arc formation
25-22 Ma
(This paper)
L3KR
Arc
NR
decompression
melting
Flux
melting
100 km
No vertical exageration
SW
NE
D
Trench retreat acceleration
After 22 Ma
LCR
~10 cm/year
L3KR
SFB
NR
SW
NE
Continental crust
Oceanic crust
Peridotite Nappe
of New Caledonia
Buoyant crust :
oceanic plateau or continental crust
>50 Ma lithospheric mantle
Other mantle : asthenosphere
and young lithosphere (dark grey)
Compression (or extension) resulting
from convergence (or divergence)
between NR and the subduction front
Sediment melts
Motion of slab and arc
relative to Norfolk Ridge