

# The role of melt depletion versus refertilization in the major element chemistry of four-phase spinel peridotite xenoliths

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Mantle peridotites are interpreted as either residues after partial melting and melt extraction or products of igneous refertilization of refractory peridotites. The simple distinction between these models is difficult to assess because in chemical variation diagrams, both processes lead essentially to the same results. The only exception is the Ti-in-Cpx versus Ti-in-whole-rock plots, which can successfully discriminate between these models. In this study, a modified version of Ti-in-Cpx versus Mg#-in-olivine plots was applied to ~1,500 spinel peridotite xenoliths from worldwide localities. The results showed that the vast majority of shallow mantle samples are consistent with the partial melting model; however, a minority of samples may indicate refertilization of formerly refractory mantle domains.

**Keywords:** peridotite xenoliths, subcontinental mantle, melt extraction, igneous refertilization, petrology

## Introduction

Four-phase spinel peridotite xenoliths occurring in alkaline basaltic rocks provide direct information about the conditions prevailing in the shallow subcontinental and oceanic lithospheric mantles. Peridotite xenoliths exhibit a considerable range of chemical composition that was attributed to partial melting and subsequent melt

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depletion of the upper mantle, resulting in decreased FeO, CaO, Al<sub>2</sub>O<sub>3</sub>, and alkalis, and enrichment of MgO in the residue, which becomes the lithospheric mantle (Carter 1970; Kuno and Aoki 1970; Frey and Green 1974; Maaløe and Aoki 1977; Varne 1977). Mg-value [ $100 \text{ Mg}/(\text{Mg} + \text{Fe}^{2+})$ ] is a widely used index to demonstrate the degree of depletion in melt component. It varies between 89 and 93, such that the undepleted or fertile samples, i.e., those containing maximum concentrations of melt-loving elements, have the lowest Mg-value, whereas severely depleted refractory xenoliths have the highest Mg-value. Chemical composition of the undepleted peridotites has also been used to estimate the chemical composition of Earth's primitive mantle (Jagoutz et al. 1979; McDonough and Sun 1995). Mineralogically, undepleted lherzolites are rich in clinopyroxene and spinel, whereas depleted residual harzburgites have less than 5% clinopyroxene and small quantities of spinel, which are compensated by higher amounts of olivine. This is because melting reactions at low P (<2.5 GPa) along the peridotite solidus produce olivine and liquid at the expense of pyroxenes and spinel.

Although the major element variation had unanimously been interpreted as being due to progressive extraction of basaltic melt, the advance of highly sophisticated analytical techniques to obtain precise trace element and isotope ratios resulted in a more complicated picture for the chemical evolution of mantle rocks. Thus, it became evident that the majority of spinel peridotite xenoliths are light rare earth elements (LREE) enriched together with other incompatible elements, such as K, Rb, Cs, Sr, Ba, Th, and U, which reside within the diopside phase (Menzies and Murthy 1980; Stosch and Seck 1980; Dawson 1984; Hawkesworth et al. 1990). However, incompatible element-depleted and -enriched xenoliths are petrographically often indistinguishable from each other. Moreover, it occurs that xenoliths severely depleted in FeO, CaO, Al<sub>2</sub>O<sub>3</sub>, and alkalis are highly enriched in LREE, e.g., some of the Ray Pic mantle xenoliths in the Massif Central, France (Zangana et al. 1997) or those of Szentbékállá, western Pannonian Basin, Hungary (Embey-Isztin et al. 1989). This clearly indicates a decoupling of the processes governing the major element and the incompatible trace element variations. Two major processes must have affected the lithospheric mantle: first, a depletion due to partial melting, which strongly affected the major oxides as well as all the trace elements, either compatible or incompatible, and second, subsequent metasomatism by small amounts of liquids issued from the asthenosphere that is reflected in variable enrichment in incompatible elements. Incompatible elements are both easily removed from the mantle by partial melting and also easily re-enriched by metasomatism. In some cases, mantle enrichment is accompanied by a visible transformation of the original mineralogy, e.g., amphibole may form at the expense of clinopyroxene + spinel (modal or hydrous metasomatism). However, precipitation of the amphibole is not necessarily linked with enrichment. Kurat et al. (1980) described such a case from Kapfenstein (Austria), where the formation of amphibole in a xenolith was entirely caused by pure water metasomatism. The time intervals separating these processes can be considerable. For example, mantle source regions of mid-ocean ridge basalt (MORB) have isotopic signatures that indicate a loss

of melt fraction at least 2 Ga ago (e.g., [Stosch et al. 1980](#)), whereas subsequent enrichment by fluids or melts rich in trace elements may be much younger (<0.5 Ga) and modal metasomatism (e.g., amphibole replacing diopside) only <0.2 Ga (e.g., [Menzies 1983](#)).

Until recently, the interpretation of the processes affecting the geochemical evolution of peridotite xenoliths from the lithospheric mantle and those of tectonically emplaced mantle bodies has been essentially the same. Fertile lherzolite massifs such as that of the Étang de Lherz in the French Pyrenees (type locality of lherzolite; [Lacroix 1917](#)) were generally regarded as pristine mantle, only weakly affected by partial melting and depleted harzburgites as residues, left after melt extraction. However, this interpretation seems to be changing at great pace. Several workers think that some tectonically emplaced mantle rocks are actually the result of igneous refertilization of refractory peridotites rather than partial melting (e.g., [Carlson et al. 2004](#); [Müntener et al. 2004](#); [Beyer et al. 2006](#); [Bodinier et al. 2008](#); [Zhang et al. 2009](#)). Using meticulously detailed structural evidence as well as major, minor, and trace elements in minerals and whole rocks, [Le Roux et al. \(2007\)](#) convincingly demonstrated that the Lherz Massif, considered as pristine, is actually secondary and formed at the expense of a depleted harzburgitic protolith. Variations of major, minor, and trace elements in minerals and whole-rock peridotites show that the lherzolites result from the igneous refertilization reaction between depleted lithospheric mantle and percolating MORB-type partial melts. Local evidence of igneous refertilization has been previously reported in orogenic peridotites; however, at Lherz, structural arguments show that the entire lherzolite body is secondary and refertilized ([Le Roux et al. 2007, 2009](#)). Thus, in the case of Lherz, the partial melting model does not work in the light of structural observations that show that the harzburgite is older than the lherzolites.

Refertilization may also be considered as a form of mantle metasomatism; however, the term “metasomatism” is more widely used to define mantle processes involving strong chemical disequilibrium between melt and fluids, marked by a selective enrichment in certain major or trace elements, such as Fe, Ti, LILE, and LREE, or in accessory minerals, such as amphibole, mica, or rutile (“cryptic” versus “modal” or “patent” metasomatism; [Harte 1983](#); [Dawson 1984](#)).

Although cryptic metasomatism is a frequent phenomenon in mantle-derived xenoliths as detailed earlier, and modal metasomatism is occasionally observed as well, peridotite xenoliths are still widely considered to be more or less depleted mantle residues left after extraction of a basaltic component. In this respect, they seem to contrast with the new findings obtained from the tectonically emplaced peridotite massifs that are increasingly interpreted as representing a refertilization rather than a depletion trend. Many workers now think that the fundamental characteristics of most orogenic lherzolites are their refertilized nature ([Godard et al. 1995](#); [Takazawa et al. 1996](#); [Rampone et al. 1997, 2004](#); [Lenoir et al. 2000](#); [Hellebrand et al. 2002](#); [Santos et al. 2002](#); [Bodinier et al. 2004](#); [Beyer et al. 2006](#); [Piccardo et al. 2007](#)).

This has far reaching implications because, together with mantle xenoliths and chondrites, the fertile Lherz massif has been used to infer the composition of the

Earth's primitive upper mantle, in particular for the highly siderophile elements. However, if the formation of the Lherz lherzolites occurred by igneous refertilization, the validity and significance of the primitive mantle values based on this type of fertile mantle rock compositions become questionable (Le Roux et al. 2007). It follows that carefully selected xenoliths may prove to be a better choice, even if refertilization processes have also been reported on mantle xenoliths in a few cases (e.g., Carlson et al. 2004; Tang et al. 2008).

### **The aim of this study**

The scientific community working with peridotite xenoliths widely believes that they represent primarily residues after partial melting of a compositionally homogeneous source, frequently followed by enrichment processes involving incompatible element-rich components. In contrast, some specialists of orogenic peridotite massifs think that this may not be the case, favoring a refertilization model instead (J.L. Bodinier, personal communication). Accidental mantle xenoliths have a major drawback over orogenic peridotites, notably the lack of the virtually unlimited possibility of sampling. Massifs provide the opportunity to study spatial and temporal relationships between different metasomatic facies (e.g., modal versus cryptic metasomatism) as well as between metasomatic rocks and their protoliths. In contrast, mantle xenoliths have the advantage over orogenic peridotites that they represent mineralogical and chemical conditions of the ambient mantle, due to their rapid rise to the surface. In addition, over 3,500 mantle xenolith localities are currently known worldwide, whereas the number of orogenic peridotite massifs is much more limited.

During this work, a worldwide survey of major element data published on spinel peridotite xenoliths from all the continents has been carried out to assess which of the two models (i.e., partial melting or refertilization) played the decisive role in shaping the chemistry and mineralogy of the shallow continental lithospheric mantle. Obviously, this is not an easy task because mafic melt extraction from a primitive mantle source progressively depleted in basaltic components, such as  $\text{Al}_2\text{O}_3$ ,  $\text{CaO}$ ,  $\text{TiO}_2$ , and  $\text{Na}_2\text{O}$ , and refertilization of an originally depleted source by melts rich in basaltic components (including Al, Ca, and Fe) produce essentially the same trends. Nonetheless, Le Roux et al. (2007) seem to have found a way to circumvent the problem by plotting the concentrations of  $\text{TiO}_2$  in clinopyroxene versus whole rocks for the primary harzburgites and secondary (refertilized) lherzolites of the Lherz Massif (Fig. 1A). The diagram clearly shows a trend of constant Ti concentration in clinopyroxene of refertilized peridotites and a rapidly decreasing Ti in the more refractory harzburgites. Their calculated partial melting trend, shown for comparison, is clearly distinctive with its evenly rising slope.

Thus, such a diagram may be a useful tool in differentiating between partial melting and refertilization processes. However, in the vast xenolith literature, one can find a great number of papers publishing whole-rock analyses and many others publishing

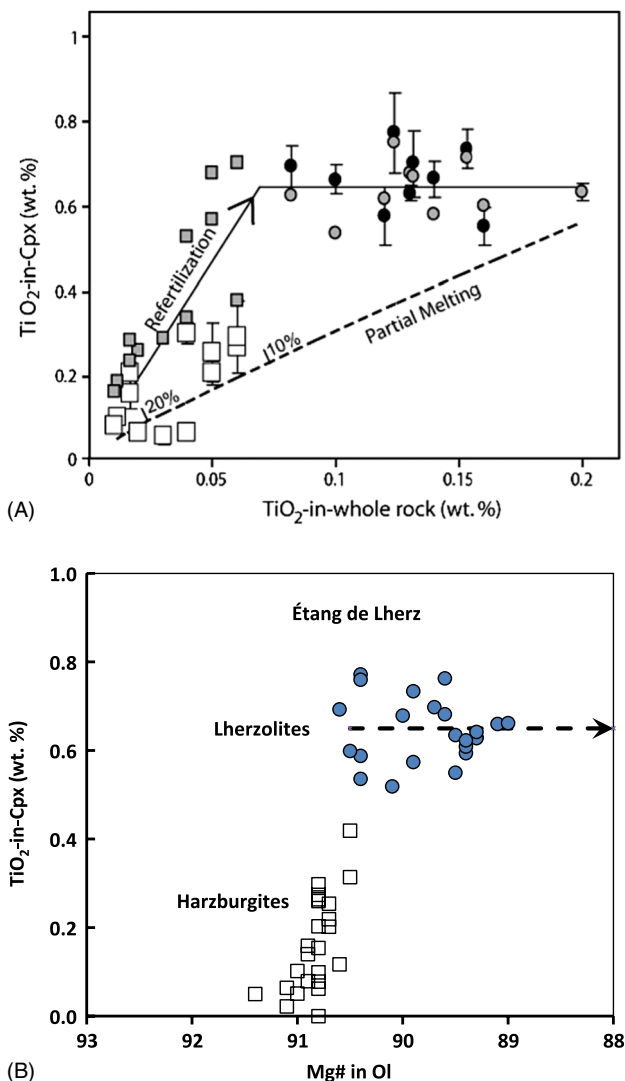


Fig. 1  
 A: TiO<sub>2</sub> concentrations in clinopyroxene versus whole rocks for the Lherz harzburgites (empty squares) and lherzolites (filled circles). Gray symbols represent Cpx compositions recalculated for near-solidus temperature (1,250 °C). Numerical models of TiO<sub>2</sub> variations during partial melting and magmatic refertilization are shown for comparison (after Le Roux et al. 2007). B: Mg-value in olivine versus TiO<sub>2</sub> in the coexisting clinopyroxene from the same rocks, plotted on the basis of microprobe analyses of Le Roux (2008). Empty squares: harzburgites, filled circles: lherzolites



Fig. 2

World map showing the main peridotite xenolith localities involved in this study. 1: Massif Central; 2: Rhenish Massif, Rhine Graben; 3: Eger (Ohre) Graben; 4: Carpathian (Pannonian) Basin; 5: Catalonia; 6: Spitsbergen; 7: Hoggar; 8: Cameroon Line; 9: Nosy Be archipelago; 10: East African Rift; 11: Baikal Rift, Mongolia, Inner Mongolia; 12: East China Craton; 13: Jeju Island, Korea; 14: Ichinomegata; 15: eastern Australia; 16: New Zealand; 17: Antarctica; 18: western USA; 19: northern Mexico; 20: Knippa, Texas; 21: northeast Brazil; 22: northern Patagonia

microprobe analyses for the constituent mineral phases, but relatively rarely both sets of data. Therefore, in this survey, a modified version of the original diagram has been used. The vertical axis showing the diagnostically important Ti in clinopyroxene remained the same, whereas the horizontal axis indicates the Mg-value [ $100 \text{ Mg}/(\text{Mg} + \text{Fe}_2^+)$ ] of the coexisting olivine. Olivine is the dominant phase in peridotites, and as such, its Mg-value must be close to the Mg-value of the whole-rock samples. Ti is an incompatible element, and consequently, it is negatively correlated with the Mg-value. To demonstrate that the modified diagram can reproduce essentially the same trends as the original one, microprobe analyses of mineral phases from harzburgites and lherzolites of the Lherz Massif (published in [Le Roux 2008](#)) have been plotted in Fig. 1B. In the following diagrams, some 1,500 coexisting clinopyroxene and olivine pairs from worldwide localities (Fig. 2) have been plotted. In the case of multiple analyses, core compositions of mineral grains were preferably chosen and rim compositions were avoided.

### Peridotite xenoliths in Western and Central European Tertiary–Quaternary alkali basalts

Members of this extended post-orogenic volcanic province, from southwest France to the Carpathian Basin, share a number of features in common. They all represent a typical alkali basaltic extension-related volcanism and show similar asthenospheric

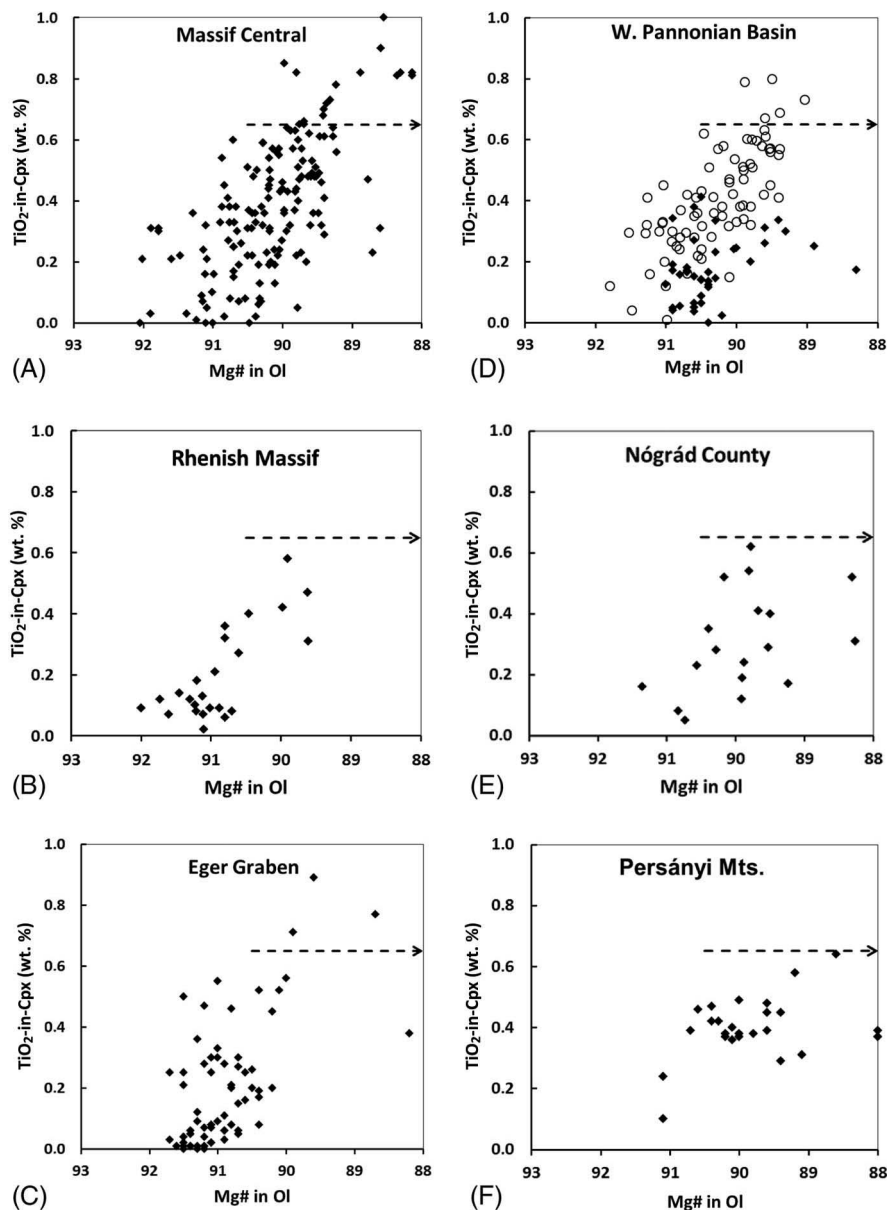


Fig. 3

Mg-value in olivine versus TiO<sub>2</sub> in coexisting clinopyroxene on the basis of published analyses. A: Coisy (1977), Brown et al. (1980), Werling and Altherr (1997), Xu et al. (1998a). B: Schütz (1967), Witt-Eickschen (1993), Witt-Eickschen and Kramm (1997), Franz et al. (1997). C: Ackerman et al. (2007, 2013, 2015). D: Embey-Isztin et al. (1989), Downes et al. (1992), Embey-Isztin et al. (2001, 2014); filled symbols: poikilitic peridotite xenoliths. E: Szabó and Taylor (1994). F: Vaselli et al. (1995)

isotopic signatures (Blusztajn and Hart 1989; Wilson and Downes 1991; Embey-Isztin and Dobosi 1995; Hoernle et al. 1995). Alkali basalts in the Massif Central, the Rhenish Massif, near the Rhine Graben, and in the Eger (Ohre) Graben, situated in the Moldanubikum, erupted on Variscan suspect terranes, whereas those of the Carpathian Basin lie on Alpine Orogen terranes. Peridotite xenoliths are abundant in all regions, especially in the Massif Central, where hundreds of localities are known. Plotted in Mg-value-in-olivine (Mg# in Ol) versus TiO<sub>2</sub>-in-Cpx diagrams (Fig. 3A–F), all of the regions seem to lack evidence for refertilization as defined previously, i.e., no constant high-Ti-clinopyroxene trends in more fertile xenoliths and abruptly dropping Ti in depleted samples can be observed.

It follows that the classical partial melting model still holds good for the Western and Central European shallow subcontinental mantle. However, Persányi Mts. xenoliths from the eastern Transylvanian Basin (Fig. 3F) may perhaps be a possible exception with their constant trend of Ti-in-Cpx for the most fertile samples. Nonetheless, these xenoliths were described by Vaselli et al. (1995) as being modally metasomatized; thus, they are richer in amphibole, compared with the mantle xenoliths from the alkali basalts of the neighboring Pannonian Basin. The latter (Fig. 3D) carries two distinctive series of peridotite xenoliths, one with well-known usual texture types (empty circles) and another with poikilitic textures (filled diamonds). The two series differ from each other in every geochemical respect (major, minor elements, and isotope ratios), and the poikilitic xenoliths were interpreted as the result of reactions between magmatic liquids issued from the uprising asthenosphere and the solid lithospheric mantle rocks (Embey-Isztin et al. 2014).

### **Other European xenolith localities**

In Fig. 4A, xenolith data from the quaternary anorogenic volcanic district of Olot (Catalonia, northeastern Spain) have been plotted. This region is located at the southern edge of the Pyrenean collisional orogenic belt, and it experienced a highly complex tectonic evolution that ended with the opening of the Liguro–Provencal and Valencia Trough inter-arc basins (e.g., Martí et al. 1992). This last tectono-magmatic event gave birth to the anorogenic alkali basalt volcanism.

Plio–Pleistocene alkaline basic lavas (basanites, hawaiites, alkali basalts, and trachybasalts) containing peridotite inclusions (Fig. 4B) are widespread on the island of Sardinia (e.g., Lustrino et al. 1999). The tectono-magmatic evolution resembles that of the Pannonian Basin. In both regions, the younger Plio–Pleistocene alkali basaltic volcanics erupted in connection with intra-continental plate tensional tectonics that was preceded by an older Oligo–Miocene orogenic calc-alkali volcanic cycle. In Sardinia, the pre-Mesozoic basement comprises metamorphic rocks and Hercynian granitoids (Tommasini et al. 1995).

In west Spitsbergen (the largest island of the Svalbard archipelago north of Norway), quaternary alkali basaltic volcanoes contain abundant ultramafic xenoliths,



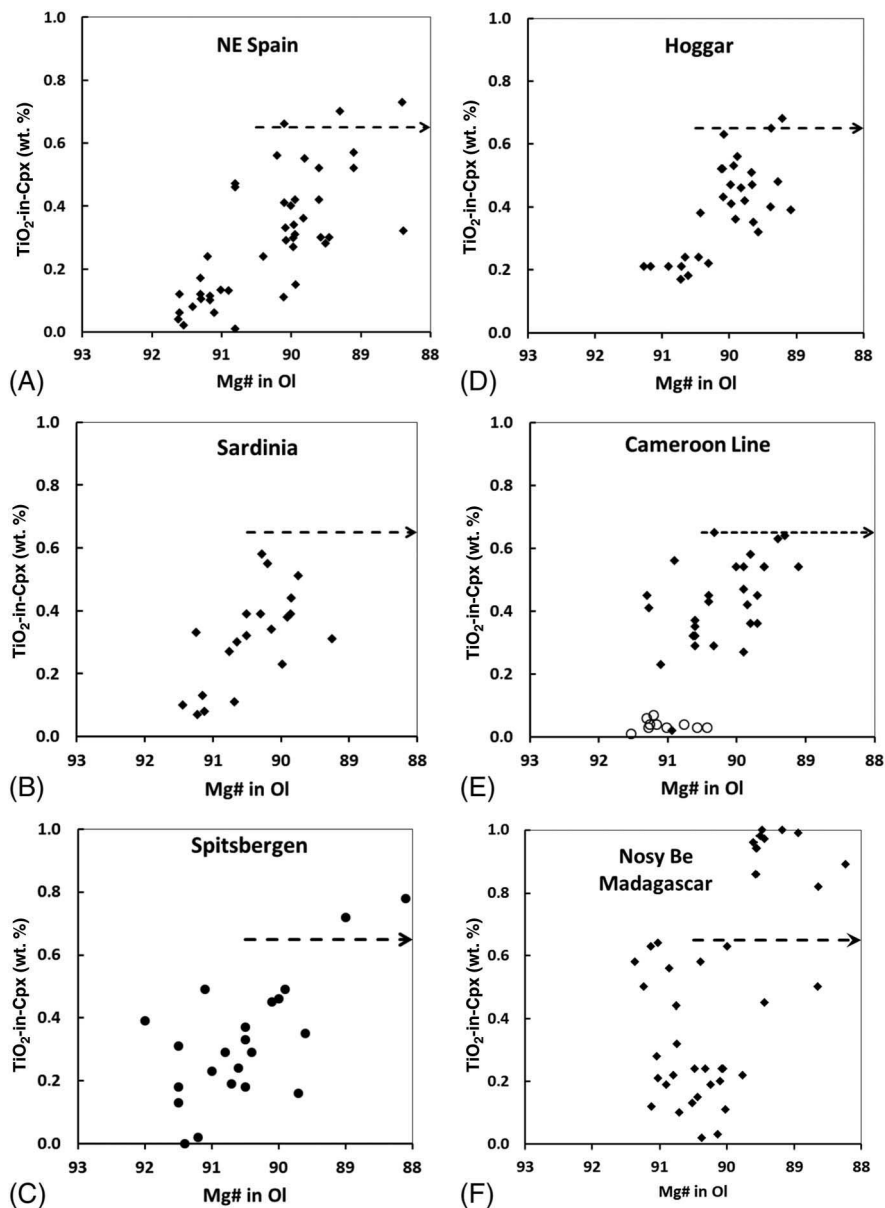


Fig. 4  
 Mg-value in olivine versus TiO<sub>2</sub> in coexisting clinopyroxene on the basis of published analyses. A: Bianchini et al. (2007), Galán et al. (2011). B: Beccaluva et al. (1989, 2001). C: Furnes et al. (1986), Ionov et al. (2002). D: Beccaluva et al. (2007). E: Lee et al. (1996), Caldeira and Munhá (2002), Nkouandou and Temdjim (2011), Temdjim (2012), Pintér et al. (2015); filled symbols: continental Cameroon Line; empty symbols: oceanic Cameroon Line. F: Rocco et al. (2013)

mostly spinel peridotites (Fig. 4C; Furnes et al. 1986; Ionov et al. 2002). Originally, Spitsbergen was an integral part of Greenland, and it was separated during the opening of the North Atlantic Ocean in the Late Cretaceous (Blythe and Kleinspehn 1998). Mineral analyses from further European xenolith localities were also examined during this work (not shown in separate diagrams). These include the Cenozoic Calatrava volcanic field (central Spain), the Lessinian basalts (northern Italy), the Mt. Vulture volcano (southern Italy), and the eastern Serbian xenoliths. In general, we can conclude that peridotite xenoliths originating from diverse European localities may indicate partial melting trends in Mg# versus Ti-in-Cpx diagrams. The Ti-rich clinopyroxenes of the Catalonian xenoliths (Fig. 4A) may be seen as a possible exception; however, the scattering of data in this diagram does not permit drawing any certain conclusions.

### African xenoliths

The Cenozoic volcanism of the Hoggar region (Algeria) represents one of the most important magmatic districts of the North African belt. It covers more than 10,000 km<sup>2</sup> and is associated with a regional crustal swell of Pan-African terranes, approximately 1,000 km in diameter (Beccaluva et al. 2007). The latest volcanic episodes are strongly alkaline (basanites and nephelinites), sometimes entraining mantle xenoliths (Fig. 4D).

The ~1,600-km-long intraplate volcanic West African Cameroon Line is a unique geologic feature because it straddles a continental margin (Norry and Fitton 1983; Fitton and Dunlop, 1985). Half of the line lies in the Atlantic Ocean and the other half erupted onto continental crust. The line has been volcanically active, mostly erupting alkali basaltic rocks, for the last 65 million years. Basaltic rocks with MgO > 4% both the oceanic and continental sectors of the Cameroon Line have similar compositions; however, the more evolved rocks are quite distinct. The similarity in more basaltic rocks may indicate that they share the same type of source material. As the lithospheric mantle below the continental Africa must be different in chemical and isotopic composition from the younger oceanic lithosphere below the Atlantic, the reasonable explanation is that the source should be in the asthenosphere rather than in the metasomatized lithosphere (Fitton 1987). Figure 4E depicts peridotite xenoliths from both the oceanic and continental sectors of the Cameroon Line. In the latter, the crust was affected by the Pan-African event, which is estimated to be at least 600 million years old (e.g., Black and Liegeois 1993). In contrast to the host basalts, peridotite xenoliths originate in the lithospheric mantle and indeed, those in the oceanic sector are extremely depleted, whereas the continental ones show a partial melting trend (Fig. 4E).

The northwestern region of Madagascar is covered by basanitic volcanics of late Cenozoic age and the Nosy Be archipelago is the northwestern most part of this igneous activity, where peridotite xenoliths are common (Rocco et al. 2013; Fig. 4F). The peculiarity of Nosy Be lithosphere is that it was involved in several orogenic

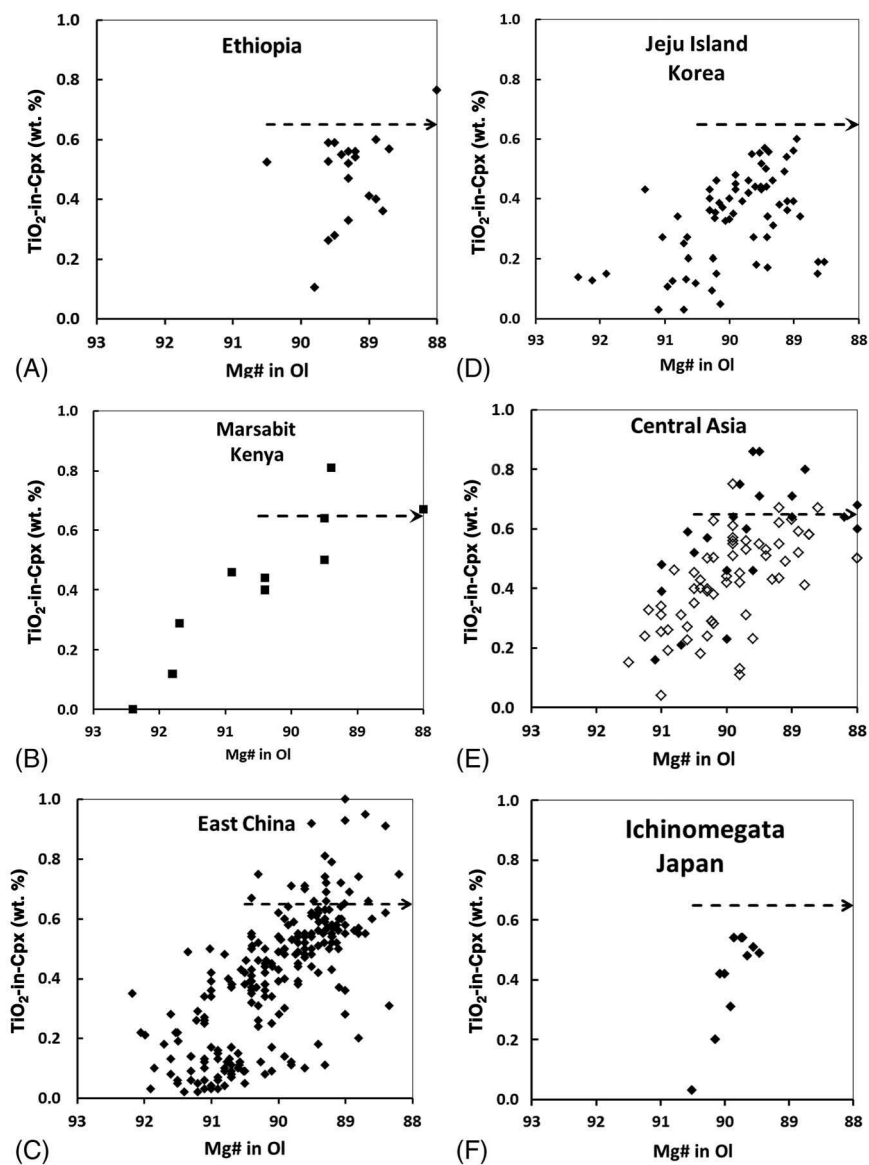


Fig. 5

Mg-value in olivine versus  $\text{TiO}_2$  in coexisting clinopyroxene on the basis of published analyses. A: Ferrando et al. (2008), Alemayehu et al. (2016). B: Kaeser et al. (2006). C: Song and Frey (1989), Xu et al. (1997, 1998b), Rudnick et al. (2004), Zheng et al. (2004), Ying et al. (2006), Tang et al. (2007, 2008), Xiao et al. (2010), Liu et al. (2012a, 2012b, 2013), Huang et al. (2013), Lu et al. (2015), Pan et al. (2015). D: Choi et al. (2001), Kil et al. (2008), Yang et al. (2010), Woo et al. (2014). E: Preß et al. (1986), Wiechert et al. (1997), Kononova et al. (2002), Ionov (2004), Egorova et al. (2006), Konc et al. (2012), Zou et al. (2014). F: Takahashi (1986), Satsukawa and Michibayashi (2014); filled symbols: Tarim peridotite xenoliths; empty symbols: other Central Asian xenoliths

cycles and rifting periods during the Madagascar–Somali and Madagascar–India separation (e.g., [De Wit 2003](#)).

Figure 5A and B shows peridotite inclusions originating from the Ethiopian and Kenyan sectors of the East African Rift System. This is another unique geologic area of the African continent where rifting, extension, and intensive volcanic activity continue to occur, which may lead to the formation of a new ocean. The distribution of the titanium data for these xenoliths accords with the partial melting trend and the same can be said for the xenoliths of the Hoggar and the Cameroon Line. The Nosy Be xenoliths (Fig. 4F) are clearly different, with a vertical rise of Ti in clinopyroxene in the range of 90–91 Mg# that may perhaps indicate refertilization.

### **Eastern Asian xenoliths**

A map showing the worldwide distribution of mantle xenolith localities published by [Menzies \(1983\)](#) did not display a single one for the whole of China. Since then, a plethora of xenolith occurrences, most of them in eastern China, has been detected and studied. Proceeding from north to south, east China is composed of the North China Craton, the South China Craton, and the Cathaysia Block. The North China Craton (Sino-Korean Craton) is one of the oldest cratons on Earth (3.8 Ga; [Liu et al. 1992](#)). Cratons have the reputation of being virtually indestructible as they have the ability to survive for a very long period of time. However, East China Cratons are unusual because locally they were strongly affected by lithospheric thinning that began in the Mesozoic, which is known to have reduced the thickness of the lithosphere from 200 km to 80 km. Xenoliths in Paleozoic kimberlites show that a thick (~200 km), cold (~40 mW/m<sup>2</sup>), and highly refractory lithospheric mantle existed until the mid-Ordovician (e.g., [Zheng et al. 2006](#)), indicating that Archean crust is underlain by a thick, cold, and refractory Archean lithospheric mantle (e.g., [Griffin et al. 1998](#); [Zhang et al. 2009](#)). However, peridotite xenoliths from the Cenozoic basalts suggest a hot (60–80 mW/m<sup>2</sup>), thin (80–60 km), and fertile younger lithospheric mantle beneath eastern China ([Griffin et al. 1998](#); [Rudnick et al. 2004](#); [Zhang et al. 2009](#)). These observations suggest that the lithospheric mantle of the East China Craton has not been only considerably thinned, but also compositionally changed from highly refractory to more fertile mantle during Phanerozoic times.

Figure 5C illustrates the titanium content of clinopyroxenes versus olivine Mg-value in xenoliths from diverse East China localities. All the xenoliths involved originate from Cenozoic basaltic volcanic rocks of alkaline affinity. As the eruptions are young, theoretically the xenoliths have the potential to reflect the refertilization and the renewal of the lower lithospheric mantle as explained above. However, Fig. 5C cannot be interpreted in a unique way; rather, it seems to show a mixture of partial melting and refertilization trends. Indeed, plotting xenoliths of individual localities separately (not shown), both trends are clearly present. For example, Ningyuan (southeast China) and Great Xing'an Range (northeast China) peridotite xenoliths

exhibit a refertilization trend, whereas Maguan, Xinchang (southeast China), and Hannuoba (northeast China) inclusions show typical partial melting trends. Again, the trend of Jeju Island xenoliths in South Korea (Fig. 5D) can be interpreted by the partial melting model.

### **Central Asian xenoliths**

Cenozoic alkali basalts containing peridotite inclusions occur in a large area in central and eastern Asia encompassing southern Siberia, central and eastern Mongolia, northwest China (Tarim Basin, Hexigten, and Inner Mongolia), and even the Russian Far East. Among the most studied localities, the Vitim volcanic province east of Lake Baikal, Siberia, lies just outside the Baikal rift zone, carrying samples of the off-craton lithospheric mantle (Ionov 2004). The Tariat volcanic field in central Mongolia is located approximately 500 km southwest of Lake Baikal. The Dariganga lava plateau is the largest Cenozoic lava field in Mongolia and arguably the largest one in central and eastern Asia. Xenoliths of the Cenozoic Atsagin-Dush volcanic center on the Dariganga Plateau (southeast Mongolia) were also intensively studied (e.g., Wiechert et al. 1997). Finally, peridotite xenoliths from the Sanglien Plateau (southern Siberia) differ from the preceding ones in that they originate from old (447–441 Ma) alkaline lamprophyre dikes (e.g., Egorova et al. 2006). In Fig. 5E, Tarim peridotite xenoliths plotted in filled symbols may perhaps suggest refertilization, whereas for all the other localities (empty symbols), no clear-cut conclusion can be drawn in this direction. Although few data exist for the Ichinomegata (Japan) xenoliths that were erupted in an island arc setting, these data suggest a partial melting trend (Fig. 5F).

### **American xenoliths**

Ultramafic inclusions are widespread in alkaline basalts and kimberlites of the western USA between the coast of California and west-central Texas (Knippa), and south of the Mexican border. These occurrences are found in widely varied geologic settings. The most conspicuous tectonic feature here is the Basin and Range Province that has been subjected to extension that thinned and cracked the crust as it was pulled apart. Cenozoic alkaline volcanism erupting peridotite xenoliths is widespread in the region. Figure 6A shows data from all parts of the western USA; in contrast Fig. 6B only that from a single locality (Dish Hill in the Mojave Desert, California). Whereas the former displays a rather diffuse picture, the Dish Hill xenoliths indicate a typical partial melting trend.

In south-central Texas, mantle xenoliths have been described from ~83 Ma basanites (Raye et al. 2011) providing the opportunity to examine the lithospheric mantle beneath southern Laurentia. These peridotites represent the lithosphere at the boundary between Mesoproterozoic continental lithosphere and the transitional

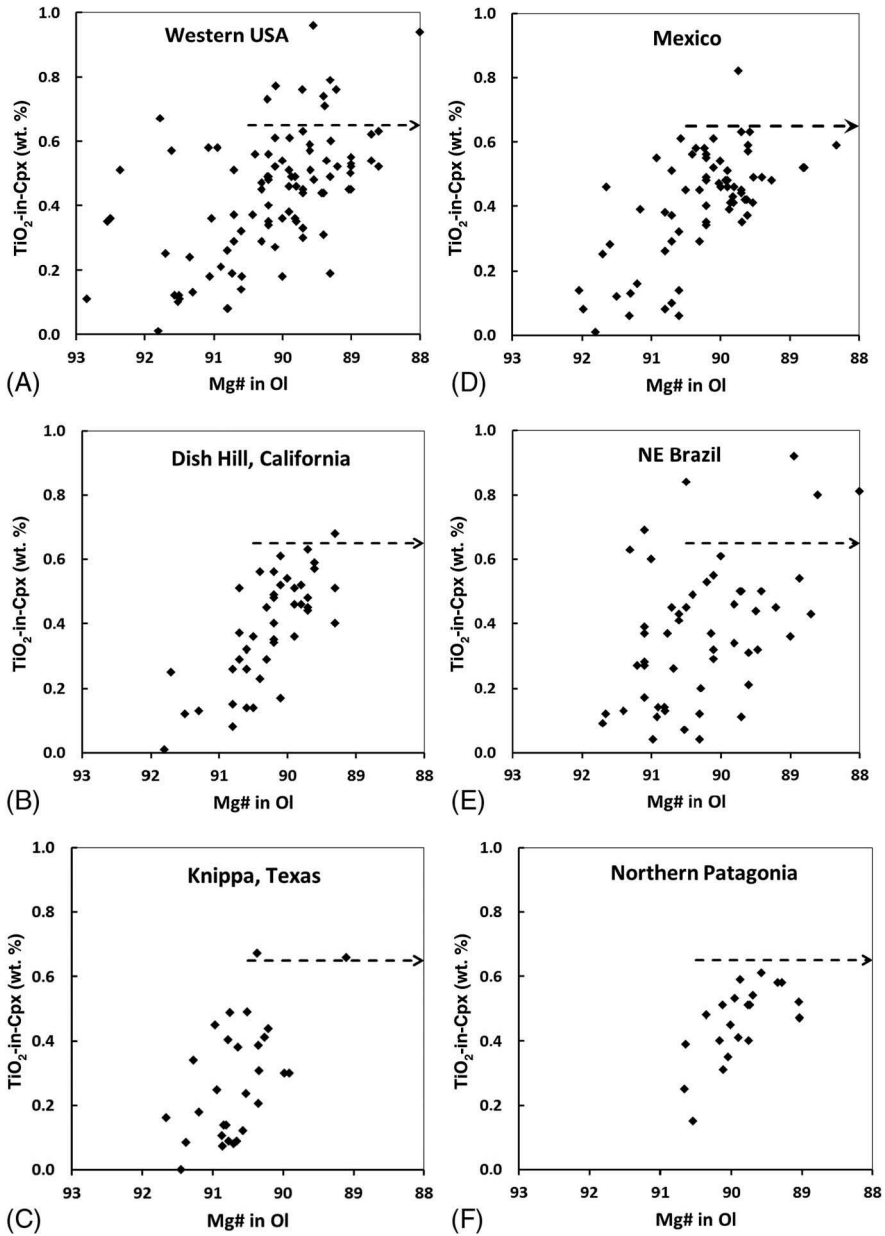


Fig. 6  
 Mg-value in olivine versus TiO<sub>2</sub> in coexisting clinopyroxene on the basis of published analyses. A: Carter (1965), Wilshire et al. (1988), Titus et al. (2007), Perkins and Anthony (2011). B: Luffi et al. (2009). C: Raye et al. (2011). D: Heinrich and Besch (1992), Luhr and Aranda-Gómez (1997). E: Rivalenti et al. (2000), Fodor et al. (2002). F: Dantas et al. (2009)

Gulf of Mexico passive margin. Again, the plot of Knippa peridotites attests a trend that corresponds to the partial melting model (Fig. 6C). The same can also be said of Mexican xenoliths (Fig. 6D).

In northeastern Brazil, near the edge of the Amazonian Craton, tertiary alkalic (3–13 Ma) basalts and spinel lherzolite inclusions therein provide valuable information about the conditions of the subcontinental lithosphere. The host basalts had origins with the Fernando de Noronha plume together with the older tholeiitic flood basalts emplaced during the beginning of continental rifting some 200 Ma ago (e.g., Fodor et al. 2002). In Fig. 6E, Brazilian xenolith data form a rather diffuse array, so it is difficult to see whether refertilization has played a role or not in their genesis. In contrast, a suite of anhydrous spinel-bearing lherzolites hosted in Cenozoic alkali basalts and pyroclastic rocks associated with a back-arc tectonic environment occurring at Cerro de los Chenques and Cerro Clark localities, north Patagonia (Dantas et al. 2009; Fig. 6F) is consistent with an origin by partial melting of varying degrees of a fertile mantle source.

### **Xenoliths of Eastern Australia, New Zealand, and Antarctica**

Ultramafic and mafic xenoliths derived from the lower crust and upper mantle are common in the predominantly tertiary basaltic rocks that extend the length of eastern Australia (e.g., Griffin et al. 1984). Figure 7A depicts spinel peridotite xenoliths from Victoria, the southernmost part of eastern Australia. This region is situated in the Paleozoic Tasman Fold Belt of eastern Australia, which borders the older cratonic areas to the west.

Tertiary (24–9 Ma) intraplate volcanics in southern New Zealand contain peridotite spinel-facies dunite, harzburgite, lherzolite, and wehrlite mantle xenoliths (Fig. 7B). These xenoliths have repeatedly sampled the mantle lithosphere of southern Zealandia since it broke away from Gondwana at ~85 Ma (Laird and Bradshaw 2004).

In Victoria Land (west Antarctica), alkaline magmas have erupted since Cenozoic times, connected with the Ross Sea rift system. The West Antarctic rift system is an example of continental rifting comparable in scale with the southwestern Basin and Range province in western North America or the East African Rift System. Peridotite and pyroxenite xenoliths allow the study of the shallow Antarctic lithospheric mantle (Fig. 7C). Spinel peridotite xenoliths plotted in Fig. 7 seem to be in agreement with the partial melting model, but the conspicuously low content of Ti in clinopyroxenes in the New Zealand samples (Fig. 7B) indicates a subsequent interaction between peridotite and a metasomatizing carbonatitic melt (Scott et al. 2014).

Besides the xenoliths shown in Figs 3–7, an important number of xenoliths from additional localities have been involved in this work that cannot be shown in separate plots due to lack of space. However, they have been included in a single diagram containing all the 1,520 xenoliths considered in this study (Fig. 8). Names of the additional localities and references are given in the figure caption. As expected, Fig. 8 corroborates the fact that the vast majority of shallow lithospheric mantle peridotite

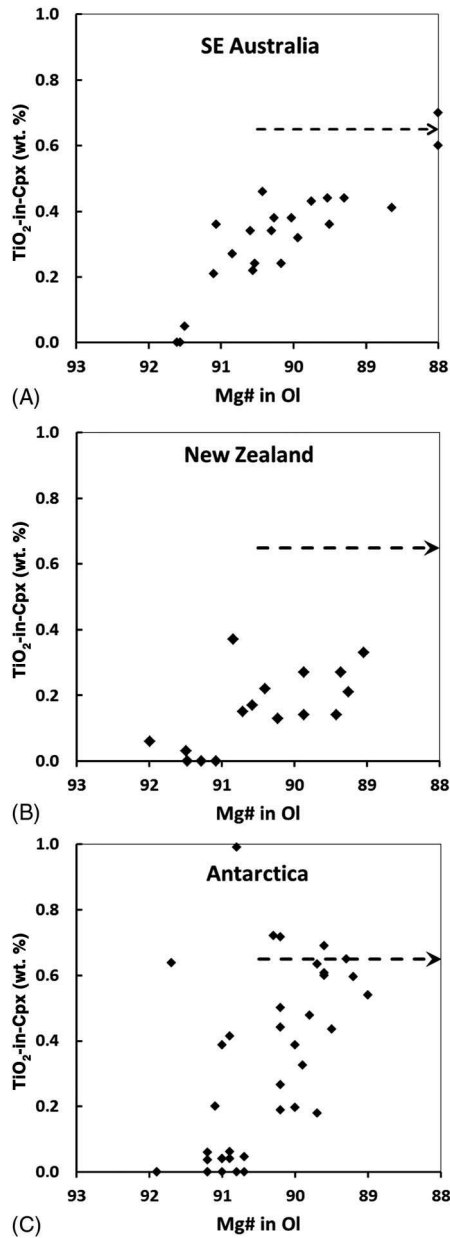


Fig. 7  
Mg-value in olivine versus TiO<sub>2</sub> in coexisting clinopyroxene on the basis of published analyses. A: Frey and Green (1974), Griffin et al. (1984), Chen et al. (1989), Norman (1998). B: Scott et al. (2014). C: Zipfel and Wörner (1992), Foley et al. (2006)



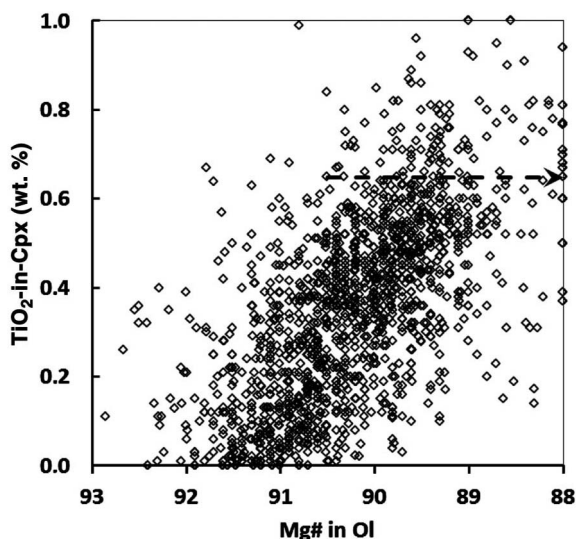


Fig. 8

Mg-value in olivine versus  $\text{TiO}_2$  in coexisting clinopyroxene on the basis of published analyses. In addition to the data plotted in Figs 3–7, similar values from the following localities have been added: Calatrava volcanic field, Spain (Villaseca et al. 2010); Lessinian basalts, northern Italy (Siena and Coltorti 1989); Mt. Vulture volcano, southern Italy (Jones et al. 2000); eastern Serbia (Cvetković et al. 2004, 2007); northwest Turkey (Aldanmaz et al. 2005); Kola Peninsula (Beard et al. 2007); Bir Ali, Yemen (Ali and Arai 2007; Sgualdo et al. 2015); Damara Belt, northwest Namibia (Baumgartner et al. 2000; Le Roex and Class 2014); Lorena Butte, Simcoe Mts., southern Washington, USA (Draper 1992); southern British Columbia (Greenfield et al. 2013); Canadian Cordillera (Shi et al. 1998); east Oman (Grégoire et al. 2009); Malaita, Solomon Islands (Ishikawa et al. 2004); Grenada, Lesser Antilles (Parkinson et al. 2003); Bo Ploi, Thailand (Sritthai 2005); northeast Iran (Su et al. 2014); Tasmania (Varne 1977)

xenoliths seem to be consistent with evolution by partial melting rather than a refertilization process. However, a minority of them, especially those with more or less constant high  $\text{TiO}_2$  clinopyroxenes in the range of 90–88 Mg# in olivine, may reflect refertilization.

## Discussion

In the last decades, the refertilization model has gained an ever wider acceptance among earth scientists working with tectonically emplaced orogenic ultramafic bodies. Some of these scientists think that the same model may or should be applicable to peridotite xenoliths found in alkaline basaltic rocks as well, in spite of the general belief that these samples indicate a depletion trend due to progressive extraction of basaltic melt from a fertile mantle source. Compared with orogenic peridotite massifs, the much smaller size and the accidental nature of xenoliths minimize the chances of

tracing textural and chemical variations in the source mantle. This makes it difficult to tell the two types of model apart in any given region, all the more so in that partial melting and refertilization produce the same trend on variation diagrams. Hence, a modified version of Le Roux's titanium diagram has been used here as a tool to differentiate between the models for a large number of spinel lherzolite and harzburgite xenoliths around the world.

In general, the results indicated depletion trends, somewhat surprisingly even in eastern China, where barren old lithospheric mantle had been replaced by a more fertile asthenospheric mantle. However, some of the Chinese xenoliths did imply refertilization, which is in agreement with the view that current lithospheric mantle below this region is hybridized with an old lithosphere in the shallowest part and newly created "oceanic" type lithosphere in the deeper part (e.g., [Griffin et al. 1998](#); [Fan et al. 2000](#); [Xu 2001](#)). The majority of spinel lherzolite xenoliths entrained in the Cenozoic basalts of eastern China show that these lherzolite xenoliths have an "oceanic" affinity and thus may represent newly accreted lithospheric mantle formed by low-degree partial melting characterized by low-Mg# ( $Fo \leq 91$ ). In contrast, strongly depleted high-Mg# ( $Fo \geq 91$ ) inclusions may come from the shallower old cratonic lithospheric mantle. Since the pioneering work of Boyd ([1973](#), [1984](#), [1989](#)), we know that the Archean cratonic mantle most likely formed as residue after about 30% melting of ambient mantle at potential temperatures of 1,500–1,600 °C, producing severely depleted high Mg# peridotites. Younger lithospheric mantle became progressively more fertile, reflecting the secular cooling of the mantle since the Archean.

Presently, the modern MORB indicates ~7% melting at a potential temperature of 1,350 °C. Most of the peridotite xenoliths considered in this study were found in Cenozoic basaltic rocks and originated from the shallow subcontinental mantle. Their  $TiO_2$ -in-Cpx versus Mg#-in-olivine diagrams are consistent with "oceanic" affinity and with the idea that the main process that controls the geochemistry of the shallow subcontinental mantle is depletion by the removal of basaltic melt (e.g., [Downes 2001](#)). An important question is how subcontinental mantle becomes "oceanic." Oceanic residues may have formed in a variety of tectonic environments but are believed to be of relatively shallow origin. They may have derived from oceanic lithosphere that has been accreted to older continental nuclei. Others may have originated in subcontinental magmatic events at relatively shallow depths, comparable to those at which lithosphere has formed beneath the oceans. In terms of chemical composition, there is no difference between the upper part of the asthenosphere and the lower part of the lithosphere. In fact, if the upper part of the asthenosphere cools down, it becomes a part of the lithosphere.

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