Lithos 124 (2011) 200–214

Contents lists available at ScienceDirect

Lithos

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

# Gabbro-norite cumulates from strongly depleted MORB melts in the Alpine–Apennine ophiolites

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ARTICLE INFO

*Article history:*
Received 8 March 2010
Accepted 31 January 2011
Available online 12 February 2011

*Keywords:*
Gabbro-norite suite
Strongly depleted MORB melts
Melt percolation
Ligurian ophiolites
Alpine–Alpine orogenic system

ABSTRACT

Hundred-meter wide cumulate bodies and decimetric dykelets of gabbro-norites are widespread within the distal ophiolitic peridotites from the Jurassic Ligure-Piemontese oceanic basin, now emplaced in the Alpine–Apennine orogenic system. These peridotites derived from the sub-continental mantle of the pre-Triassic Europe–Adria lithosphere and underwent profound modifications of their structural and compositional characteristics via melt–rock interaction during diffuse percolation by porous flow of upwelling asthenospheric melts. Gabbro-norite cumulates show the peculiar association of high forsteritic olivine, high-Mg# clinopyroxenes and orthopyroxenes and high anorthitic plagioclase with respect to mineral compositions in common ophiolitic and oceanic MORB gabbros. Abundance and early crystallization of magnesian orthopyroxene suggests that parental magmas of the gabbro-noritic cumulates were relatively silica-rich basaltic liquids. Clinopyroxenes and plagioclase have anomalously low Sr and LREE, resulting in highly fractionated C1-normalized LREE patterns in clinopyroxenes and negatively fractionated C1-normalized LREE patterns in plagioclases.

Modal mineralogy and mineral major and trace element compositions indicate that these gabbro-norites crystallized from MORB-type basaltic liquids that were strongly depleted in Na, Ti, Zr, Sr and other incompatible trace elements relative to any erupted liquids of MORB-type ophiolites and modern oceanic lithosphere. Computed melt compositions in equilibrium with gabbro-norite clinopyroxenes are closely similar to depleted MORB-type single melt increments after 5–7% of fractional melting of a DM asthenospheric mantle source under spinel-facies conditions.

Present knowledge on the ophiolitic peridotites of Monte Maggiore indicate that they were formed by interaction of lithospheric mantle protoliths with depleted, MORB-type single melt increments produced by the ascending asthenosphere. Their composition was progressively modified from olivine-saturated to orthopyroxene-saturated by the early reactive melt–peridotite interaction (i.e., pyroxene dissolution and olivine precipitation).

Gabbro-norite cumulates marked the change from diffuse porous flow percolation to intrusion and crystallization when cooling by conducive heat loss became dominant on heating by melt percolation. Progressive upwelling and cooling of the host peridotite during rifting caused transition to more brittle conditions and to hydration and serpentinization.

The Monte Maggiore peridotite body was then intruded along fractures by variably evolved, Mg–Al- to Fe–Ti-rich gabbroic dykes. Computed melt compositions in equilibrium with clinopyroxenes from less evolved gabbro dykes are closely similar to aggregated MORBs. The event of gabbro intrusion indicates that aggregated MORB-type liquids: i) migrated through and stagnated in the mantle lithosphere and ii) underwent evolution into shallow ephemeral magma chambers to form the parental magmas of the gabbroic dykes and the basaltic lava flows of the Ligurian oceanic crust.



## 1. Introduction

Peculiar cumulates from strongly depleted MORB-type liquids were described at DSDP Site 334 on the Mid Atlantic Ridge (MAR) (Hodges and Papike, 1976; Ross and Elthon, 1993).These unique suite of oceanic cumulates are plagioclase lherzolites, olivine gabbro-norites, gabbro-norites and noritic anorthosites that contain olivine (Fo 90–85), high-Ca and low-Ca pyroxenes (Mg# 91–70) and plagioclase (An 90–75). They have plagioclase with anomalously high anorthite content and very high Mg# and Cr abundances in pyroxenes, coupled with low Na and Ti in high-Ca pyroxenes and very low incompatible element abundances in pyroxenes. Orthopyroxene

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doi:10.1016/j.lithos.2011.01.017

is an abundant cumulus phase in the gabbro-norites. Abundance and early crystallization of magnesian orthopyroxene suggests that parental magmas of Site 334 cumulates were high silica (52–55 wt.%) liquids. According to Ross and Elthon (1993) the mineral compositions of this unique suite of oceanic cumulates indicate that these rocks crystallized from basaltic liquids that were strongly depleted in Na, Ti, Zr, Y, Sr and Rare Earth Elements (REE) relative to any erupted MORB. This suite of cumulates provides supporting evidences for the existence of strongly depleted liquids in the oceanic lithosphere and for the fact that such magmas did not mix with more enriched MORB liquids and remained sufficiently isolated to form distinctive cumulates (Ross and Elthon, 1993). Ross and Elthon (1993) showed that fractional melting of the upwelling sub-oceanic mantle produces magmas with a much wider range of compositions than erupted MORBs and that strongly depleted primary magmas are routinely produced by melting beneath ridges (e.g., Johnson et al., 1990). Such magmas remained sufficiently isolated to form distinctive intrusive rocks. These authors remarked that the absence of strongly depleted melts as erupted lavas prompts the question of how long such magmas survive before their distinctive compositions are erased by mixing with more enriched magmas to give aggregated MORB.

Gabbro-norites have been studied in the Oman ophiolites (e.g., Benoit et al., 1999; Boudier et al., 2000; Juteau et al., 1988; Lachize et al., 1996; Python and Celeneer, 2003; Yamasaki et al., 2006) and a new set of gabbro-norites drilled at DSDP Site 334 (MAR) was recently studied by Nonnotte et al. (2005). The genetic processes of the parental melts of mid-oceanic/ophiolitic depleted MORB gabbro-norites were discussed taking into account the high modal orthopyroxene (i.e., high whole rock silica contents), the strong incompatible trace elements depletion and the high whole rock and clinopyroxene Sr isotope ratios.

The different authors did not propose an univocal petrogenetic model. The most recent papers suggest that the hydrous melting of altered lithospheric peridotites at mid-ocenic ridges can contribute to the genesis of their parental melts.

Benoit et al. (1999) studied a suite of cumulates from a fossil mantle diapir (Maqsad area) of the Oman ophiolite the called "D-cumulates" that show MORB type εNd (+6.56 to +9.03) and seawater Sr isotopic signatures ($^{87}Sr/^{86}Sr = 0.70357–0.70832$). These authors proposed that the Sr isotopic signature is a characteristic inherited from the parent melt that was formed by hydrated melting of the depleted lithosphere above an asthenosphere diapir. The Oman D-gabbro-norites are thus considered as cumulates from parental melts formed by remelting of hydrothermally altered peridotites at mid-ocean ridges.

Python and Ceuleneer (2003) studied a rock suite consisting of pyroxenites, orthopyroxene-rich gabbro-norites, diorites, and tonalite–trondhjemites from the Oman ophiolites. They suggested that the parent melts derived by in situ partial melting of the shallow and partly hydrated lithosphere residual after MORB extraction.

Nonnotte et al. (2005) studied new samples of gabbro-noritic cumulates drilled at DSDP Site 334. They used the measured isotopic signatures to trace magma sources. They proposed that the depleted gabbro-norites originated from a MORB-type liquid that assimilated a highly hydrated silica-rich melt which was derived from a source highly depleted in incompatible elements, likely residual peridotite left after MORB extraction. Nonnotte et al. (2005) suggest that their data qualitatively support the view that the melts in equilibrium with Site 334 clinopyroxenes result from the mixing of depleted and variously evolved MORB-type melts with melt fractions issued from the remelting of the serpentinized lithosphere. Mixing likely occurred during emplacement and fractional crystallization of these cumulates.

Nonnotte et al. (2005) proposed that hydrated melting is an important process for the petrogenetic evolution of mid-ocean ridges and that magmatic rocks with andesitic/boninitic affinities and having highly radiogenic Sr can form at mid-ocean ridges. They concluded that geochemical evidence from DSDP Site 334 gabbro-noritic cumulates indicate that andesitic–boninitic magmas can be formed at mid-ocean ridges resulting from melting of hydrated peridotites.

Recent field work on the Ligurian ophiolitic peridotites revealed the widespread presence of pods and dykelets of peculiar gabbro-noritic rocks that are related to the early melt percolation events recorded by these peridotites. Some gabbro-norite dykelets were sporadically described in the peridotites of the Ligurian MORB-type ophiolites (e.g., Piccardo et al., 2004) but the gabbro-norite intrusive suite was never fully recognized before and there has been no detailed study and interpretation of this peculiar intrusive suite.

The aim of this paper is therefore to investigate the petrologic and geochemical features of the gabbro-norite suite to unravel the compositional characteristics of the parental melts and the mantle processes responsible for their peculiar compositions. The formation of these rocks is discussed in the context of the melt–peridotite interaction processes that were related to porous flow migration of asthenospheric melts through the subcontinental lithospheric mantle during the pre-oceanic rift evolution of the future Ligure-Piemontese basin. This study is aimed at improving our understanding of the evolution of the lithosphere–asthenosphere system during pre-oceanic rifting to oceanization of slow/ultraslow spreading oceans.

## 2. Present knowledge on ophiolitic peridotites from the Alpine–Apennine system

Over the past few decades the wealth of structural and petrologic–geochemical studies on mantle peridotites from the Alpine–Apennine MORB-type ophiolites (Fig. 1) have improved our knowledge of the mantle processes recorded in these sections of lithospheric mantle. Present knowledge indicates that: i) the peridotites were derived from the subcontinental lithosphere of the pre-Triassic Europe–Adria system, ii) they were exhumed from the Triassic as a consequence of passive extension of the Europe–Adria continental lithosphere and iii) they were exposed during Jurassic on the sea-floor of the Ligure-Piemontese oceanic basin following continental break-up and formation of the paired Europe and Adria non-volcanic passive margins (see discussion in Piccardo et al., 2009, and references therein).

Some ophiolitic peridotites from the Jurassic Ligure-Piemontese basin record subsolidus evolution and non-adiabatic exhumation from sub-continental spinel-facies mantle depths to the sea-floor (e.g., Hoogerduijn Strating et al., 1993; Montanini et al., 2006; Piccardo and Vissers, 2007), whereas other bodies record significant interaction with percolating asthenospheric melts (e.g., Müntener and Piccardo, 2003; Piccardo and Vissers, 2007; Piccardo et al., 2004, 2007a). Exhumed sub-continental peridotites and melt-interacted peridotites characterized, respectively, the marginal ophiolite sequences deriving from ocean–continent transition (OCT) zones and the distal ophiolite sequences deriving from more internal oceanic (MIO) settings of the basin. Thus, the ophiolitic peridotites show strong compositional heterogeneity and close relationships between palaeogeographic settings and petrologic features, indicating that peridotite bodies from different settings record mantle processes that are related to distinct periods of lithosphere evolution during continental extension and rifting (Piccardo, 2008; Piccardo et al., 2009, and references therein).

Continental rifting and stretching of the subcontinental lithosphere favored near-adiabatic upwelling and decompression melting of the underlying asthenosphere, starting in the lateTriassic–early Jurassic (see discussion in Piccardo et al., 2009, and references therein). Asthenospheric melts percolated through the extending lithospheric mantle via diffuse and focused porous flow. Melt–peridotite interaction strongly modified the structural, modal and compositional characteristics of the lithospheric peridotites (Müntener and Piccardo, 2003; Piccardo et al., 2004, 2009).