

What ‘anorogenic’ igneous rocks can tell us about the chemical composition of the upper mantle: case studies from the circum-Mediterranean area

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(Received 24 November 2009; accepted 28 June 2010; first published online 7 September 2010)

Abstract – The composition of the upper mantle bounded by the Canaries, Eastern Anatolia, Libya and Poland is indirectly investigated by means of the chemical composition of igneous rocks with ‘anorogenic’ geochemical characteristics emplaced during the Cenozoic. The relatively homogeneous composition of these products in terms of incompatible trace-element content and Sr–Nd–Pb isotopic composition is unexpected, considering the variable lithospheric structure of this large area and the different tectono-thermal histories of the various districts. In order to reconcile the geochemical characteristics with a statistical sampling model, it would be necessary to propose volumes of the enriched regions much lower than the sampling volumes for each volcano (that is, less than 10 cubic metres), or alternatively, efficient magma blending from larger areas. The data are consistent with a relatively well-stirred and mixed sub-lithospheric upper mantle, in the solid state, which is also hard to understand. This contrasts with the situation under oceans where magma blending from diverse sources and sampling theory can explain the compositional statistics.

Keywords: petrology, mantle, geochemistry, geodynamics, Mediterranean, basalt, SUMA.

1. Introduction

The rheological behaviour, the mineralogical mode and the chemical composition of the mantle are as yet unresolved problems (e.g. Tackley, 2000). In particular, no clear consensus has yet been reached on the possible existence of one single convecting system (whole mantle convection) involving the entire sub-lithospheric mantle (e.g. Morgan & Shearer, 1993) or the existence of two or more different convecting systems separated at the 670 km (e.g. Hofmann, 1997; Anderson, 2007) or ~ 900–1000 km mineralogical and rheological discontinuities (Anderson, 1998). Whole-mantle convection with a filtering barrier at 410 km was proposed by Bercovici & Karato (2003). Van Keken, Hauri & Ballentine (2002) note that ‘no single model to date adequately addresses all the main constraints of the physio-chemical state and evolution of the Earth’s mantle’.

From a chemical point of view, the existence of magmas with different incompatible trace-element and isotopic compositions emplaced in within-plate or diverging-plate oceanic settings has allowed the proposition of the existence of discrete enriched volumes in their mantle regions (e.g. see discussion in Niu & O’Hara, 2003). The problems not completely addressed refer to: (1) where such enriched volumes (or metasomes) are located (upper or lower mantle, grain boundaries or blobs); (2) what is the origin causing such enriched compositions (such as recycling

of continental lithosphere via subduction/delamination, involvement of primitive, undegassed, mantle regions, metasomatized lower oceanic lithosphere; e.g. Willbold & Stracke, in press) and (3) the composition of the ‘non-enriched’ peridotitic matrix (that is, depleted, fertile, enriched, re-fertilized).

The isotopic (and incompatible trace-element) heterogeneities recorded in oceanic basalts have been related to the presence of 10^2 – 10^5 m sized exotic (that is, non-peridotitic or olivine-poor lithologies compared to typical peridotitic assemblages) material in a variably depleted/enriched peridotitic matrix (e.g. Hofmann, 1997, 2003; Meibom & Anderson, 2003; Stracke, Hofmann & Hart, 2005; Pilet, Baker & Stolper, 2008; Humphreys & Niu, 2009). The exotic material would be the result of a long-term plate tectonic recycling of sedimentary and crustal components, as well as the products of metasomatic reactions between ambient mantle and fluids/melts not directly related to crustal recycling (e.g. Hofmann, 1997; Lustrino, Mascia & Lustrino, 2004; Pilet, Baker & Stolper, 2008; Warren *et al.* 2009; Willbold & Stracke, in press). The structure of this type of upper mantle has been termed ‘SUMA’ (Statistical Upper Mantle Assemblage; Meibom & Anderson, 2003). Although based on the old ‘marble-cake’ model of Allègre & Turcotte (1986), the SUMA model counts on a strong statistical approach, being based on a wealth of geochemical data of mid-ocean ridges and oceanic island basalts.

Where does this ‘exotic material’ come from? Mantle melting and lithospheric recycling along

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subduction zones or via delamination processes are plate tectonic processes able to introduce chemical, mineralogical and rheological heterogeneity into the mantle (e.g. Anderson, 2006; Willbold & Stracke, in press). Recycling of lithospheric lithologies cools the mantle, is an obstacle for convective movements and variably changes the chemical composition of the ambient mantle (e.g. Anderson, 2007). Depending on the amount of silica excess of the subducting oceanic crust (eventually responsible for the stabilization of the high-density SiO₂ polymorph, stishovite), the oceanic slab could penetrate to the lower mantle or fold and accumulate at the 670 km discontinuity (e.g. van Keken, Hauri & Ballentine, 2002; Anderson, 2007). The rate of heterogeneity addition (recycling of oceanic lithospheric plates + continental lithosphere-derived material) to the upper mantle may be much more rapid than convective stirring of the same volume. The result is that, without the presence of a connecting partial melt, the recycled lithologies can survive for a long time before reaching chemical equilibration with ambient mantle, because of extreme sluggish diffusive equilibration kinetics (in the order of 10⁻¹⁶ to 10⁻²³ m/s: van Orman, Grove & Shimizu, 2001). The resulting state of the upper mantle is 'a highly heterogeneous assemblage of enriched and depleted lithologies representing a wide range in chemical composition and fertility and, as a result of different ages of these lithologies, widely different isotopic compositions' (van Keken, Hauri & Ballentine, 2002; Hofmann, 2003; Meibom & Anderson, 2003). In a more general way, it is considered that 'the compositional heterogeneity in the Earth's mantle in general is intrinsic to the recycling process' (Willbold & Stracke, in press). The SUMA concept (Meibom & Anderson, 2003) differs from the 'plum-pudding' mantle theory because the latter requires the existence of a relatively homogeneous ambient mantle (pudding) with depleted chemical composition with which are randomly associated variably sized heterogeneities (plums).

The role of recycled oceanic crust alone has been considered a viable solution to explain the isotopic and trace-element variability of oceanic basalts (e.g. Hofmann & White, 1982). On the other hand, the idea that these lithologies have an important role has been criticized because this material would not be able to produce high-MgO, incompatible element-rich and Sr–Nd–Pb–Hf isotopically evolved Ocean Island Basalts (OIB; Niu & O'Hara, 2003). Pilet, Baker & Stolper (2008) propose a major role for metasomatized veins of the lithospheric mantle (hornblende veins) as the source of alkaline OIB and intraplate continental mafic alkaline rocks (e.g. Cantal Volcano, French Massif Central).

In the Circum-Mediterranean Anorogenic Cenozoic Igneous (CiMACI) Province (Lustrino & Wilson, 2007), the bulk of the mafic products (with low to very low magma production volume) show a surprisingly homogeneous trace-element and Sr–Nd–Pb isotopic composition despite the very large area of sampling, the

very complex tectonic evolution and the very different lithospheric structure where the single districts are located (e.g. Lustrino, Duggen & Rosenberg, in press). The CiMACI rocks are indeed emplaced on continental areas with different composition (oceanic, transitional to continental), age (from Precambrian to Recent) and lithospheric thickness (from ~5 km to > 120 km). The different areas experienced very complex tectonic evolutions, with important effects of melt extraction (formation of pure oceanic and back-arc oceanic crust) and recycling of crustal lithologies (Hercynian, Alpine, Apennine–Maghrebide, Aegean subduction systems and orogenies: Wilson & Bianchini, 1999; Lustrino, 2000; Carminati & Doglioni, 2004; Harangi, Downes & Seghedi, 2006; Lustrino, Melloso & Morra, 2007; Lustrino *et al.* 2009; Lustrino, Duggen & Rosenberg, in press, and references therein), likely producing highly heterogeneous mantle regions with depleted and enriched geochemical compositions.

2. The SUMA perspective: homogeneous v. heterogeneous upper mantle

The rationale of Meibom & Anderson (2003) is simple: they assume an upper mantle structure (the volume of mantle above the 670 km discontinuity) that is heterogeneous in terms of chemistry and mineralogy. Effectively, the upper mantle seems to be characterized by isotopic heterogeneities over a large range of scales, from several kilometres down to 0.1 m (e.g. Warren *et al.* 2009 and references therein). The continued melt extraction and lithosphere recycling (both via subduction and delamination processes) have produced a sort of 'leopard skin' mantle (e.g. Perugini *et al.* 2004) with fertile blobs (recycled crustal lithologies, including the sedimentary cover, in the form of eclogite/garnet pyroxenite) in a variably depleted/fertile lherzolitic matrix (e.g. Willbold & Stracke, in press). Relatively large degrees of melting (e.g. those likely occurring beneath diverging plate margins, along mid-ocean ridges) have the effect of diluting the geochemical differences between the peridotite matrix and the 'exotic' material (e.g. Hirschmann, 2000). In this way the trace-element and, if existing, the isotopic differences tend to converge to average values (Meibom & Anderson, 2003). Magmas emplaced along mid-ocean ridges with such 'average' geochemical compositions are those classically defined as 'Normal' or N-MORB. The homogenization of the MORB source is therefore not necessary (as instead proposed in other models, e.g. Kellogg, Jacobsen & O'Connell, 2002), being the homogenization of the melt developed during melt sampling, as predicted by the central limit theorem (e.g. Anderson, 2007). The central limit theorem indeed states that the mean of a distribution is relatively stable, as the sample volume increases, but the variance decreases, and the distribution approaches Gaussian.

Where degrees of partial melting are relatively low (e.g. as the case of sodic alkaline lavas of ocean island basalts), the partial melts may reflect much

more strongly the geochemical imprint of the 'exotic' lithologies, and therefore they may have relatively large trace-element and isotopic excursions. Nearly a quarter century ago, Zindler & Hart (1986) wrote a milestone paper in igneous geochemistry proposing the existence of four main geochemical end-members. These end-members are defined as DMM (Depleted MORB Mantle), HIMU (high μ , where $\mu = {}^{238}\text{U}/{}^{204}\text{Pb}$, with ${}^{238}\text{U}$ decaying in ${}^{206}\text{Pb}$), EM-I and EM-II. The last two end-members are considered to reflect the presence of Enriched Mantle (EM) regions with peculiar trace-element and isotopic compositions.

More than twenty years of intense geochemical research on oceanic (and continental) basalts has changed several aspects of the original Zindler & Hart (1986) model of chemical geodynamics. In particular, new geochemical jargon terms have been proposed (PreMa, FoZo1, FoZo2, PHeM, LVC, EAR, C, CMR, EM-III, ItEM; e.g. Hart *et al.* 1992; Granet, Wilson & Achauer, 1995; Stracke, Hofmann & Hart, 2005; Lustrino & Wilson, 2007; Willbold & Stracke, in press, and references therein). These acronyms indicate the existence of alleged physical reservoirs with peculiar isotopic characteristics. Worth noting is that these physical concepts are mostly based on geochemical arguments and only to a minor extent on geophysical (tomographic) considerations. The isotopic definition of the single end-members has also changed a great deal, and a general agreement has not yet been reached (e.g. Stracke, Hofmann & Hart, 2005). The classical example of this lack of agreement is the still poorly constrained Pb isotopic composition of the DMM end-member, with ${}^{206}\text{Pb}/{}^{204}\text{Pb}$ placed in the wide range of < 17 to ~ 19 in different geochemical models.

Meibom & Anderson (2003) presented evidence that the geochemical differences seen in OIB (e.g. HIMU-, EM-I and/or EM-II-rich compositions) are not related to the presence of different mantle source regions. This strongly contrasts with the common view that deep, undegassed and physically separated mantle sources can feed OIB volcanoes. Instead, the authors suggest that the 'anomalous' isotopic composition of OIB, partially or completely different from DMM-like values, is related to the sampling of relatively small (10^2 – 10^5 m) heterogeneities at upper mantle depths, reflecting the different composition of crustal-sedimentary recycled components (Meibom & Anderson, 2003).

3. The Circum-Mediterranean Anorogenic Cenozoic Igneous Province

The SUMA model works well for oceanic basalts (but see criticism of the role of recycled oceanic crust raised by Niu & O'Hara, 2003), but, when applied to basalts erupted in continental areas, some problems emerge. According to the SUMA sampling theory, a low degree of partial melts in continental areas directly unrelated to subduction zones should be statistically characterized by distinct trace-element and isotopic compositions.

Rubin *et al.* (2009) have recently presented evidence that the isotopic and key trace-element variance is greater in slow spreading-rate ridges. Melt supply rate along passive oceanic margins indeed seems to be the main explanation for the 'anomalous' composition of Indian MORBs (slowly to very slowly spreading) compared to North Atlantic MORBs (spreading faster). The presence of relatively shallow magma lenses beneath oceanic ridges, continuously replenished by abundant melt supply rates, can be at the base of the mixing of partial melts with different geochemical characteristics. The net effect is a smaller chemical variance under ridges characterized by high melt production, and the opposite under poorly magmatic (slowly spreading) oceanic ridges. According to this model, a better mantle signal preservation is observed at low-melt-supply ridges, where chemical heterogeneities can survive (Rubin *et al.* 2009).

This approach is here used to infer the distribution of the heterogeneities in the mantle sources of the CiMACI Province rocks (Lustrino & Wilson, 2007). As case studies, the sodic alkaline to tholeiitic igneous rocks belonging to the CiMACI Province have been compared to the sodic alkaline and tholeiitic OIBs. The bulk of the mafic (MgO-rich, with Mg no. > 0.65) CiMACI lavas plot in a relatively restricted Sr–Nd–Pb isotopic field, irrespective of the extremely large area of sampling, with longitude coordinates ranging from the Canaries to Anatolia and with latitude coordinates ranging from Libya/Egypt to Germany/Poland (Figs 1, 2). Many of the CiMACI mafic lavas are sodic alkaline (~ 90 – 95 % of the outcrops), nearly all associated with mantle debris in the form of peridotite xenoliths. This suggests a rapid ascent of the magma with limited crustal interaction (e.g. O'Reilly, 1989). On the other hand, the rarer tholeiitic rocks (essentially basalts and basaltic andesites) show in some places geochemical characteristics related to slightly higher degrees of interaction with crustal lithologies at shallow depths (e.g. Lustrino & Wilson, 2007 and references therein). In this sense, the geochemical composition of a part of the tholeiitic rocks belonging to the CiMACI Province cannot be considered as the true 'message' (*sensu* Hofmann, 1997) of their mantle sources, as the rocks may be affected by post-melting processes (e.g. AFC-type; Assimilation and Fractional Crystallization; DePaolo, 1981). This does not mean that the CiMACI rocks all have a uniform trace-element and Sr–Nd–Pb isotopic composition. Rather, I wish to highlight that the trace-element and Sr–Nd–Pb isotopic variability of these rocks is surprisingly small, compared to what should be expected in such a geologically complex area.

With few exceptions (e.g. the Harrat Ash Shaam district, Middle East), most of the CiMACI lavas belong to igneous districts with a small to very small areal extent. Nearly all the volcanoes cover much less than 1000 km^2 and only in a couple of cases (e.g. Mt Karacadağ, SE Turkey) do single volcanoes extend for more than 5000 km^2 (Lustrino *et al.* 2010).

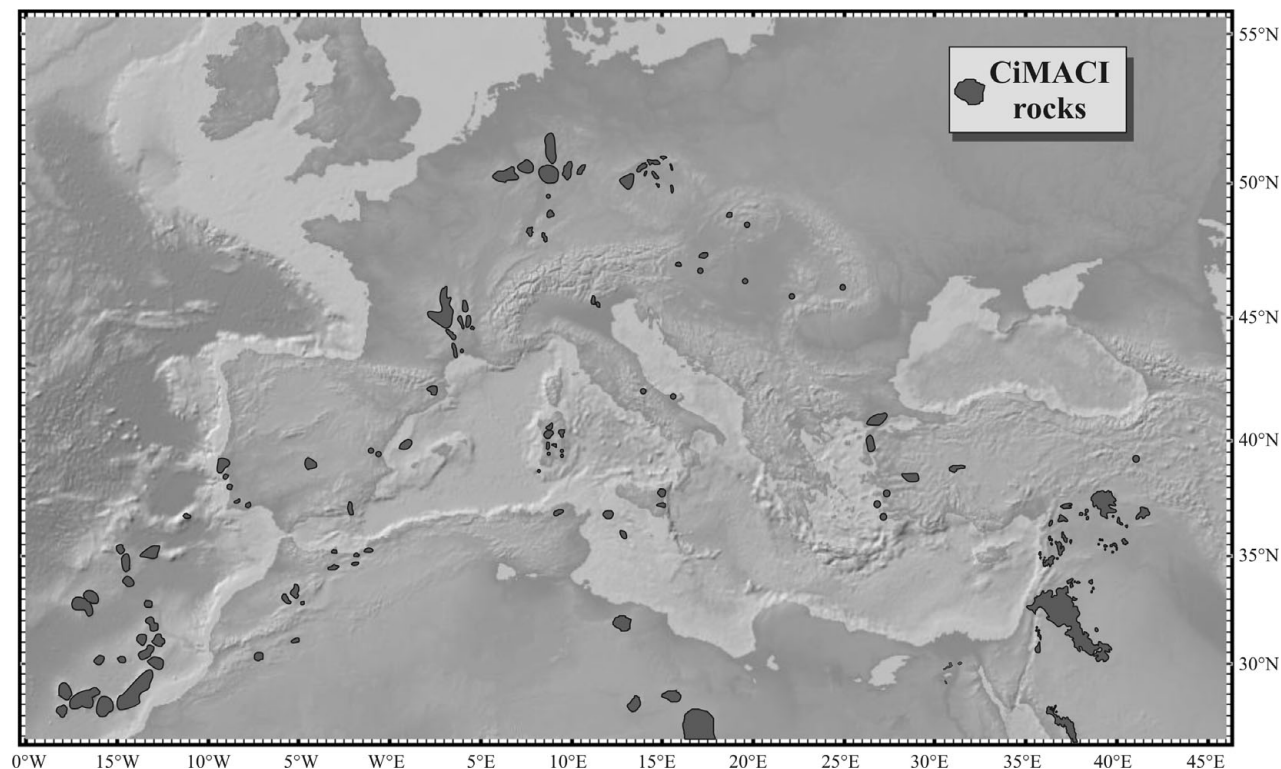


Figure 1. Digital topographic and bathymetric map of the circum-Mediterranean area showing the Cenozoic igneous rocks with 'anorogenic' geochemical compositions reviewed in this study. Full references for each igneous district are given in Lustrino & Wilson (2007). A colour version of this figure is available in the online Appendix at <http://www.cambridge.org/journals/geo>.

Compared to typical OIBs, the CiMACI volcanoes are characterized by a smaller volume of igneous rocks. The small volume of rocks is associated with partial melting of a relatively small volume of mantle and/or small degrees of partial melting. As an example, the volume of the volcanic products of Mt Etna (Sicily, Italy; less than 1000 km²) is about twenty times smaller than the volume of the St Helena Island lavas in the South Atlantic Ocean. It is noteworthy that St Helena Island is considered to be the classical HiMU end-member (Zindler & Hart, 1986; Hart *et al.* 1992; Hofmann, 1997).

On the basis of a whole-rock database comprising more than 8400 samples of the CiMACI Province (database in Lustrino & Wilson, 2007 plus new data, downloadable from the GeoRoc web site: http://www2.mpch-mainz.mpg.de/~geo/Databases/GEOROC/Expert_Datasets.htm), no statistically relevant isotopic differences have been observed with regard to: (1) the size of the igneous edifice; (2) the age of the lavas; (3) the degree of melting (calculated using incompatible trace-element ratios). These considerations are based on unconstrained assumptions, such as: (1) the volume of the erupted magma is proportional to the volume of partial melt generated, and (2) the degree of melting can be qualitatively estimated using incompatible trace-element concentration. These are two important assumptions, not necessarily completely true because an unknown volume of partial melt could be stored as cumulate at the Moho or at shallower depths, and because the incompatible trace-element content is

principally a function of the composition of the mantle sources. However, to consider these assumptions as not particularly critical for the aim of this paper is realistic.

Following the SUMA model, a relatively large chemical and isotopic range should be expected for the various igneous districts of the CiMACI Province. What is observed, however, is the existence of relatively homogeneous incompatible trace-element and isotopic compositions for most of the primitive CiMACI samples (Fig. 3; Table A1 in online Appendix at <http://www.cambridge.org/journals/geo>). These also cluster in a relatively small isotopic area, with almost no samples plotting towards extreme geochemical compositions (e.g. HIMU, EM-I and EM-II; Fig. 2). Only very few Palaeogene samples from the Bohemian Massif tend to reach isotopic compositions close to the HIMU field (as defined by the St Helena basalts, Atlantic Ocean: Zindler & Hart, 1986). Only one example of EM-I-like lavas is found (Sardinia, Italy) and no true EM-II lavas are found among CiMACI rocks.

Figure 3 shows primitive mantle-normalized incompatible element diagrams with the average values of the most mafic samples belonging to the CiMACI Province. The same data are listed in Table A1 in the online Appendix at <http://www.cambridge.org/journals/geo>. A clear homogeneity of incompatible elements is shown, with an overall bell-shaped pattern, with peaks at the Nb–Ta pair and troughs at K and, less commonly, Pb.

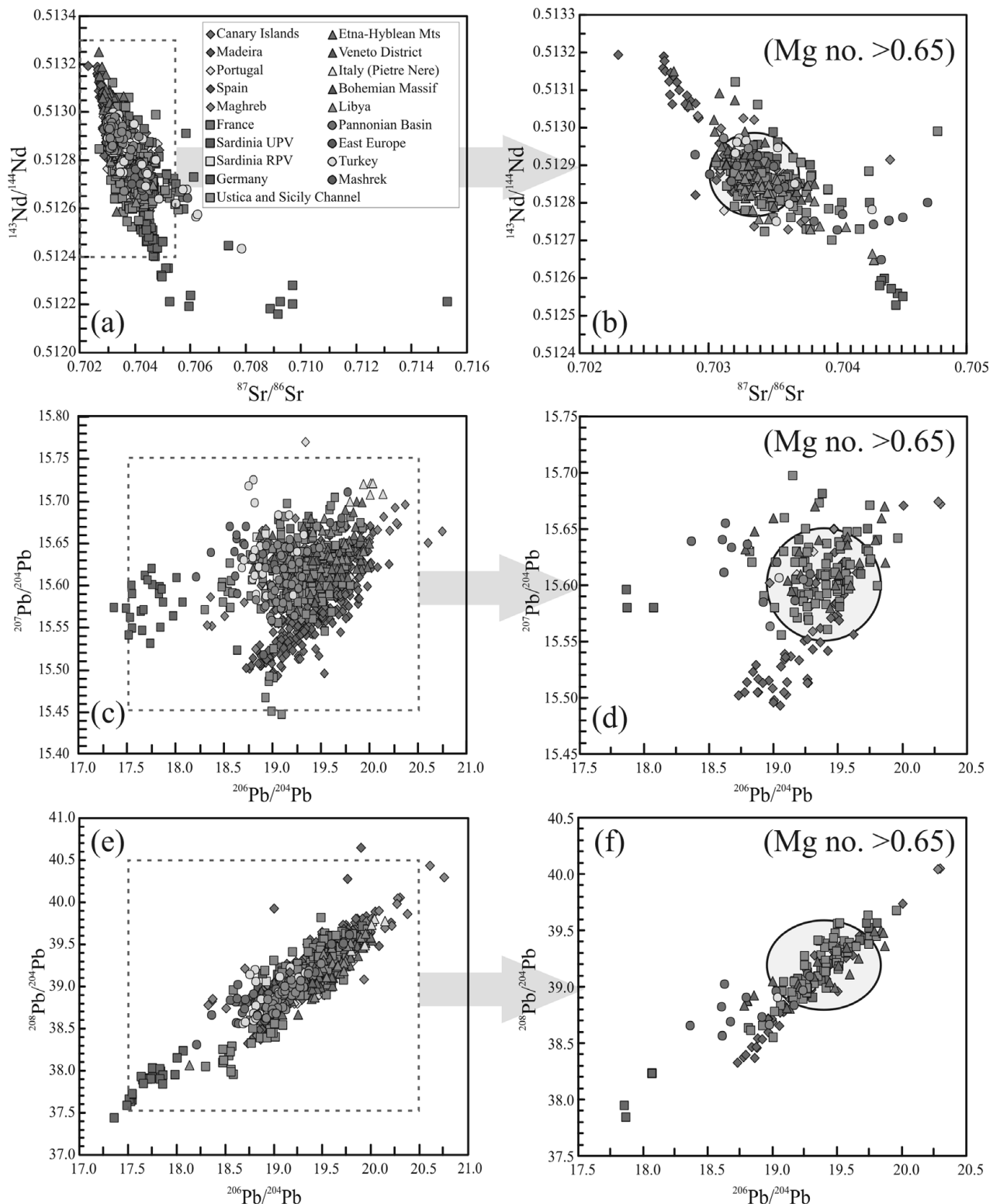


Figure 2. $^{143}\text{Nd}/^{144}\text{Nd}$ v. $^{87}\text{Sr}/^{86}\text{Sr}$, $^{207}\text{Pb}/^{204}\text{Pb}$ v. $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ v. $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams for the CiMACI rocks. The left column comprises all the available data, also including evolved compositions (e.g. crustal anatectic rhyolites). The right column comprises only CiMACI samples with Mg no. > 0.65. The ellipse in the right column indicates the CMR (Common Mantle Reservoir) end-member as proposed by Lustrino & Wilson (2007). References are given in Lustrino & Wilson (2007). A colour version of this figure is available in the online Appendix at <http://www.cambridge.org/journals/geo>.

The logarithmic scale normalization certainly has the effect of smothering the trace-element variance, but this is the classical method of representing a large set of data in a single plot. The existence of this incompatible trace-element similarity among the most

primitive CiMACI rocks has been used to argue for the existence of a common sub-lithospheric mantle source (e.g. Granet, Wilson & Achauer, 1995; Hoernle, Zhang & Graham, 1995; Oyarzun *et al.* 1997; Wilson & Patterson, 2001; Macera *et al.* 2003; Piromallo

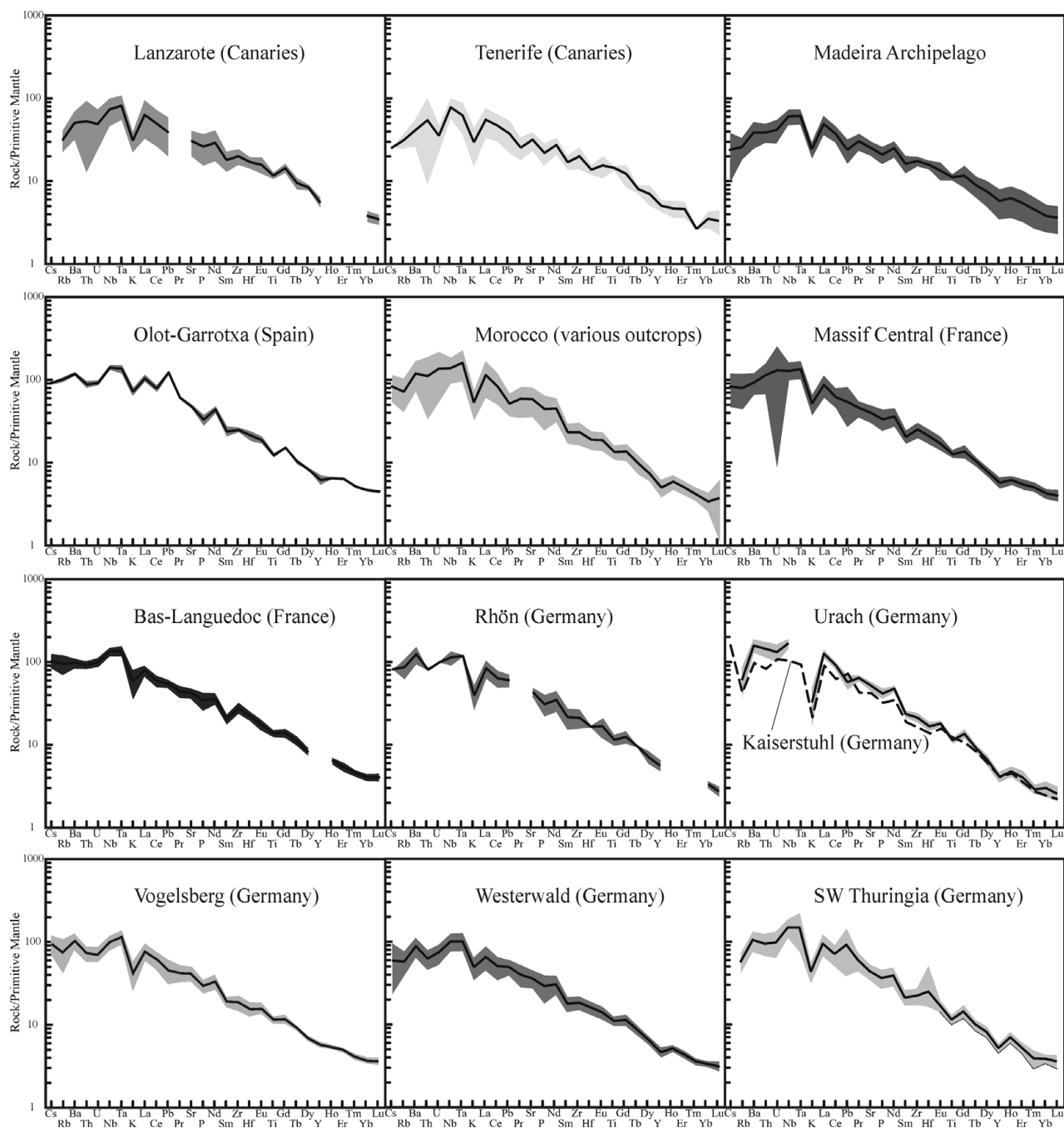


Figure 3. Primitive mantle-normalized incompatible element diagrams (normalization factors after Sun & McDonough, 1989) for selected igneous districts of the CiMACI Province. UPV – Unradiogenic Pb Volcanics; RPV – Radiogenic Pb Volcanics (Lustrino, Melluso & Morra, 2000). The thick black line in each diagram represents the average of the mafic samples (Mg no. > 0.65), whereas the grey field represents the two sigma variation from the average value. References in Lustrino & Wilson (2007). A complete list of the samples (> 8400) can be requested from the author. A colour version of this figure is available in the online Appendix at <http://www.cambridge.org/journals/geo>.

et al. 2008; Duggen *et al.* 2009, and references therein).

Similar conclusions arise if Sr–Nd–Pb isotopic ratios of the most mafic rocks are taken into consideration. The right side of Figure 2 shows CiMACI rocks with Mg no. > 0.65. More than 95 % of the rocks have $^{87}\text{Sr}/^{86}\text{Sr} < 0.704$. Only a group from the island of Sardinia shows consistently more radiogenic values (clustering around 0.7045; Lustrino, Melluso & Morra, 2007). The rest of the rocks with $^{87}\text{Sr}/^{86}\text{Sr} > 0.704$ have

been mostly related to contamination with continental crust at shallow depths, that is, they are considered as secondary effects rather than true messages from their mantle sources. With the exception of a consistent group of the Madeira rocks, nearly all the CiMACI lavas with Mg no. > 0.65 have $^{87}\text{Sr}/^{86}\text{Sr}$ between 0.703 and 0.704 (Fig. 2). The same isotopic homogeneity can be seen for Nd isotopic ratios. $^{143}\text{Nd}/^{144}\text{Nd}$ of the same subset of samples is essentially clustered between 0.51297 and 0.51273 (Fig. 2). Again, only

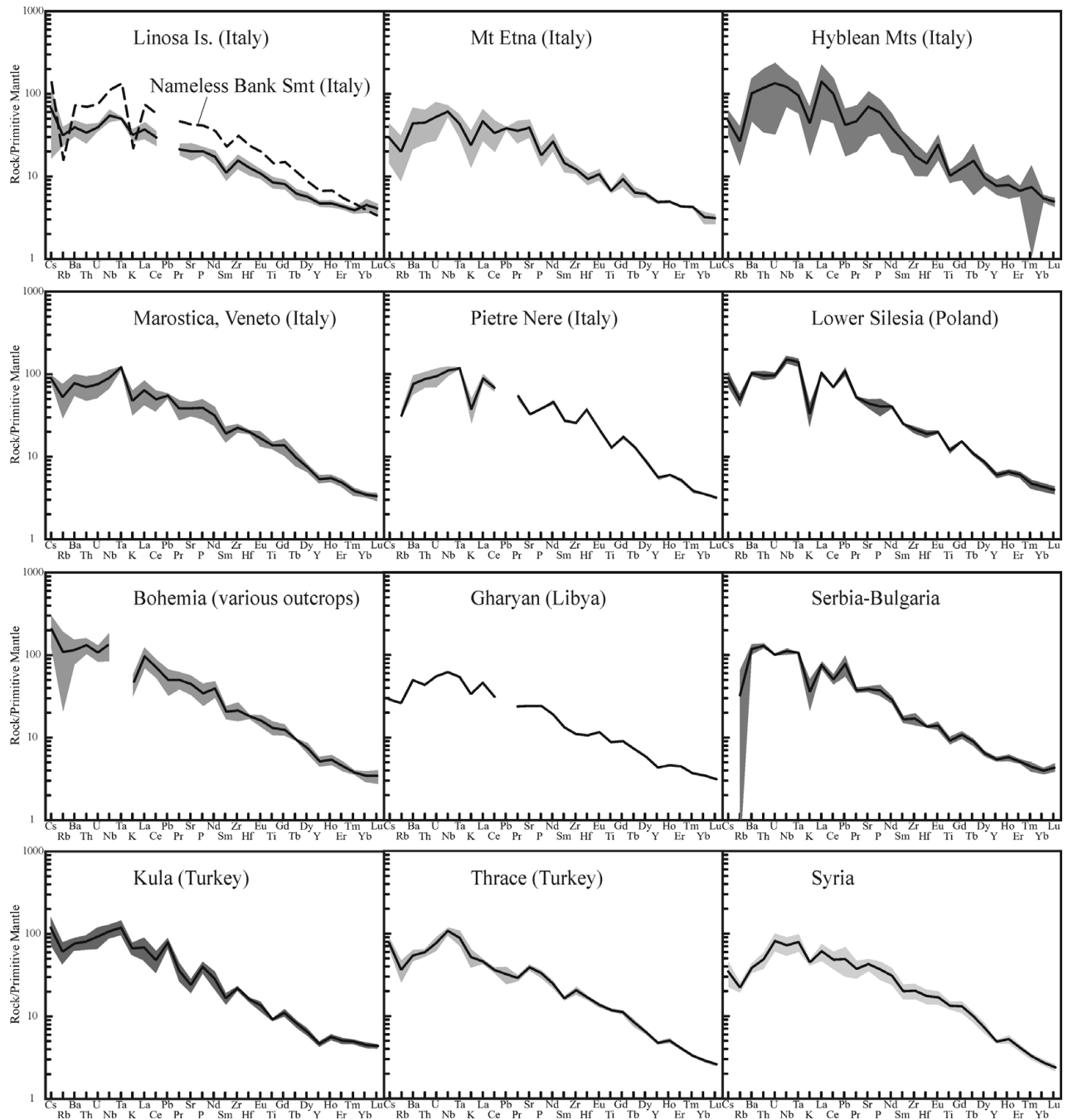


Figure 3. Continued.

the Sardinian and Madeira rocks (plus rarer samples from other igneous districts) plot outside this range. For comparison, typical OIB values are 0.7025–0.7070 ($^{87}\text{Sr}/^{86}\text{Sr}$) and 0.5131–0.5124 ($^{143}\text{Nd}/^{144}\text{Nd}$; Hofmann, 2003). The bulk of the CiMACI rocks cluster between 19 and 20 for $^{206}\text{Pb}/^{204}\text{Pb}$, between 15.50 and 15.70 for $^{207}\text{Pb}/^{204}\text{Pb}$ and between 38.5 and 39.5 for $^{208}\text{Pb}/^{204}\text{Pb}$ (Fig. 2). The anomalous composition of the volcanic rocks of Sardinia has been related to mantle sources contaminated by delaminated lower continental crust (Lustrino, Melluso & Morra, 2000, 2007). The Pb isotopic composition of the mafic CiMACI rocks strongly contrasts with the oceanic basalts characterized by a much wider isotopic range

(e.g. $^{206}\text{Pb}/^{204}\text{Pb}$ from < 17 to ~ 22 ; $^{207}\text{Pb}/^{204}\text{Pb}$ from 15.45 to 15.85; $^{208}\text{Pb}/^{204}\text{Pb}$ from 37.3 to 40.8; Hofmann, 2003).

How such an absence of extreme compositions can be explained with a SUMA model is not clear. According to the SUMA model, the smaller the degree of melting, the more it is probable that extreme isotopic compositions should be expected. However, what is observed in the CiMACI Province is at odds with this: almost all small volume volcanoes, derived by small degrees of upper mantle melting (sodic alkaline), from very distant localities (up to 5000 km in linear distance) show similar Sr–Nd–Pb isotopic compositions (and incompatible trace-element signature). This feature is

particularly important, considering that the temperature regime responsible for mantle partial melting should have been only a few tens degrees higher than the solidus temperature (see discussion in Lustrino & Carminati, 2007), thereby allowing mobilization of only the volumes of mantle with the lowest solidus temperature (that is, the plum part of the plum-pudding system).

To reconcile the presence of a SUMA model sampling theory and the geochemical homogeneity of the CiMACI rocks, it would be necessary to hypothesize metre-sized heterogeneities of the CiMACI rocks' mantle sources with melting domains in the order of kilometre-sized. However, this would be an *ad hoc* solution to the problem, and is not a reason to invoke different sizes of heterogeneities for continental and oceanic basalts (10^0 – 10^2 m versus 10^2 – 10^5 m, respectively). It is noteworthy that Harangi, Downes & Seghedi (2006) proposed the existence of heterogeneities in the upper mantle of the Alpine–Mediterranean region at least of 10^4 m in size, well within in the range of the SUMA model.

4. Discussion

The relatively homogeneous trace-element and Sr–Nd–Pb isotopic characters of the CiMACI rocks can be explained as being the result of: (1) deep-seated homogeneous mantle sources tapped by uprising mantle plumes; (2) a rheologically and chemically heterogeneous mantle whose melts are homogenized during fluid transport, and distillation effects mimicking stirring; (3) an upper mantle more homogeneous and convectively well stirred than the SUMA model suggests.

The possibility of reconciling the existence of CiMACI activity with thermal anomalies (mantle plumes) has been taken into consideration by several authors who proposed various thermo-chemical–rheological models involving the existence in single cases of tabular, narrow, fat, head-free, cold, intermittent, depleted, lazy, super, finger-like, patchy, fossil, channelled, recycled, not-very-energetic, deflected, dehydrated, wet, thin cactus, 'splash' or 'baby' mantle plumes (see the review of the existing models in Lustrino & Carminati, 2007; www.mantleplumes.org). In a few cases (e.g. Eifel, Germany), the existence of a deep mantle plume, with roots anchored at the core–mantle boundary, has been proposed in literature (e.g. Goes, Spakman & Bijwaard, 1999; Ritter, 2007). More commonly, mantle plumes have been supposed to be shallower, possibly anchored at the 670 km discontinuity (e.g. Granet, Wilson & Achauer, 1995; Wilson & Patterson, 2001; Lustrino & Wilson, 2007). In the latter case it would better to use the term 'thermal instability' or 'mantle diapir' rather than the term 'mantle plume', in order to avoid any troublesome relation between mantle plumes and very deep (core–mantle boundary depth) origin. The geochemical basis of the mantle plume model is the relative constancy of incom-

patible trace-element ratios, the overall overlapping incompatible trace-element pattern in primitive mantle-normalized diagrams and the relatively narrow Sr–Nd–Pb isotopic range of the more primitive and less crustally-contaminated mantle melts (e.g. Piromallo *et al.* 2008; Duggen *et al.* 2009 and references therein). The use of incompatible trace-element and Sr–Nd–Pb isotopic composition to infer the existence of a physically continuous (common) mantle source is very questionable. As outlined also in Lustrino & Carminati (2007), the geochemical similarity among two or more igneous rocks reflects only the existence of similar petrogenetic processes and mantle sources with similar chemical and mineralogical composition. Similarly, the same petrogenetic process (e.g. adiabatic partial melting beneath a rifting continent) can produce partial melts with different chemical compositions, depending on the thermal state before stretching, the mineral–chemical composition of the mantle and the lithosphere/asthenosphere boundary depth. Surprisingly, however, in many cases geochemical models are based on such incorrect assumptions (e.g. a geochemical signal is interpreted in physical terms: Bell *et al.* 2004; Cadoux *et al.* 2007). The mantle plume theory can in principle explain some geological features (crustal doming before abundant emission of relatively large volumes of mantle partial melts, temporal sequence of linear chains of volcanoes, anomalously high heat flow fluxes) but not chemical homogeneity of the supposed plume-derived partial melts.

Most of the CiMACI rocks show strong trace-element similarities with St Helena basalts, a volcano more than 8000 km from the Bohemian Massif alkaline rocks. It is obviously impossible to imagine the existence of a single source feeding the Palaeogene (*c.* 70–60 Ma) volcanic rocks of the Bohemian Massif and the Late Miocene (*c.* 10 Ma) St Helena basalts. Triassic, within-plate, sodic alkaline lavas of Mallorca (Balearic Islands, Spain, Western Mediterranean: Lustrino & Duggen, unpub. data) are geochemically indistinguishable from Pliocene within-plate sodic alkaline lavas from the Valencia coast (SE Spain, less than 300 km away from Mallorca Island) and from the average composition of the CiMACI lavas. Harangi *et al.* (2003) report the existence of Early Cretaceous (*c.* 115 Ma) alkaline melts from Central Europe (Czech Republic, Poland and Hungary), with chemical compositions resembling the average of Neogene French Massif Central and Rhine Graben volcanic rocks. These latter rocks were classically interpreted to have been derived from a common sub-lithospheric mantle source, called the European Asthenospheric Reservoir (EAR; Granet, Wilson & Achauer, 1995). On the basis of trace-element and isotopic similarities between Early Cretaceous and Neogene rocks from Central Europe, Harangi *et al.* (2003) proposed either (1) the presence of a sort of fossil mantle plume (originally responsible for the opening of the Central and North Atlantic Ocean) now located at the base of the upper mantle, or (2)

ambient sub-lithospheric mantle, extending laterally from the eastern North Atlantic to Central Europe, with EAR-like geochemical characteristics. I consider the existence of very long-lasting thermal anomalies or very wide physically continuous mantle regions highly improbable.

The second possibility is the existence of a heterogeneous upper mantle (e.g. Anderson, 2006) which, upon melting, produces melts with a homogeneous chemical composition, irrespective of the chemical and mineralogical variations of the source regions. Such homogeneous melts may be produced during porous melt flow and distillation processes, producing chromatographic fractionation effects with constant enrichment of incompatible trace-element ratios. Khazan & Fialko (2005) explained the nearly identical REE patterns of kimberlites from South Africa, India and Yacutia (Russia) with the effects of chromatographic exchange between a percolating melt and host peridotite. Interestingly, Khazan & Fialko (2005) proposed for these kimberlites a derivation from 'a mantle source of an ordinary composition'. The extremely high incompatible trace-element content (up to more than 1000 times chondrite estimates) of these lithologies would be related to prolonged chromatographic column fractionation and not to the presence of recycled lithospheric lithologies or very low degrees of melting or fertile sources. During the chromatographic separation, the melt fraction at the top of the column may have a composition typical of an infinitesimal degree of melting, even though the melt fraction at the base of the column is not necessarily small (e.g. Navon & Stolper, 1987; Khazan & Fialko, 2005). Several considerations render this mechanism unsuitable for the CiMACI Province: (1) the REE similarity demonstrated by Khazan & Fialko (2005) applies only to the most enriched compositions in the three kimberlite localities. Kimberlites less enriched in incompatible trace elements do not show such a similarity, probably due to the absence of saturation of the percolating melts (Khazan & Fialko, 2005). On the other hand, the CiMACI rocks show similarities in incompatible trace-element ratios at different amounts of enrichment (nephelinites, basanites, alkali basalts, hawaiiites). (2) CiMACI rocks do not contain incompatible trace-element contents as high as those recorded in the kimberlites. (3) The chromatographic percolation cannot produce isotopic homogenization, as is noted in the CiMACI Province. In conclusion, chromatographic effects may play an important role in the enrichment of kimberlites but cannot be the cause of the chemical and isotopic homogeneity of most of the CiMACI mafic alkaline rocks.

Moreover, if zone refining, percolation and chromatographic effects are responsible for chemically homogeneous magmas, it means that the basis on which igneous petrology is developed needs rethinking. It is, indeed, classically believed that the composition of the solid mantle sources can be inferred by studying the chemistry (and mineralogy) of primitive partial

melts (basaltic, kimberlitic, carbonatitic, melilititic, and so on), using partial melt models (equilibrium, fractionated, dynamic and all the possible alternatives) adopting given trace-element partition coefficients. The percolation–saturation–distillation model, on the other hand, does not predict any correlation between the melt fraction produced and the composition of mantle sources with the degree of trace-element enrichment of partial melts. Geochemical variability in the source would play a much smaller role in the generation of these melts (metasomatic fluids, carbonatites?) than is usually assumed.

The collection of near-fractional partial melts into large magma pools has the effect of averaging the isotopic composition of the individual drops of melt. Indeed, Pb isotopic measurements on melt inclusions belonging to the same oceanic basaltic hand specimen have shown a large spread of data accounting for more than 50 % of OIB–MORB isotope variability (e.g. Saal *et al.* 2005; MacLennan, 2008, and references therein). It is also true, however, that a large spread of isotopic compositions still survive in the single basaltic rock sample, showing peculiar HIMU-EMI-EMII geochemical characteristics (Saal *et al.* 2005). This is not observed in the CiMACI Province, where nearly all the rock samples are characterized by a relatively uniform isotopic composition.

Many of the most primitive alkaline lavas of the CiMACI Province (melilitites, nephelinites, basanites) have been explained with very low degrees of melting of a CO₂-bearing peridotitic source (see discussion in Lustrino & Wilson, 2007). The presence of a carbonatitic metasomatic agent could have had the effect of homogenizing the incompatible trace-element content of the bulk of the CiMACI mafic lavas. I believe that this is not a likely process on the basis of at least two considerations: (1) worldwide carbonatitic melts do not show a uniform trace-element and isotopic signature; (2) subduction and recycling of marine carbonate lithologies in the Tyrrhenian area (Avanzinelli *et al.* 2009) is considered to be the main cause of the large CO₂ emission in the Italian area and western Mediterranean in general (e.g. Frezzotti, Peccerillo & Panza, 2009, and references therein). However, in this case the volcanic rocks show very variable chemical and isotopic characteristics (e.g. Peccerillo, 2005; Avanzinelli *et al.* 2009; Conticelli *et al.* 2009), opposite to what is observed for the CiMACI rocks. In conclusion, the possibility of the existence of a homogenizing carbonatitic fluid/melt can also be excluded with confidence.

The third possible explanation for the overall geochemical similarity of the CiMACI rocks concerns the existence of relatively homogeneous (but not necessarily physically continuous) sources. No clear consensus has yet been reached on the chemical composition of the lithospheric mantle compared to sub-lithospheric (e.g. asthenospheric or even deeper) regions. Strictly speaking, no consensus has yet been reached on the definitions themselves of lithosphere, asthenosphere

or upper mantle using rheological, thermometric, geochemical and seismological tools. Several models are based on the unconstrained assumption that the entire lithospheric mantle is depleted in the basaltic components (it is CaO-, Al₂O₃-, FeO, Na₂O-poor), with high olivine/pyroxenes ratios (e.g. Cadoux *et al.* 2007), whereas it is clear that only the ancient cratons (those beneath Archaean cores of the continents) are likely to have these features, in order to prevent their sinking in the sub-lithospheric mantle (being Fe-poor they are less dense than primitive mantle). Lithospheric keels under Archaean cratons can reach depths up to 300–400 km (e.g. O'Reilly *et al.* 2009 and references therein), compared to younger lithosphere, characterized by average thickness in the order of 100 km, away from actively colliding orogens (e.g. McKenzie & Bickle, 1988). It is not clear whether the lithospheric mantle should be more properly considered the source of the metasomatic effects commonly recorded in primitive lavas or the sink of metasomatic fluids coming from higher depths or from recycled lithologies. Dozens of papers have been written for or against the hypothesis of a lithospheric mantle involvement in continental and oceanic basalt genesis, but what seems clear is that the relative rigidity of the lithospheric mantle renders it the best place for trace-element heterogeneities to survive and isotopic heterogeneities to develop after age-integration processes (e.g. Niu & O'Hara, 2003). On these grounds, the existence of relatively homogeneous geochemical compositions throughout the CiMACI Province should be considered as evidence against their derivation from a lithospheric mantle source. This does not imply that lithospheric mantle may never be tapped by partial melting processes, as instead proposed in several papers aiming to explain some anomalous compositions recorded in the CiMACI Province. The presence of unusually K-rich anorogenic lavas in the Calatrava district of central Spain (Cebrià & Lopez-Ruiz, 1995), in the French Massif Central (e.g. Wilson & Patterson, 2001) and in the Eifel Region (Germany; e.g. Mertes & Schminke, 1985), and the anomalously low ²⁰⁶Pb/²⁰⁴Pb lavas of Sardinia (Lustrino, Melluso & Morra, 2000) has indeed been related to lithospheric mantle sources or lithospheric mantle-contaminated asthenospheric melts.

The involvement of a homogeneous sub-lithospheric mantle is fundamental not only to explain the chemistry of 'anorogenic' igneous rocks of the CiMACI Province, but also to explain the geochemical characteristics of subduction-related magmatism in the entire Alpine–Mediterranean region (e.g. Lustrino, Duggen & Rosenberg, in press, and references therein). Indeed, nearly all of the geochemical models proposed to explain the origin of subduction-related igneous rocks of this area are based on incompatible trace elements and Sr–Nd–Pb isotopic ratios requiring the existence of at least one or two 'enriched' end-members (recycled crust and/or lithospheric mantle or lithospheric mantle-derived melts) mixed in various amounts with an ambient mantle with FoZo/HIMU composition (Harangi,

Downes & Seghedi, 2006 and references therein). In conclusion, such a common sub-lithospheric source is likely involved both during the genesis of 'anorogenic' magma (representing almost entirely the source region) and of 'orogenic' magma (in this case representing only a component, often volumetrically important).

5. Conclusions

Some conclusions raised in this review can be summarized as follows:

(1) The relative chemical homogeneity of the mafic igneous rocks emplaced during the Cenozoic in the large area bounded by the Canaries, Eastern Anatolia, Libya and Poland (CiMACI Province of Lustrino & Wilson, 2007) is a striking feature. Such a homogeneity is surprising, considering the different mantle sources to be tapped during partial melting processes and the numerous oceanic subduction and continent–continent collision histories recorded during the Phanerozoic in this area. The surprise increases considering that much of the igneous rocks with such homogeneous geochemical characteristics are low-degree mantle melts produced by relatively small-volume volcanoes. According to the Statistical Upper Mantle Assemblage (SUMA) model of Meibom & Anderson (2003), the lower the degrees of melting, the higher the range of trace-element and isotopic composition should be expected. In the SUMA model, the sampling volumes beneath each single volcano are in the same order of the volume of 'exotic material', dispersed after repeated cycles of lithospheric recycling in the upper mantle, like a sort of 'plum-pudding cake'. When the degrees of melting are low and the volumes of mantle tapped by basaltic extraction are limited, a large chemical heterogeneity is expected. On the other hand, when the sampling volume increases, the different heterogeneities can be 'averaged' and a more uniform geochemical message would emerge from the mantle.

(2) The chemical homogeneity of the bulk of the CiMACI rocks is not compatible with the SUMA model. Either the CiMACI upper mantle is homogeneous, as assumed by the phrase 'the convecting mantle', or processes of melt or fluid percolation and exchange can make homogeneous magmas, regardless of source (of fluids) heterogeneity. In the plume hypothesis, ambient mantle is the MORB source, homogenized by convection, and non-MORB is delivered into the upper mantle by plumes. I propose the existence of a more homogeneous sub-lithospheric mantle where enriched regions with 'exotic', non-peridotitic lithologies are relatively small in size (metre-sized). The decrease of seismic wave velocities below the lithosphere is not sufficient to allow a complete convection of the asthenospheric mantle, indicating the possible presence of small amounts (<10%) of partial melts in this region. This seismic message cannot be interpreted as the presence of a fully convecting, well-stirred and chemically homogenized mantle (D. L. Anderson, pers. comm. 2010). The most anomalous compositions,

deviating from the average values of the EAR (European Asthenospheric Reservoir; Granet, Wilson & Achauer, 1995), LVC (Low Velocity Composition; Hoernle, Zhang & Graham, 1995) or CMR (Common Mantle Reservoir; Lustrino & Wilson, 2007), are inferred to be related either to lithospheric mantle sources, to lithosphere-modified sub-lithospheric mantle sources or to recycled (subducted or detached and delaminated) lithospheric mantle at sub-lithospheric depths. This classical axiom (presence of chemical anomalies in basaltic magma = derivation from lithospheric mantle) may need rethinking, because non-peridotitic lithologies (e.g. recycled crustal rocks, frozen basaltic melts, metasomatic fronts) may also exist, without homogenization, at asthenospheric depths.

(3) Nearly all the mafic sodic alkaline CiMACI rocks plot in the 'depleted' isotopic field (with reference to Sr–Nd isotopes), but these are completely different from DMM partial melts. This means that mantle sources are not DMM-like. It is not possible to hypothesize DMM-like (in terms of isotopic values) mantle sources that have been metasomatized (enriched) in recent times. There is no geological reason to invoke this process and if metasomatic processes are involved, one would expect a wide range of trace-element compositions, not uniformity. Cadoux *et al.* (2007) assume that DMM is ambient mantle everywhere, and there is, or should be, DMM under the Mediterranean area. True DMM partial melts (N-MORBs) are extremely rare in the CiMACI Province and these have never been sampled in continental areas.

(4) The geochemical similarity between two or more volcanoes or igneous districts cannot be considered as a proof for the existence of physically similar and continuous mantle sources but only a proof for similar petrogenetic processes, not necessarily involving the same regions. Prolonged chromatographic percolation of partial melts through a peridotitic matrix can result in enrichment of incompatible trace elements but can hardly explain the similar enrichment and the nearly constant incompatible trace-element ratios of the CiMACI rocks (e.g. Khazan & Fialko, 2005). Moreover, chromatography cannot explain the relatively narrow range of Sr–Nd–Pb isotopic composition of the CiMACI rocks.

The conclusions raised in this paper can also be applied in other areas characterized by igneous activity ascribed to 'anorogenic' or 'within-plate' or 'subduction-unrelated' both in oceanic and continental settings, being characterized by the same average geochemical characteristics seen for the bulk of the CiMACI rocks. Is this then ambient mantle, and is DMM deeper? Considering all the subduction and long complex history, the sub-continental (asthenospheric) mantle should be more variable unless certain lithologies are preferentially sampled by melting. These average values roughly overlap the FoZo values (although the isotopic composition of this mantle component has greatly changed since its first proposal:

Hart *et al.* 1992; Stracke, Hofmann & Hart, 2005) and therefore could represent the average chemical composition of the upper mantle, with no need to invoke deeply-seated uniform mantle sources tapped by mantle plumes.

Acknowledgements. The author warmly thanks Don L. Anderson (Pasadena, USA) for his enthusiastic approach to deciphering the complex geophysical and geochemical characteristics of the system Earth and his immense patience for discussing basic concepts of mantle dynamics. Don is able to furnish at the same time large amounts of doubts and solid certitudes on key aspects of geochemistry, geophysics and petrology. This, of course, does not mean that he agrees with the conclusions raised in this manuscript. Many thanks also to Jim Natland (Miami, USA) and Szabi Harangi (Budapest, Hungary) for their constructive and 'philosophical' reviews. The author thanks also Enrica Mascia, Bianca and Laura for their support during the writing. The 'Iron Men' Ozzy Osbourne, Tony Iommi, Geezer Butler, Bill Ward and, last but not least, the late Randy Rhoads are thanked for their emotional lift.

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