Lithos 148 (2012) 247–261

Contents lists available at SciVerse ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Invited Review Article

A global overview of isotopic heterogeneities in the oceanic mantle

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A R T I C L E   I N F O

Article history:
Received 30 December 2011
Accepted 14 June 2012
Available online 23 June 2012

Keywords:
Isotopic equilibrium
Upper mantle isotopic heterogeneity
Oceanic peridotites
Oceanic crust
Alpine/Apennine ophiolites

A B S T R A C T

Studies on modern oceanic lithosphere and ophiolites have revealed high degrees of chemical and isotopic heterogeneity in the mantle, as well as isotopic contrasts between mantle and crust. These features cannot be explained just by simple extraction of partial melt, but require considerably more complex petrogenetic processes. Here we present an overview of the present knowledge on isotopic heterogeneities of Sr, Nd, Hf and Os in oceanic peridotites (by reviewing data on modern abyssal peridotites and the Alpine–Apennine ophiolites), and discuss their significance in terms of i) length scale and extent of isotopic heterogeneities in the upper mantle and ii) isotopic mantle–crust relations at oceanic settings. Overall results show that mantle peridotites record significant isotopic heterogeneity, detectable on a wide range of length scales, much larger than observed in associated MORB. In addition, abyssal peridotites are on average more depleted than MORB. The high degree of isotopic heterogeneity is clear evidence for the inefficiency of mantle convection in homogenizing mantle rocks. It may be caused by i) variably old depletion events (unrelated to recent MORB production), ii) pyroxenite components in the mantle source, iii) recent pre- and/or post-melting metasomatism. Some abyssal peridotites have extremely depleted isotopic compositions, not seen in MORBs, and these have been interpreted as the evidence for old (1 to 2 Ga) refractory domains in the asthenospheric mantle or, alternatively, as evidence for recent incorporation of (also old) subcontinental lithospheric mantle, potentially through delamination during continental breakup. The first hypothesis has been corroborated by finding, in a few ridge segments (e.g. Gakkel Ridge) of correlations between chemical fertility indexes and isotopic (Os, Hf) ratios, indicative of recycling of old residual oceanic lithospheric mantle into the MORB source. However, no general consensus exists yet on the two proposed models. The difference in average isotopic depletion between peridotites and basalts has been also ascribed to the presence of pyroxenites, which have "enriched" isotopic signature relative to the peridotite component. The origin and composition of such small-scale lithological heterogeneities remain however still controversial and poorly constrained, due to the difficulty to link petrologic and geochemical studies with direct field observations, and to the scarcity of chemical and isotopic data on pyroxenites in ophiolitic and abyssal peridotites, i.e. the closest available "proxies" of the MORB mantle. Larger isotopic homogeneity observed in MORB relative to peridotites in single ridge segments clearly reflect their origin as aggregated melts which inevitably "smooth" and average mantle source heterogeneities. Overall, the questions about the origin and spatial distribution of chemical and isotopic heterogeneities are not resolved, and this calls for detailed field-based studies in spatially-controlled settings to shed light on the issue of small-scale mantle heterogeneities and the role of enriched (e.g. pyroxenites) and highly depleted domains in MORB melting.

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0024-4937/$ – see front matter
doi:10.1016/j.lithos.2012.06.018

1. Introduction

The theory of formation of the oceanic lithosphere assumes that mid-ocean ridge basalts (MORB) are produced by partial melting of upwelling asthenosphere which is then cooled to form the residual oceanic lithospheric mantle. This genetic relationship between mantle peridotites and associated crust is expected to result in identical isotopic compositions, provided that i) the mantle source is homogeneous, ii) partial melting takes place under equilibrium conditions and iii) the melt is not subsequently contaminated during extraction and solidification. Although experimental diffusion studies certainly bear on this issue, diffusion is not the sole factor that determines whether or not such equilibrium is achieved. Other factors, especially reaction and recrystallization rates also affect the ultimate outcome. Therefore, it is important to study geological settings where the isotopic compositions of the basaltic melting products can be compared with the peridotitic residues. This requires isotopic studies on crustal rocks and spatially and/or genetically related peridotites.

At modern mid-ocean ridge settings, in spite of a large amount of isotope data on MORBs, only a few isotopic studies have focussed on abyssal peridotites, and very few report data on peridotites and MORBs from the same ridge segment. A pioneering study by Snow et al. (1994) documented the existence of abyssal peridotites with Nd isotopic compositions identical to those of nearby MORBs, and therefore consistent with an equilibrium residue–melt relationship between oceanic mantle and crust. However, more recent isotope work at modern oceanic environments and ophiolites has shown a more complex scenario. Isotopic studies on abyssal peridotites at slow- and ultraslow-spreading ridges give evidence of significant heterogeneity at variable length scales (from regional to within-sample centimeter scale), and of extremely depleted Nd, Os and Hf isotopic compositions in oceanic peridotites, so far not documented in MORBs, and until now considered unique to the ancient subcontinental mantle (Alard et al., 2005; Cipriani et al., 2004; Harvey et al., 2006; Liu et al., 2008; Salters and Dick, 2002; Stracke et al., 2011). This has raised some fundamental questions about i) the efficiency of asthenospheric mantle convection in erasing chemical and isotopic heterogeneities, ii) the length (and time) scale of equilibrium or disequilibrium between mantle and melts, and ii) the "subcontinental-" vs. "asthenosphere" origin of some mantle peridotites exposed at the ocean floors (O'Reilly et al., 2009; Stracke, 2008). This in turn has raised doubts whether isotopic compositions of peridotites can be used to identify a specific tectonic setting.

This paper presents an overview of the current state of knowledge about the isotopic aspects of the oceanic mantle and mantle–crust relations. We review recent isotope studies on crust–mantle sections at modern oceanic settings, and on the Alpine–Apennine ophiolites (Fig. 1), i.e. a well-studied analogue of passive margin and slow spreading oceanic settings (Manatschal and Müntener, 2009; Moh et al., 2010; Piccardo, 2009; Piccardo and Guarnieri, 2010a; Rampone and Piccardo, 2000). Major aims are to define the present-day limits on the extent and scale of isotopic heterogeneity of the oceanic mantle and related implications on the existence of a cogenetic link and isotopic equilibrium between oceanic mantle and crust.

To address the issues above, we first provide a brief overview of the present knowledge about the structural and genetic variability of the oceanic lithosphere created at distinct oceanic settings (i.e. passive margins, ultraslow-, slow-, and fast- spreading ridges), because this has clear implications on the existence of mantle–crust genetic relations, or their absence. We then review the available data pertaining to the question of isotopic equilibrium between mantle and crust.

2. Variability of structure of the oceanic lithosphere

Recent studies of modern oceanic settings and ophiolites have revealed that processes of accretion and final architecture of oceanic lithosphere can diverge significantly from the classic Penrose model (Nicolas, 1995). This variability exists both along ridge axes, depending on spreading rates in different mid-ocean ridge systems, and perpendicular to ridge axes, from inner to marginal (i.e. ocean–continent transitions) oceanic

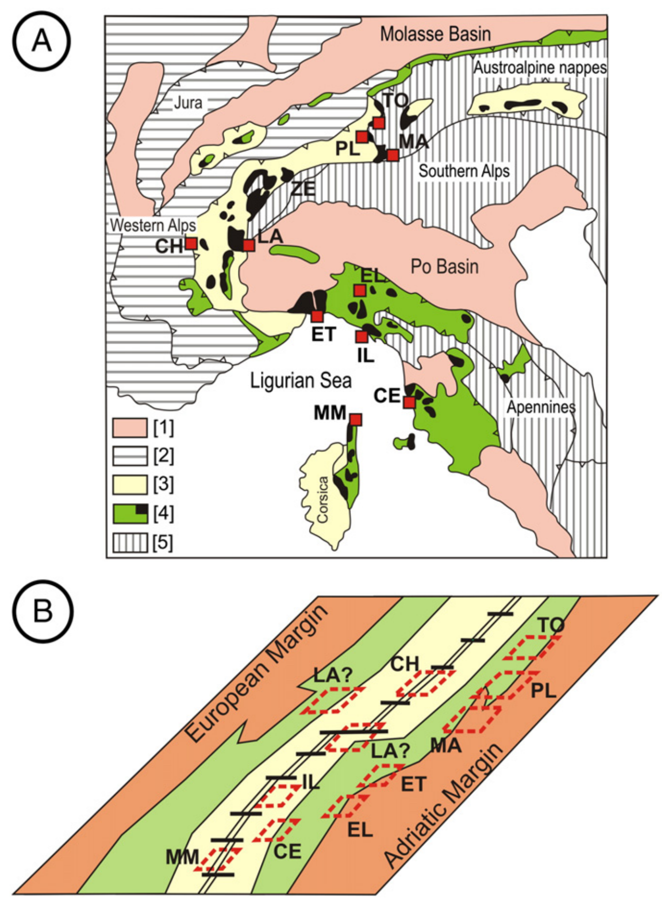

Fig. 1. (A) Location of the major ophiolite massifs in the Central–Western–Ligurian Alps and Northern Apennines (and Corsica) (redrawn after Schaltegger et al., 2002). TO: Totalp, MA: Malenco, PL: Platta, LA: Lanzo, CH: Chenaillet, ET: Erro-Tobbio, EL: External Ligurides, IL: Internal Ligurides; MM: Monte Maggiore (Alpine Corsica). [1]: Tertiary basins; [2]: European Units; [3]: Pennidic Units; [4]: Ophiolitic Units; [5]: Adriatic Units. (B) Schematic palaeogeographic reconstruction of the Piemont–Ligurian ocean during the Late Jurassic, with inferred location of the major ophiolite sequences (redrawn after Manatschal and Müntener, 2009).