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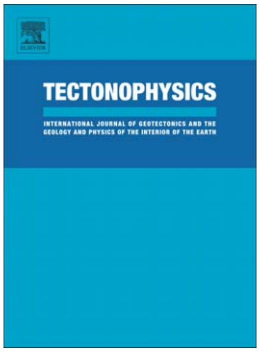

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Mantle evolution in the Variscides of SW England: geochemical and isotopic constraints from mafic rocks

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Abstract

The geology of SW England has long been interpreted to reflect Variscan collisional processes associated with the closure of the Rhenohercynian Ocean and the formation of Pangea. The Cornish peninsula is composed largely of Early Devonian to Late Carboniferous volcanosedimentary successions that were deposited in pre- and syn-collisional basins and were subsequently metamorphosed and deformed during the Variscan orogeny. Voluminous Early Permian granitic magmatism (Cornubian Batholith) is broadly coeval with the emplacement of ca. 280-295 Ma lamprophyric dykes and flows. Although these lamprophyres are well mapped and documented, the processes responsible for their genesis and their relationship with regional Variscan tectonic events are less understood.

Pre- to syn-collisional basalts have intra-continental alkalic affinities, and have REE profiles consistent with derivation from the spinel-garnet lherzolite boundary. εNd values for the basalts range from +0.37 to +5.2 and TDM ages from 595 Ma to 705 Ma. The lamprophyres are extremely enriched in light rare earth elements, large iron lithophile, and depleted in heavy rare earth elements suggesting a deep, garnet lherzolite source that was previously metasomatised. They display εNd values ranging from -1.4 to +1.4, initial Sr values of ca. 0.706, and TDM ages from 671 Ma to 1031 Ma, suggesting that metasomatism occurred in the Neoproterozoic.

Lamprophyres and coeval granite batholiths of similar chemistry to those in Cornwall occur in other regions of the Variscan orogen, including Iberia and Bohemia. By using new geochemical and isotopic data to constrain the evolution of the mantle beneath SW England and the processes associated with the formation of these post-collisional rocks, we may be able to gain a more complete understanding of mantle processes during the waning stages of supercontinent formation.

Keywords: lamprophyre; Variscides; continental collision; postcollisional magmatism; mantle evolution; Pangea

Introduction

The tectono-stratigraphic zonation of the Variscan orogen indicates that SW England is located along the northern margin of the Late Paleozoic Variscan suture zone (Fig. 1), which resulted from the closure of the Rheic Ocean and the collision between Laurussia and Gondwana during the amalgamation of Pangea (Matte 1986; Franke 1989; Woodcock et al. 2007; Arenas et al. 2014). The majority of research into the regional tectonic evolution of SW England has focused on the late Paleozoic stratigraphy and structure of meta-sedimentary and subsidiary meta-volcanic rocks and has resulted in a well-constrained model that accounts for the pre- to post-Variscan evolution of the upper crust from the early Devonian through the Permian (e.g. Holder and Leveridge 1986a; Shail and Leveridge 2009). However, the effect of collisional tectonics on the lower crust and sub-continental lithospheric mantle are relatively poorly understood (e.g. Schoonmaker et al. 1995; Lustrino 2005). Magmatism in SW England includes pre- to syn-collisional Devonian-Carboniferous mafic volcanic rocks (e.g. Floyd 1982; Floyd et al. 1993), post-collisional Early Permian lamprophyres and coeval alkali/shoshonitic basalts, and the voluminous post-collisional Cornubian Batholith (c. 293-274 Ma; Leat et al. 1987; Chesley et al. 1993; Chen et al. 1993; Clark et al. 1994). A comparison between the geochemical and isotopic signatures of the pre-collisional to post-collisional mafic intrusive and extrusive rocks therefore provides insights into the evolution of mantle sources over the course of the orogenic cycle.

Dupuis et al. (2015) presented new ^{40}Ar-^{39}Ar data for selected lamprophyre dykes, which, together with previously published data (Miller et al. 1962; Rundle 1981; Hawkes 1981; Edwards and Scrivener 1999; Roberts 1997) showed that their intrusion was contemporaneous with emplacement of the Cornubian Batholith (ca. 293-274 Ma; U-Pb monazite/xenotime; Chesley et al. 1993; Chen et al. 1993; Clark et al. 1994). In this paper, we present new geochemical and isotopic data for pre- and syn-collisional basalts and post-collisional lamprophyres and use these data to investigate changing mantle sources during late Paleozoic Variscan orogenesis.

There are several interpretations of the tectonic processes responsible for pre- and syn-collisional magmatism in SW England. Rifting in local dextral pull-apart basins within the southern margin of Laurussia (Avalonia and Baltica) in response to oblique Early Devonian collision between Laurussia and a promontory of Gondwana has been proposed by Barnes and Andrews (1986) and Arenas et al. (2014). Franke (2000) proposed a two-stage process for the development of the Rhenohercynian margin involving earlier closure of the Rheic Ocean followed by opening of the Rhenohercynian Ocean, and the applicability of this model to SW England has been suggested (e.g. Shail and Leveridge 2009).

The tectonic processes responsible for post-collisional magmatism in this region are less constrained. Generally, post-collisional magmatism has been attributed to slab break off or lithospheric delamination (e.g. Von Blanckenburg and Davies 1995; Dilek 2006), lithospheric extension related to post-orogenic collapse (e.g. Dewey 1988; Turner et al. 1999) or a combination of these processes. Post-collisional lamprophyres are traditionally interpreted to be products of low degrees of partial melting of a previously enriched sub-continental lithospheric mantle (SCLM). The timing and source of SCLM enrichment are poorly understood, although recent studies suggest upper crustal sediment recycling and multi-stage enrichment during subduction may play an important role in SCLM metasomatism (e.g. Tommasini et al. 2011; Aghazadeh et al. in press).

Lamprophyres in post-collisional tectonic settings are often spatially and temporally associated with composite batholiths. The genetic relationships between these rocks are unclear, however the common presence of mafic xenoliths and enclaves in felsic plutons suggests a mantle component is involved in their genesis. Post-collisional lamprophyres and batholiths are common in the Variscan orogen and in several localities lithospheric delamination processes are thought to be responsible for this magmatism (Gutierrez-Alonso et al. 2011; Neubauer et al. 2003).

Geologic setting

The European Variscan belt is a result of the collision between Gondwana, Laurussia and various peri-Gondwanan microplates during Devonian-Carboniferous times. Voluminous tonalite-granodiorite-granite plutonism with coeval mafic – ultramafic intrusions occurred across the entire belt between 295-285 Ma (Fernandez Suarez et al. 2000).

The Late Paleozoic massif of SW England lies along the northern flank of the European Variscan orogen (Fig. 1). Paleogeographic reconstructions (Scotese 2003; Woodcock et al. 2007; Arenas et al. 2014) indicate that this massif resided along the southern flank of Laurussia at the time of Variscan orogenesis. The massif includes ophiolitic rocks of the Lizard Complex (397 ± 2 Ma; U-Pb zircon; Clark et al. 1998), and Gondwana-derived Ordovician quartzite clasts in olistostromes, both of which suggest proximity to a suture zone that separates Laurussian from Gondwanan elements (Cocks and Fortey, 1982). This suture zone, commonly referred to as the Rhenohercynian suture zone, is likely a remnant of a marginal or successor basin to the Rheic Ocean that formed in the Early-Mid Devonian and was fully closed by the Early Carboniferous (Shail and Leveridge 2009; Holder and Leveridge 1986b; Matte 2001). Geochemical, isotopic and geochronological data from the Iberian Massif (Gondwana) suggest that the Variscan collision occurred in two stages (at ca. 400 Ma and ca. 370 Ma, respectively; Arenas et al. 2014).

SW England is generally correlated with the Rhenohercynian tectonostratigraphic zone of mainland Europe, which lies to the north of the Bohemian massif (e.g. Holder and Leveridge 1986b; Shail and Leveridge 2009; Nance et al. 2010; Strachan et al. 2013) and includes the South Portuguese Zone of southern Iberia. Collectively these three regions define most of the outer limb of the Ibero-Armorica Arc (IAA; Franke 1989) and the only portion of the IAA that was part of Laurussia prior to Variscan orogenesis. This region is interpreted to have occupied the upper plate above a northward-dipping subduction zone during contraction of the Rheic Ocean in the Silurian (e.g. Arenas et al. 2014). After collision with the Gondwanan margin at ca. 400 Ma (Nance et al. 2010; Arenas et al. 2014), most models for the tectonic evolution of SW England place this region on the lower plate (e.g. Holder and Leveridge 1986a). This change in subduction polarity in the northern (mid-European) segment of the Variscides has been interpreted to document a history in which the late Silurian closure of the Rheic Ocean by northward subduction was immediately succeeded by the ephemeral opening and subsequent southward subduction of the short-lived Rhenohercynian Ocean (Franke 2000). Subduction polarity change during the closure of the Rhenohercynian Ocean is also indicated by the model of Stampfli et al. (2013). These regional models involving subduction polarity change are consistent with with data from SW England (Shail and Leveridge 2009).

Despite the lack of exposed autochthonous pre-Devonian rocks, the basement of SW England is variously inferred to be of: (i) Avalonian affinity, based on its position to the north of the Rhenohercynian suture and the demonstrable Avalonian affinity of neighboring crustal blocks (e.g. Strachan et al. 2013), or a (ii) distinct (non-Avalonian) Gondwana-derived terrane (Shail and Leveridge 2009), or of (iii) Meguma terrane affinity, based on similar and distinctive isotopic characteristics of source rocks for the crustally-derived granitoid rocks (Nance et al. 2015)

The Devonian-Early Carboniferous geology of SW England (Fig. 2) is preserved in a series of six east-west trending sedimentary basins that formed as grabens or half-grabens during continental rifting beginning in the late Lockhovian. The evolution of these basins is summarized in Leveridge (2011), Shail and

Leveridge (2009), Leveridge and Hartley (2006), Leveridge et al. (2002), and Merriman et al. (2000). Distinct stratigraphies within these basins indicate diachronous initiation from south to north, beginning with the Looe Basin (Lockhovian-Emsian) and ending with the Culm Basin (Late Famennian; Fig. 2). Collectively, these basins are interpreted to have formed on the northern side of the Rhenohercynian basin that was locally floored farther south by oceanic lithosphere now preserved in the Lizard Complex.

The Gramscatho Basin, located between the Lizard Complex to the south and the Looe Basin to the north, consists of southerly-sourced, deep marine strata that are interpreted to have prograded across the distal passive margin of the Rhenohercynian basin in the Late Devonian (Holder and Leveridge 1986a; Leveridge et al. 1984). The onset of Variscan convergence in the latest Eifelian to early Givetian is recorded in the Gramscatho Basin by a transition from syn- to post-rift hemipelagic sedimentation to deep marine siliciclastic sedimentation and olistostromal deposits (Holder and Leveridge 1986a; Shail and Leveridge 2009; Leveridge and Shail 2011). Zircons from olistostromal deposits in the Gramscatho Basin contain Armorican-derived (Gondwanan) ages (ca. 518- 710 Ma; ca. 1800-2200 Ma.) (Sadler 1974; Strachan et al. 2013), supporting the hypothesis that SW England records the terminal collision between Laurussia and Gondwana (Cocks and Fortey 1982).

Continental collision began with the initial accretion of the Gramscatho Basin and Lizard Complex to the continental slope. This convergence, resulted in basin inversion in the southerly basins and was contemporaneous with the northward propagation of basin development and syn-rift sedimentation (Tavy and Culm basins), which themselves were subsequently inverted and deformed (Leveridge and Hartley 2006; Shail and Leveridge 2009). Peak metamorphism reached anchizonal-epizonal conditions (Dodson and Rex 1971; Warr et al. 1991), and has been dated at 333-327 Ma in the Looe Basin ($^{40}Ar/^{39}Ar$ muscovite, Clark et al. 1998). Mafic magmas were erupted in small half-graben and graben basins in a continental pre- to syn-collisional rift setting (e.g. Floyd et al. 1993; Floyd 1995; Merriman et al. 2000; Leveridge et al. 2002).

Some regional syntheses indicate that rifting likely initiated in dextral pull-apart basins along the southern margin of Laurussia (Avalonia and Baltica; Holder and Leveridge 1986a; Barnes and Andrews 1986), which formed in response to oblique Earliest Devonian collision between a promontory of Gondwana and Laurussia (Quesada, 1991; Arenas et al. 2014). Basin development in SW England migrated northwards through the Devonian and earliest Carboniferous (Leveridge and Hartley 2006). Alternatively, it has been proposed that rifting initiated in a back-arc or marginal basin setting during subduction of the Rheic Ocean in the Devonian (e.g. Stampfli et al. 2013). Seafloor spreading and the generation of a narrow oceanic tract are thought to have initiated south of the Looe Basin by the Eifelian, as indicated by U-Pb zircon dating of plagiogranite in the Lizard Complex ophiolite (c. 397 ± 2 Ma, Eifelian; Clark et al. 1998). This age is consistent with the development of oceanic lithosphere at *c.* 395 Ma elsewhere in the 'upper allochthons' of Arenas et al. (2014), but is inconsistent with the Early Frasnian development of oceanic lithosphere in the Rhenohercynian Ocean realm of Stampfli et al. (2013). The latest Visean volcanism in the Culm Basin was the last magmatic event before basin closure and inversion. (Leveridge and Hartley, 2006).

Convergence continued until the latest Carboniferous, when it was replaced by a NNW-SSE extensional regime that persisted through most of the Early Permian and resulted in extensional reactivation of earlier thrust faults as well as the development of new extensional fault systems (Shail and Alexander 1997). This upper crustal extension was also associated with sedimentary basin formation (e.g. Crediton Graben; Fig. 2) and voluminous post-collisional magmatism (Shail and Wilkinson 1994).

Development of the Crediton Graben is a local expression of the regional transition from Variscan convergence to post-Variscan extension. The graben had initiated by the earliest Permian and deposits within the basin (Exeter Group), which predominantly comprise 'red-beds' with extrusive rocks of lamprophyric and basaltic compositions near the base of the succession (Edwards et al. 1997), unconformably overlie folded and thrusted Culm Basin sedimentary rocks. The deformed Devonian and Carboniferous successions of the Gramscatho, Looe, South Devon and Tavy basins were intruded by voluminous granitoid rocks of the Cornubian Batholith between ca. 293 Ma and 274 Ma (U-Pb monazite/xenotime; Chesley et al. 1993; Chen et al. 1993; Clark et al. 1994). Lamprophyric dykes also intrude deformed Devonian-Carboniferous strata and range in age from 292.15 ± 1.5 Ma to 284.38 ± 1.07 Ma (Fig. 2; Leat et al. 1987; Dupuis et al. 2015). Although crosscutting relationships are absent, the available geochronological data indicate the lamprophyres are broadly coeval with the generation and emplacement of the Cornubian Batholith (e.g. Rundle 1981; Chesley et al. 1993; Chen et al. 1993; Clark et al. 1994; Edwards and Scrivener 1999). In addition to the close spatial associations, genetic linkages between coeval mantle and crustal melts have been inferred on the basis of mafic enclave compositions (Stimac et al. 1995), geochemical and isotopic data from the Cornubian Batholith (Darbyshire and Shepherd 1994), and He isotope systematics of associated penecontemporaneous magmatic-hydrothermal mineralization (Shail et al. 2003).

Sample descriptions

A total of 12 lamprophyre and 5 basalt samples were collected from locations around Cornwall and south Devon (Fig. 2) from exposures mapped by the British Geological Survey (BGS). Sample targets were chosen from BGS maps and memoirs and include (i) pre- and syn-collisional subordinate mafic volcanic rocks from the Looe, Gramscatho, South Devon and Tavy basins, and (ii) post-collisional lamprophyre that intrudes Devonian and Carboniferous strata and less common basalt lavas whose depositional ages are constrained by either geochronological or palynological data from under- and overlying strata (e.g. House and Selwood 1964; Orchard 1977; Turner et al. 1979). Sample locations and host rock information are provided in Table 1 and a compilation of geochronological analyses is provided in Dupuis et al. (2015). For the purpose of this paper, we subdivide samples into pre and syn-collisional (Devonian-Carboniferous basalts) and post-collisional (Permian lamprophyres and alkali basalt (one sample)) categories in order to compare and contrast their respective mantle sources and tectonic evolution.

Petrography

Nearly all Devonian-Carboniferous mafic volcanic samples show evidence of alteration; chlorite and calcite are abundant and preservation of original minerals is rare (Fig. 3a-b). Their mineralogy is consistent with prehnite-pumpellyite to lower greenschist facies metamorphism (Floyd et al. 1993 and references therein). Samples BAS02, BAS04 and BAS13 are from shallow-level sills whose primary mineralogies have been completely altered. These samples are dominated by chlorite and carbonate minerals, with minor epidote. Sample BAS14 is from a volcaniclastic rock that has a distinct foliation defined by albite, chlorite and epidote (Floyd et al. 1993), and vesicles infilled with calcite.

Lamprophyres are minettes (alkali feldspar > plagioclase) with the exception of the Fremington dyke (NED13), which is a kersantite (plagioclase > alkali feldspar). Bergman (1987) suggested that the Pendennis dyke (NED07; Table 1) has lamproitic affinities based on its alkalic chemistry and the presence of richterite. All sampled lamprophyres (Fig. 3c-d) typically exhibit porphyritic texture, with phenocrysts of phlogopite and/or biotite in a matrix of phlogopite/biotite, alkali feldspar and/or plagioclase, augite, apatite, titanite, rutile, ilmenite, chromite, pyrite, magnetite and barite. Secondary phases include calcite, chlorite and ferromagnesian carbonates.

Geochemistry

Analytical methods

Samples were crushed and powdered at the University of Portsmouth, UK. Powders were then sent to the Regional Geochemical Center, St. Mary's University, Canada, for major and trace element analysis by X-ray fluorescence (XRF) using a Philips PW2400 X-ray spectrometer. Detailed analytical procedures are given in Dostal et al. (1994). Rare earth and selected trace elements were analyzed by ICP-MS at the TERRA facility, Memorial University of Newfoundland using a Fisons/Applied Research Laboratories 8420+ wavelength dispersive X-ray spectrometer. Details of analytical procedures can be found in Jenner et al. (1990). Sm-Nd isotopes were also analyzed at the TERRA facility, according to methods outlined in Kerr et al. (1995), using a Finnigan MAT 262V TI mass spectrometer. The extent of alteration precludes using Rb-Sr isotopic whole-rock data. However, apatite phenocrysts in the lamprophyres are unaffected by this alteration. Because Rb/Sr in apatite is negligible, measured $^{87}Sr/^{86}Sr$ ratios are interpreted to reflect the initial ratio $(^{87}Sr/^{86}Sr)_0$ of the magma at the time apatite crystallized. These ratios were measured in situ in polished thin sections of four lamprophyre dykes by LA-ICP-MS, according to methods outlined in Horstwood et al. (2008), using a ThermoFinnigan Neptune mass spectrometer at the Queen's Facility for Isotope Research, Kingston, Ontario. Due to the small number of meaningful analyses obtained from each apatite grain, single grain analyses were averaged to obtain a mean $^{87}Sr/^{86}Sr$ ratio for each lamprophyre sample.

Major, trace and rare earth elements

Selected major/trace element data for both the basalts and the lamprophyres are presented in Table DR-1. Loss-on-ignition (LOI) values for the basalts and lamprophyres are highly variable (3.9-13.9% and 3.5-14.6%, respectively). As these values, together with the secondary mineralogy, indicate variable effects of post-emplacement alteration, we rely on the concentrations of high-field strength elements (HFSE) and rare earth elements (REE) for petrogenetic interpretations. These elements remain relatively immobile during weathering/alteration processes and help to constrain the nature of the mantle source and degree of fractionation (Winchester and Floyd 1977). Rare earth and selected trace element data for the lamprophyres and the basalts are provided in Table DR-2.

The pre and syn-collsional basalts have SiO_2 contents between 42 and 53 wt% and magnesium numbers (Mg#; (100 × MgO /(MgO + 0.9FeO_{tot})) that range from 28 to 54 (fig. 4). All of the basalts have high Nb/Y (1.5-2.3) and high (> 4) Zr/Y which are typical of alkalic within-plate basalts (Fig. 5; Pearce and Norry 1979; Pearce 1983). Pre-Variscan basalts are moderately enriched in LREE and LILE (La/Sm_n=2.0-2.6) and slightly depleted in HREE (Tb/Lu_n= 1.63-2.24; Fig. 6a). No negative Eu anomalies are evident.Multi-element plots (Fig. 6c) show positive Nb and Ta anomalies, with Nb/La_n ranging from 1.7 to 2.5.

The lamprophyres have moderate SiO_2 contents (43-54 wt%) and Mg#s ranging from 35 to 58 (Fig. 4). Most samples are relatively potassic (K_2O = 1.5-7.6 wt%), and have elevated Ba contents (221-15,341 ppm). They also have high Nb/Y (1.1-4.9) and Zr/Y (17.6-39.9; Fig. 5).

The lamprophyres have elevated REE abundances (La_n=175-1695; Yb_n=9-14.5) and are highly enriched in light rare earth (LREE) and large ion lithophile (LILE) elements (La/Sm_n= 4.28-7.62) relative to heavy rare earth elements (HREE; Tb/Lu_n= 1.92-5.10; Fig. 5d). La/Yb_n ranges from 19.5 to 116. Multi-element plots are characterized by significant negative Nb, Ta and Ti anomalies (Fig. 6b) with Nb/La_n generally varying from 0.15 to 0.5. The post-collisional basalt (BAS17) is moderately enriched in LREE and LILE (La/Sm_n=2.56), relatively depleted in HREE (Tb/Lu_n=1.92), and does not show any negative Nb, Ta or Ti anomalies.

Sm-Nd and Sr isotopes

Sm-Nd isotopic data for the basalts and the lamprophyres are summarized in Table 2. Depleted mantle model ages (T_{DM}) were calculated according to De Paolo (1988; 1981). Pre and syn-collisional basalts have εNd_t values (t = 350-410 Ma) that range from +4.2 to +6.3 and T_{DM} values that range from 495 Ma to 705 Ma (Fig. 6a). There are no apparent correlations between εNd_t values and sample age.

Sm-Nd isotopic analysis of the lamprophyres yielded $\varepsilon Nd_{(t=300\ Ma)}$ values between -3.6 and +1.4 (Fig. 7a), implying the lamprophyres are less juvenile than the basalts. T_{DM} values range from 763 Ma to 1031 Ma, and are considerably older than those of the basalts.

Sr isotopic data for apatite in the lamprophyres are summarized in Table 3. Because the Rb/Sr ratio in the analyzed apatites is negligible (Table DR-3), $^{87}Sr/^{86}Sr$ ratios, which range from 0.7056 to 0.7062, are interpreted to be intial $^{87}Sr/^{86}Sr$ ratios $(^{87}Sr/^{86}Sr)_0$. Only four samples had large enough apatite grains for analysis.

On the Nd-Sr isotope evolution plot, these samples fall within the enriched mantle array (Fig. 7b).

Interpretation

Interpretation: *Pre-collisional and syn-collisional magmatism*

Devonian-Carboniferous basalts are moderately enriched in LREE and have flat HREE profiles, indicating they were generated from partial melting of a spinel lherzolite mantle. The absence of negative Nb, Ta and Ti anomalies in multi-element plots suggests that crustal contamination had no discernible effect on the Sm-Nd signatures (e.g. Murphy et al. 2008). The positive and high εNd_t values yielded by Devonian-Carboniferous basalts suggest the source mantle was relatively juvenile and indicate that an asthenospheric mantle component was involved in the generation of these magmas. However, the T_{DM} values (ca. 495-705 Ma) are significantly older than the crystallization age suggesting the additional involvement of an older SCLM source. These geochemical and isotopic signatures are consistent with previously published geochemical and isotopic data from SW England rift-related magmatism (for details see Floyd 1982; 1984; Floyd et al. 1993; Merriman et al. 2000). These data are also in agreement with detailed structural and stratigraphic analyses of SW England, which indicate that mafic magmas were erupted in small half-graben and graben basins in a continental pre- to syn-collisional rift setting (e.g. Floyd et al. 1993; Floyd 1995; Merriman et al. 2000; Leveridge et al. 2002)

Interpretation: *Post-collisional magmatism*

The geochemical data presented above is consistent with previously published data for post-collisional lamprophyres and basalts (Thorpe et al. 1986, 1987; Leat et al. 1987). Significant LREE enrichment and moderate HREE depletion, as well as high La/Yb indicate that the lamprophyres were derived from enriched, garnet lherzolite SCLM. Their high incompatible trace element and REE concentrations (Fig. 6b) indicate low degrees of partial melting of this enriched garnet lherzolite source, which is consistent with petrogenetic models for the generation of lamprophyres (e.g. Rock 1991). Negative Nb, Ta and Ti anomalies indicate either crustal contamination of the lamprophyre magma or modification of the original mantle source by subduction zone fluids (e.g. Grimmer and Floyd 1986). If these anomalies were a result of crustal contamination, they should also be reflected in the Sm-Nd signature, resulting in a negative correlation between parameters such as Nb/La and εNd_t (Fig. 6c). Since no such correlation is present, the negative trace element anomalies probably reflect the composition of the metasomatized mantle source, implying the low εNd_t values also directly reflect the composition of the mantle from which the lamprophyres were derived. Taken together, these data suggest that the lamprophyres were derived from partial melting of a garnet lherzolite mantle source that had been previously chemically modified by: (i) the addition of upper crustal material, or (ii) the addition of fluids derived from upper crustal material.

The post-orogenic basalt sample is geochemically similar to the pre-orogenic basalts indicating they were also generated from partial melting of a spinel lherzolite mantle. The absence of negative Nb, Ta and Ti anomalies in multi-element plots suggests that crustal contamination had no discernible effect on the Sm-Nd signatures (e.g. Murphy et al. 2008).

Discussion and Conclusions

The origin of lamprophyric and basaltic magmas in a collisional to post-collisional setting involves asthenospheric upwelling caused by extensional tectonics associated with orogenic collapse, lithospheric delamination or slab breakoff (e.g. Seyitoğlu and Scott 1996; Gutierrez Alonso et al., 2011; Dilek and Altunkaynak 2009). It has also been suggested that the development of Pangea contributed to anomalous mantle temperatures over wide areas (Doblas et al. 1998). In each of these processes, asthenospheric upwelling results in coeval melting of the overlying metasomatized SCLM and continental crust, often resulting in at least partial replacement of the SCLM.

The mechanism(s) driving post-collisional asthenospheric upwelling, SCLM refertilisation and mantle melting in SW England are not fully resolved. Orogenic collapse is an unlikely mechanism as evidence for substantial convergence-related crustal thickening and subsequent exhumation of associated high-grade metamorphic rocks is lacking. The Cornubian Batholith and SW England lamprophyres/basalts were emplaced into/erupted onto host rocks that have experienced peak regional metamorphic P-T conditions of *c.* 3.5 kbar (~12 km lithostatic burial) and 330°C (Shail and Wilkinson 1994).

The lithospheric mantle beneath SW England is considered to be either Avalonian or Meguma (Nance et al. 2015), which both have a well-defined envelope of εNd values with time, consistent with a Sm/Nd ratio of 0.24 (Murphy and Dostal 2007). Because of their lower εNd values and Sm/Nd ratios (0.13-0.20), the lamprophyres plot beneath this Avalon/Meguma mantle envelope, and this disparity is consistent with pervasive alteration of the mantle source, as is the elevated $(^{87}Sr/^{86}Sr)_o$ (e.g. Hoch et al. 2001).

Subduction-related geochemical signatures are absent from both Devonian-Carboniferous pre- and syn-collisional basalts and Middle Devonian Lizard oceanic crust (Floyd 1982). However post-collisional lithospheric extension is a possible mechanism for lamprophyre/basalt emplacement (Fig. 8a). In SW England there was a fundamental change in the latest Carboniferous to a dextral transtensional regime controlled by major NW-SE faults (Dearman 1970; Hawkes 1981; Shail and Wilkinson 1994). This change occurs during the latest Carboniferous throughout most of NW Europe following Variscan convergence, (e.g. Arthaud and Matte 1977; Henk 1999; Ziegler and Dèzes 2006). Distinguishing between process allocated with the far-field effects (plate-boundary) such as stress-induced rifting, lithospheric delamination (Fig. 8b), and slab break-off (Fig. 8c) is potentially problematic as all may result in asthenospheric upwelling, mantle refertilisation, partial melting, bimodal magmatism and extension in the vicinity of the suture zone. The available data are broadly in permissive agreement with all three mechanisms (Fig. 8). The spatial and temporal coincidence of the Cornubian Batholith with post-collisional lamprophyres and basalts suggests that there may be a genetic relationship (e.g. Leat et al. 1987; Darbyshire and Shepherd 1994; Shail and Wilkinson 1994) Such a scenario is consistent with asthenospheric upwelling providing sufficient heat to melt the overlying SCLM and crust. Thus the lamprophyres of the SW England may be a local example of the products of post-collisional asthenospheric upwelling that occurred in various parts of the Variscides. Whether these occurrences can be attributed to orogen-wide delamination event(s), or to localized zones where slab break-off occurred requires further investigation

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Figure Captions

Figure 1. Simplified map of the European Variscides (from Strachan et al. 2013, modified from Ballevre et al. 2009)

Figure 2: (**a**) Simplified geological map of SW England (after Shail and Leveridge 2009). Sample locations are denoted by stars (basalt), crosses (lamprophyre lavas) and lines (lamprophyre dykes). Sample locations are approximate; for OS grid references see Table 1. (b) Inset showing distribution of lamprophyre dykes in South Cornwall.

Figure 3: (a) and (b) representative thin sections of pre- and syn-collisional basalts. (c) and (d) representative thin sections of post-collisional lamprophyres.

Figure 4: Harker diagrams of selected major and trace element data.

Figure 5: (a) Zr vs. Zr/Y discrimination diagram (after Pearce and Norry 1979). (b) Nb/Y vs. Ti/Y discrimination diagram (after Pearce 1983).

Figure 6: REE diagrams (after Sun and McDonough 1989) for (a) pre and syn-collisional basalt and (b) post-collisional basalt and lamprophyres, and multi-

element plots (after Thompson 1982) for (c) pre- and syn-collisional basalts and (d) post-collisional basalt and lamprophyres.

Figure 7: (a) Sm-Nd isotopic data for pre-collisional magmatism (t=350-410 Ma) and post-collisional magmatism (t=300 Ma). (b) Sr-Nd istopic data for lamprophyre dykes; values fall within enriched mantle array. (c) Nb/La vs. $\varepsilon Nd_{(t=300Ma)}$ plot for lamprophyres. No correlation between Nb/La and $\varepsilon Nd_{(t=300Ma)}$ is present.

Figure 8: Permissive mechanisms for the generation of post-collisional magmatism in SW England (after: Stampfli et al., 2013). (a) post-collisional extension of previously thickened lithosphere. (b) lithospheric delamination. (c) slab break-off.

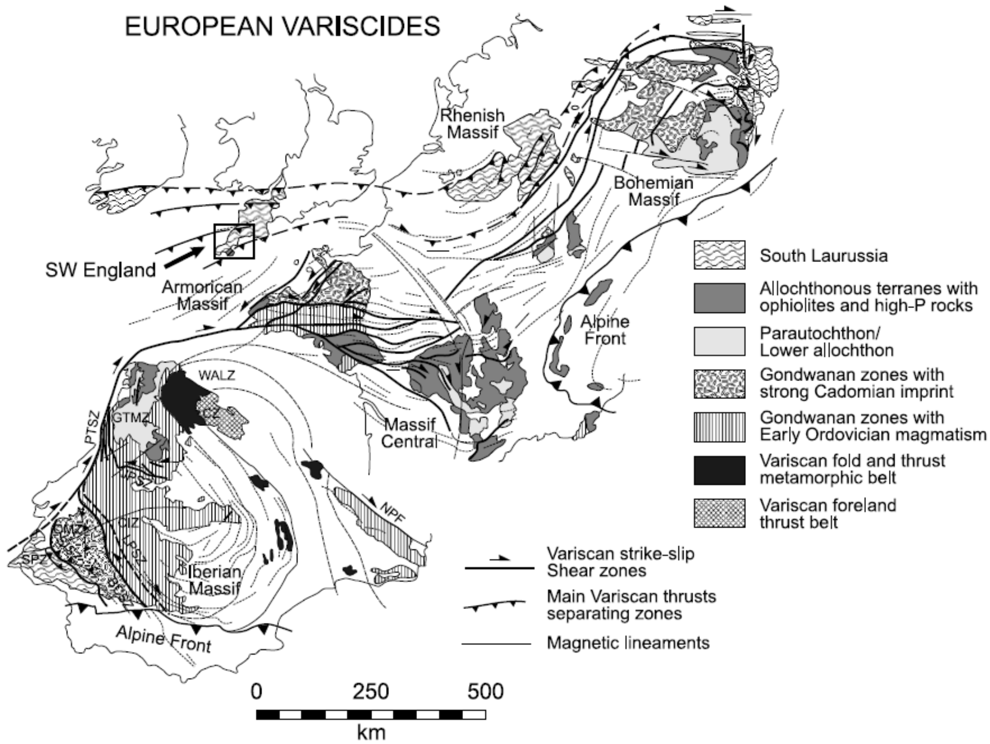

EUROPEAN VARISCIDES
Rhenish Massif
Bohemian Massif
SW England
Armorican Massif
Alpine Front
WALZ
GTMZ
PTSZ
CIZ
NPF
Massif Central
Iberian Massif
Alpine Front
South Laurussia
Allochthonous terranes with ophiolites and high-P rocks
Parautochthon/ Lower allochthon
Gondwanan zones with strong Cadomian imprint
Gondwanan zones with Early Ordovician magmatism
Variscan fold and thrust metamorphic belt
Variscan foreland thrust belt
Variscan strike-slip Shear zones
Main Variscan thrusts separating zones
Magnetic lineaments
0
250
500
km

Figure 1

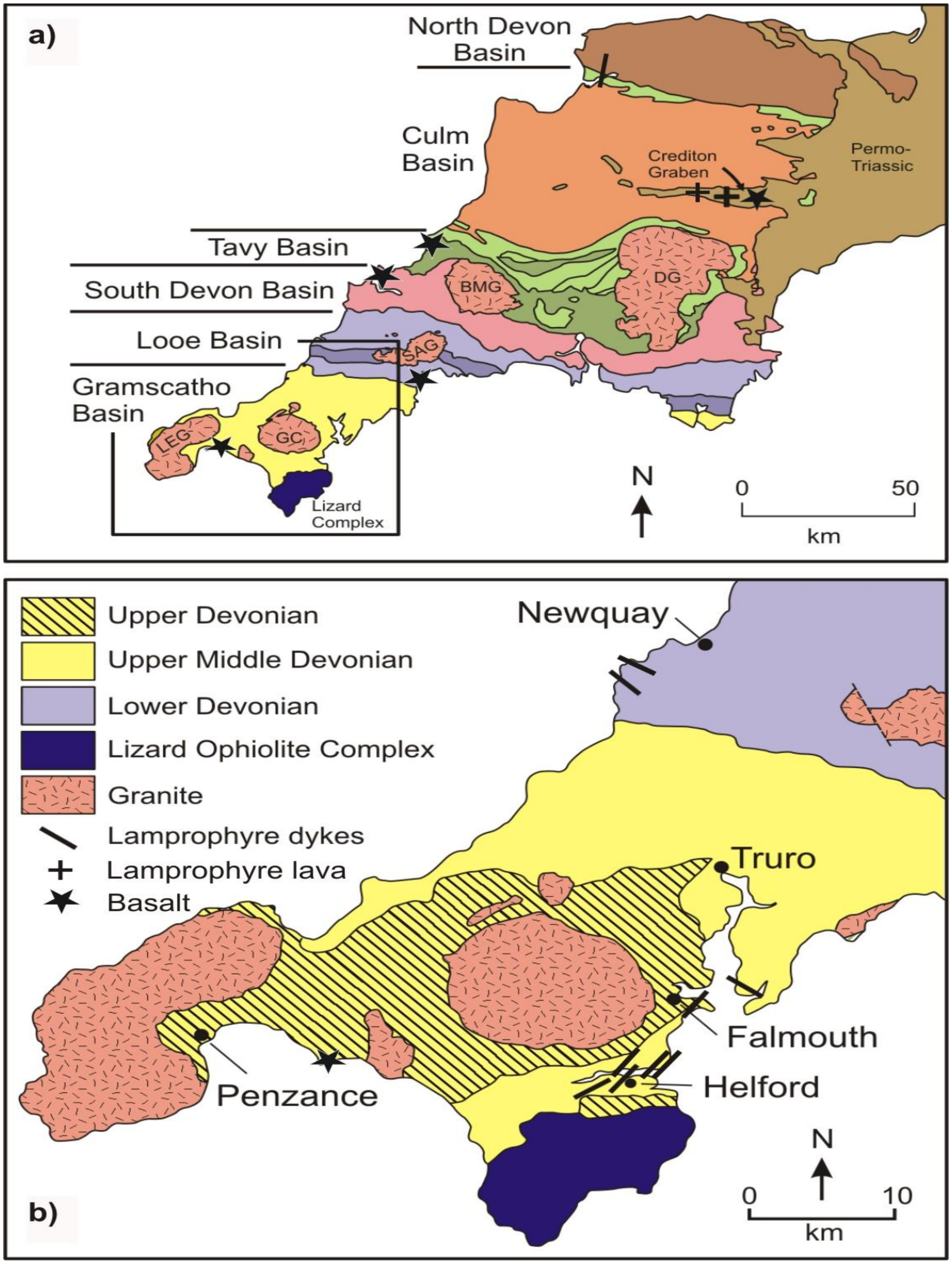

a)
North Devon Basin
Culm Basin
Crediton Graben
Permo-Triassic
Tavy Basin
South Devon Basin
BMG
DG
Looe Basin
SAG
Gramscatho Basin
LEG
GC
Lizard Complex
N
0
50
km
Upper Devonian
Upper Middle Devonian
Lower Devonian
Lizard Ophiolite Complex
Granite
Lamprophyre dykes
Lamprophyre lava
Basalt
Newquay
Truro
Falmouth
Helford
Penzance
N
0
10
km
b)

Figure 2

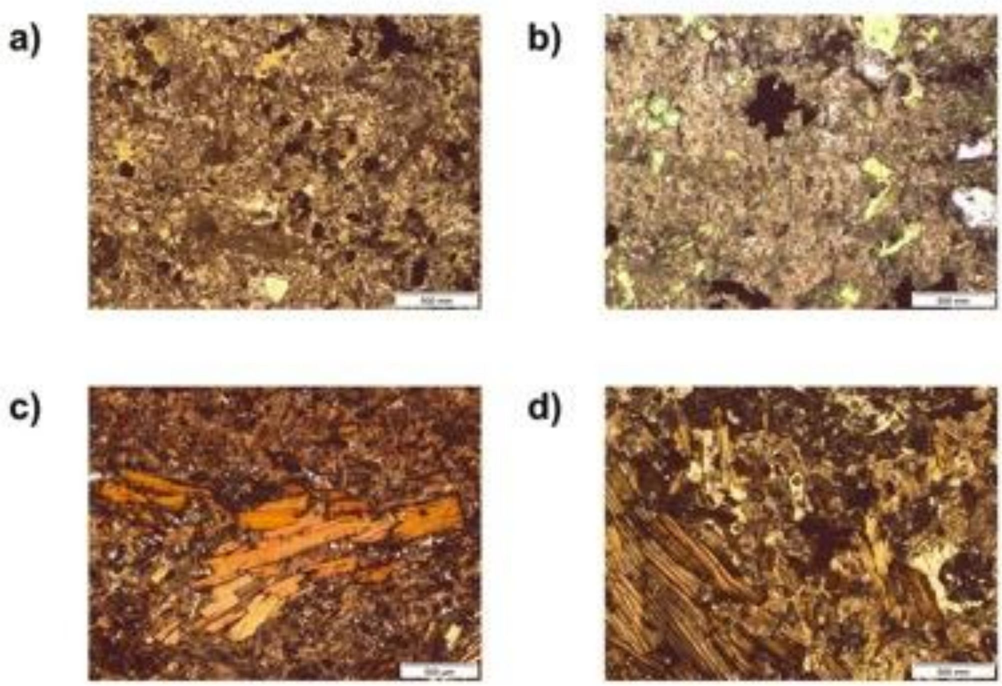


Figure 3

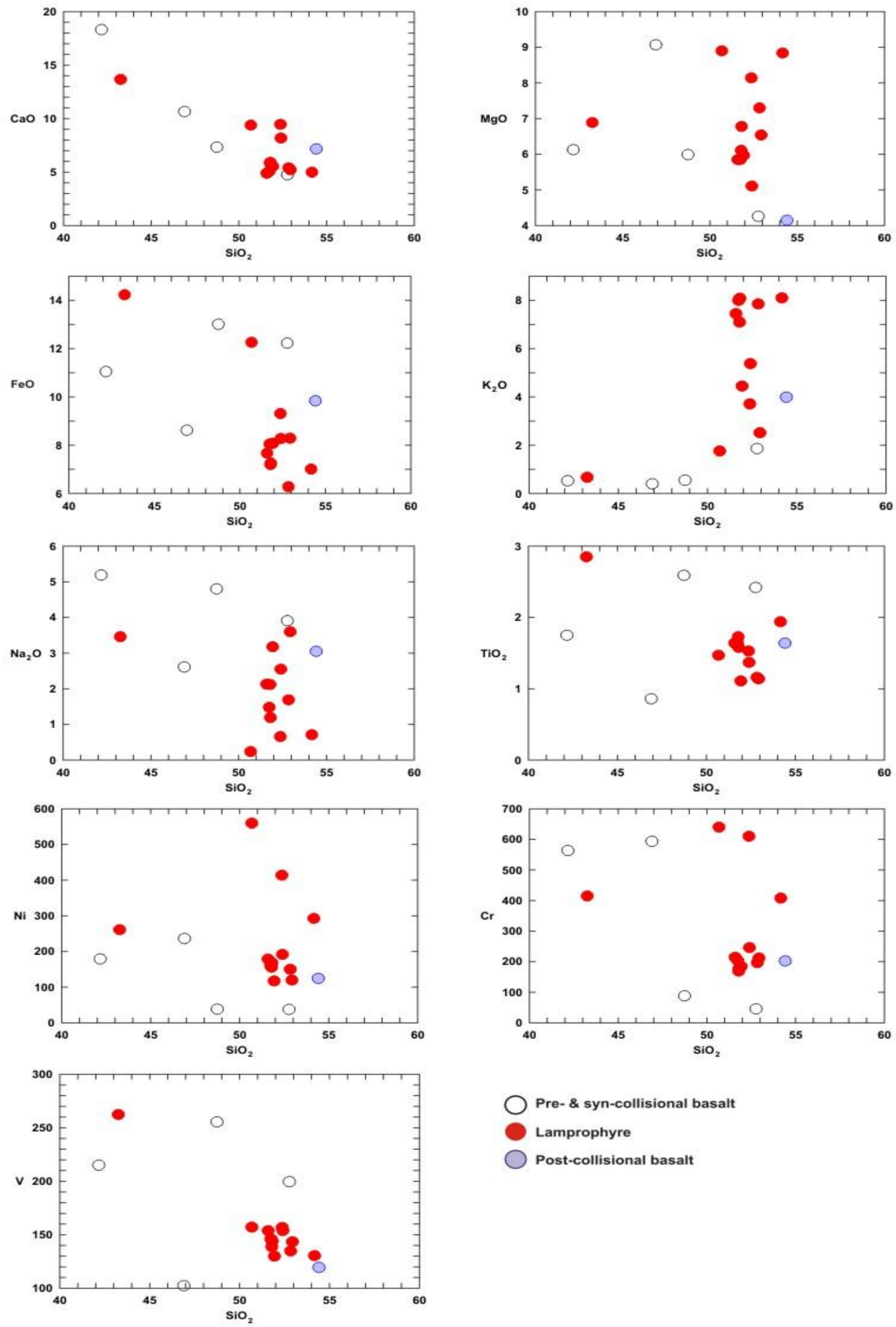
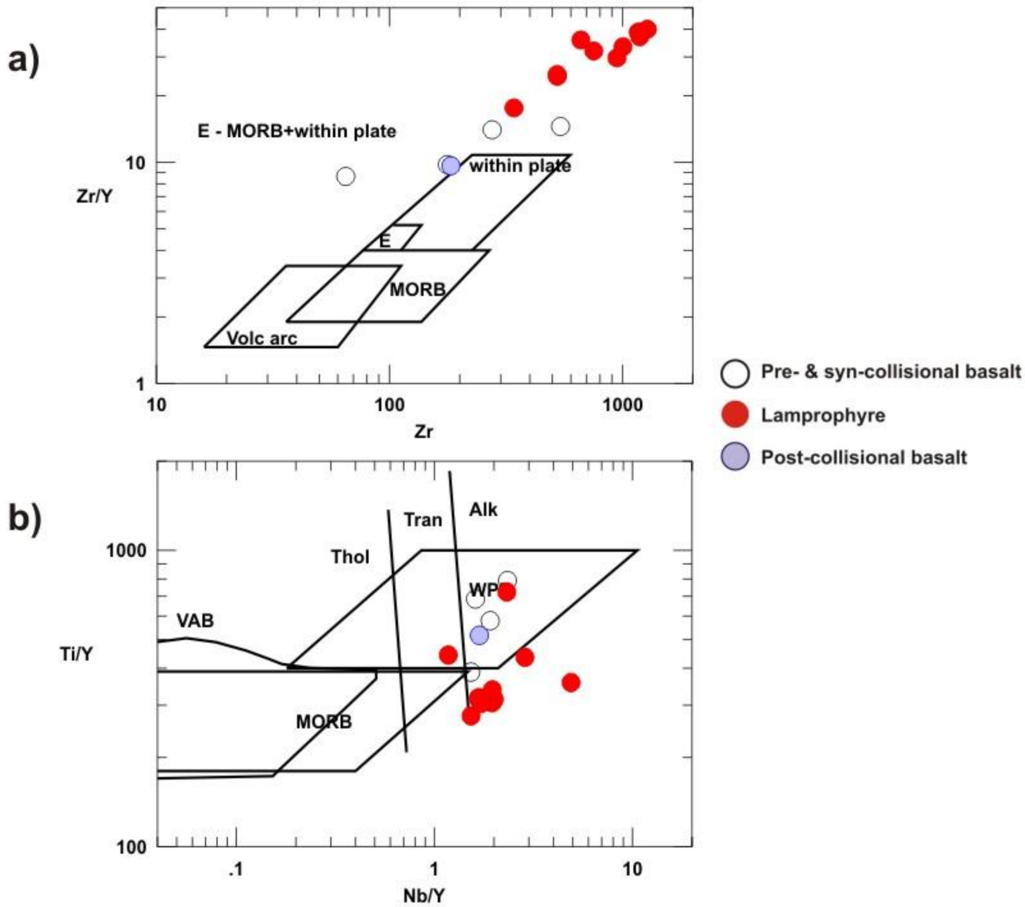

CaO
MgO
FeO
K_2O
Na_2O
TiO_2
Ni
Cr
V
SiO_2
Pre- & syn-collisional basalt
Lamprophyre
Post-collisional basalt

Figure 4



a)
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within plate
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MORB
Volc arc
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Zr
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10
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1000
Pre- & syn-collisional basalt
Lamprophyre
Post-collisional basalt
b)
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Alk
Thol
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VAB
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Nb/Y
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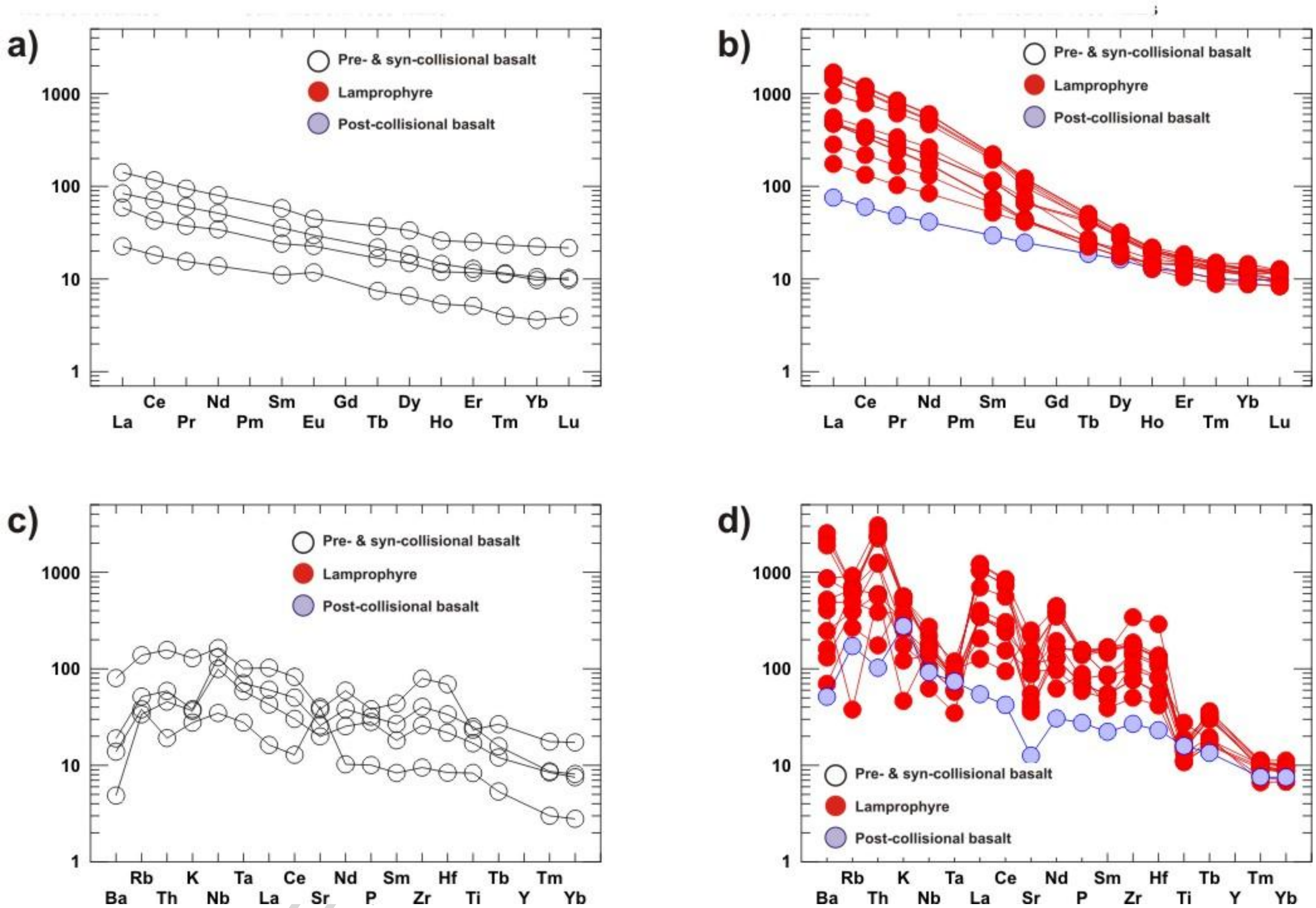
Figure 5


a)
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Lamprophyre
Post-collisional basalt
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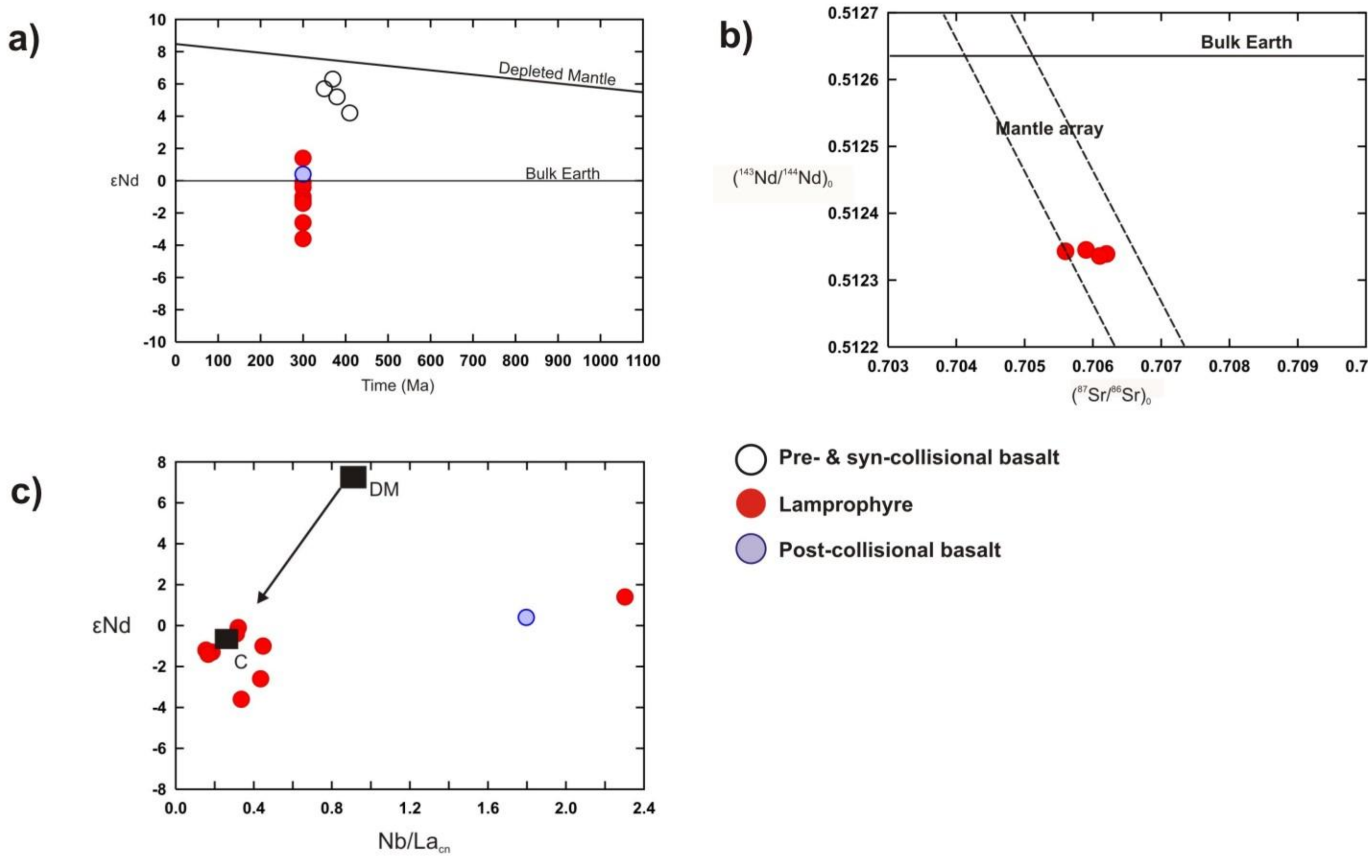
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Ba Rb Th K Nb Ta La Ce Sr Nd P Sm Zr Hf Ti Tb Y Tm Yb

Figure 6



a)
Depleted Mantle
Bulk Earth
εNd
Time (Ma)
b)
Bulk Earth
Mantle array
(^{143}Nd/^{144}Nd)$_0$
(^{87}Sr/^{86}Sr)$_0$
c)
DM
C
εNd
Nb/La$_{cn}$
Pre- & syn-collisional basalt
Lamprophyre
Post-collisional basalt

Figure 7

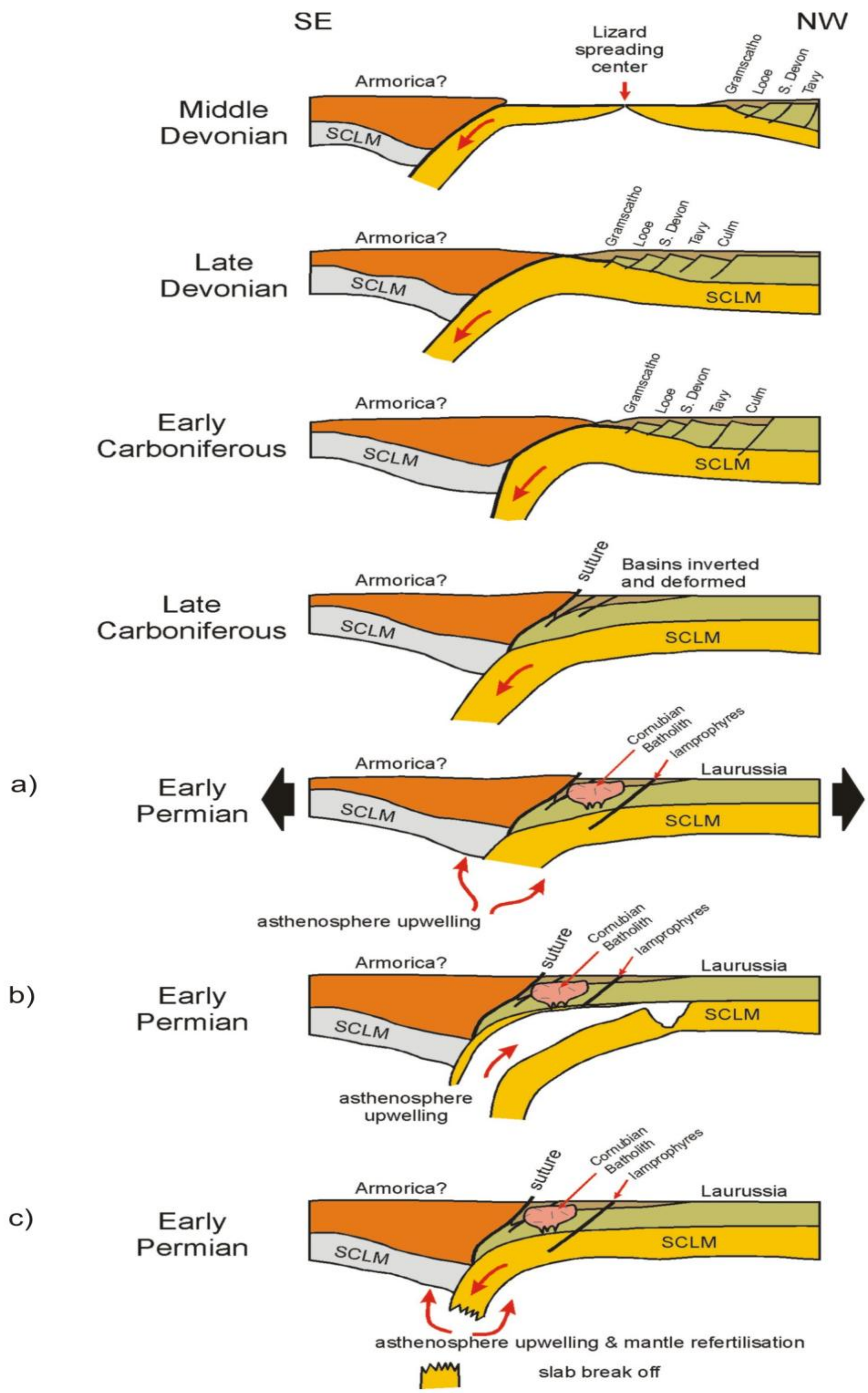

SE
NW
Lizard spreading center
Armorica?
Gramscatho
Looe
S. Devon
Tavy
Middle Devonian
SCLM
Armorica?
Gramscatho
Looe
S. Devon
Tavy
Culm
Late Devonian
SCLM
SCLM
Armorica?
Gramscatho
Looe
S. Devon
Tavy
Culm
Early Carboniferous
SCLM
SCLM
suture
Basins inverted and deformed
Armorica?
Late Carboniferous
SCLM
SCLM
a)
Early Permian
Armorica?
Cornubian Batholith
lamprophyres
Laurussia
SCLM
SCLM
asthenosphere upwelling
b)
Early Permian
Armorica?
suture
Cornubian Batholith
lamprophyres
Laurussia
SCLM
SCLM
asthenosphere upwelling
c)
Early Permian
Armorica?
suture
Cornubian Batholith
lamprophyres
Laurussia
SCLM
SCLM
asthenosphere upwelling & mantle refertilisation
slab break off

Figure 8

Table 1

Sample ID	Rock Type	Location	OS Grid Reference	Strike/Dip	Host Formation	Analyses			
BAS 02	basalt	Cudden Pt.	SW 549 276	n/a	Mylor Slate Fm.		REE	Sm-Nd	
BAS 04	basalt	Rumps Pt.	SW 932 812	n/a	Trevose Slate Fm.		REE	Sm-Nd	
BAS 13	basalt	Black Head	SX 040 479	n/a	Meadfoot Gr.		REE	Sm-Nd	
BAS 14	meta-volcaniclastic	Trebarwith Strand	SX 050 864	n/a	Tintagel Volcanic Fm.		REE	Sm-Nd	
NED 01	lamprophyre dyke	Helford	SW 753 265	040/30	Portscatho Fm.	Ar-Ar	REE	Sm-Nd	Sr
NED 03	lamprophyre dyke	Helford	SW 748 258	n/a	Portscatho Fm.	Ar-Ar	REE	Sm-Nd	Sr
NED 04	lamprophyre dyke	Holywell Bay	SW 766 600	140/68	Trendrean Mustone Fm.	Ar-Ar	REE	Sm-Nd	
NED 05B	lamprophyre dyke	Towan Head	SW 800 629	110/28	Meadfoot Gr.		REE	Sm-Nd	
NED 07	lamprophyre dyke	Pendennis Pt.	SW 827 316	060/40	Portscatho Fm.	Ar-Ar	REE	Sm-Nd	
NED 09	lamprophyre dyke	Helford	SW 759 269	n/a	Portscatho Fm.		REE	Sm-Nd	Sr
NED 10	lamprophyre dyke	Mawnan	SW 788 271	050/40	Portscatho Fm.		REE	Sm-Nd	
NED 11	lamprophyre dyke	Mawnan	SW 791 272	050/40	Portscatho Fm.		REE	Sm-Nd	
NED 12	lamprophyre dyke	Trelissick	SW 834 386	318/20	Portscatho Fm.	Ar-Ar	REE	Sm-Nd	Sr
NED 13	lamprophyre dyke	Fremington	SS 516 336	n/a	Pilton Shale Gr.		RE	Sm-	

						E R	Nd Sm
NED 14B	lamprophyre lava	Knowle	SS 738 023	n/a	Knowle/Thorverton Sandstone Fm.	E E R	- Nd Sm
NED 15	lamprophyre lava	Killerton	SS 975 004	n/a	Knowle/Thorverton Sandstone Fm.	E E R	- Nd Sm
BAS 17	basalt	Posbury	SX 815 979	n/a	Knowle/Thorverton Sandstone Fm.	E E	- Nd

Table 2

Sample ID	Nd (ppm)	Sm (ppm)	Sm/Nd	ENd (300 Ma)	T De Paolo
BAS02	9.869	2.502	0.254	6	495
BAS04	19.33	4.432	0.229	4.6	595
BAS13	38.1	8.626	0.226	3.4	705
BAS14	15.12	3.583	0.237	5.3	536
NED01	199.4	26.65	0.134	-1.3	807
NED03	226	30.08	0.133	-1.4	813
NED04	72.02	9.926	0.138	-0.3	762
NED05B	75.88	10.48	0.138	-0.3	762
NED07	168	24.89	0.148	-3.6	985
NED09	266.5	34.64	0.13	-1.4	805
NED10	101.1	18.04	0.178	-2.5	1025
NED11	101.5	18.07	0.178	-2.7	1033
NED12	211.7	27.33	0.129	-1.2	794
NED13	39.88	7.917	0.199	3.7	615
NED14B	48.92	8.567	0.175	-1.4	932
NED15	136.6	19.66	0.144	1.4	671
BAS17	19.57	4.534	0.232	0.4	1031

Table 3

Sample ID	Mean 87Sr/86Sr	Mean 85Rb	Mean 88Sr	Mean 85Rb/88Sr
NED01	0.7058	1.88 x 10-5	6.39 x 10-1	2.95 x 10-5
NED03	0.7062	2.43 x 10-5	3.24 x 10-1	7.46 x 10-5
NED09	0.7061	5.19 x 10-5	4.04 x 10-1	1.28 x 10-4
NED12	0.7056	1.88 x 10-5	6.39 x 10-1	2.95 x 10-5

Highlights

This paper presents new geochemical and isotopic data for pre-collisional basalt and post-collisional basalt and lamprophyre dykes from SW England. Our data provide insight into (i) the composition of the mantle source of pre- and post-collisional mafic rocks, (ii) the evolution of the mantle beneath SW England during Variscan orogenesis, and (iii) the regional tectonomagmatic processes responsible for the generation and emplacement of post-collisional lamprophyres and granitoids.