Petrology, geochemistry, and Sr, Nd isotopes of mantle xenolith in Nghia Dan alkaline basalt (West Nghe An): implications for lithospheric mantle characteristics beneath the region

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ABSTRACT

Study of petrological and geochemical characteristics of mantle peridotite xenoliths in Pliocene alkaline basalt in Nghia Dan (West Nghe An) was carried out. Rock-forming clinopyroxenes, the major trace element containers, were separated from the xenoliths to analyze for major, trace element and Sr-Nd isotopic compositions. The data were interpreted for source geochemical characteristics and geodynamic processes of the lithospheric mantle beneath the region. The peridotite xenoliths being mostly spinel-lherzolites in composition, are residual entities having been produced following partial melting events of ultramafic rocks in the asthenosphere. They are depleted in trace element abundance and Sr-Nd isotopic composition. Some are even more depleted as compared to mid-ocean ridge mantle xenoliths. Modelled calculation based on trace element abundances and their corresponding solid/liquid distribution coefficients showed that the Nghia Dan mantle xenoliths may be produced of melting degrees from 8 to 12%. Applying various methods for two-pyroxene temperature-pressure estimates, the Nghia Dan mantle xenoliths show ranges of crystallization temperature and pressure, respectively, of 1010-1044°C and 13-14.2 kbar, roughly about 43km. A geotherm constructed for the mantle xenoliths showed a higher geothermal gradient as compared to that of in the western Highlands (Vietnam) and a conductive model, implying a thermal perturbation under the region. The calculated Sm-Nd model ages for the clinopyroxenes yielded 127 and 122 Ma. If the age is meaningful it suggests that there was a major geodynamic process occurred beneath Western Nghe An in the middle- Early Cretaceous that was large enough to cause perturbation in the evolutional trend of the Sm-Nd isotopic system.

Keywords: Nghia Dan; alkaline basalt; mantle xenolith; spinel-lherzolite; clinopyroxene.

1. Introduction

1.1. Alkaline basalt-borne mantle xenoliths

Mantle xenoliths (inclusions) brought to the surface by alkaline basalts are residues formed following partial melting events of mantle peridotites in the upper mantle. These residual bodies are constituent components of the lithospheric mantle (Frey and Frinz, 1978; Nixon (Editor), 1987), dividing the conductive crust above and convective asthenosphere below (Anderson, 1994). Being dependent on the degree of partial melting of a fertile (primitive) mantle peridotite, the residual peridotite
may be variously enriched/fertile or deple-
ted/refractory.

The effect of partial melting experienced
along with the complex mantle interactions in
the lithospheric mantle is normally recorded
and reflected by various radiogenic isotope
systematics. Therefore, studying radiogenic
isotope systematics and element geochemical
characteristics of mantle peridotite residues,
their formation and evolution history, in par-
ticularly, and of the lithospheric mantle, in
general, may be revealed (Carlson and Lug-
mair, 1979, 1981; Carlson and Irving, 1994;
Frey and Prinz, 1978; De Paolo, 1981; De
Paolo et al., 2000; Menzies et al., 1987). Be-
sides, study of Sm-Nd, Lu-Hf isotope system-
atics, which are persistent to external factors,
in mantle peridotite residues one may be able
to understand major geodynamic processes
having occurred in the lithospheric mantle
prior to their being brought to the surface by
alkaline basalt (DePaolo and Wasserburg,
1976; DePaolo, 1981; McCulloch and Was-

1.2. Alkaline basalt in the Nghia Dan district

Pliocene basaltic volcanism occurred in the
Thai Hoa and other nearby communes of
Nghia Dan district (West Nghe An) and Xuan
Binh, Nhu Xuan district (Thanh Hoa) (Figure
1). The volcanism is viewed as part of the
widely spread Cenozoic basaltic volcanism
occurred at many localities in southeast Asia
(Barr and McDonald, 1981; Whitford-Stark,
1987; Zhou and Mukasa, 1997). In Vietnam,
the Cenozoic basalt occurred voluminously in
the Western Highlands, south-Central region,
along the coastline and in the continental shelf
of the East Vietnam Sea (Nguyen and Ngu-
yen, 1980; Barr and McDonald, 1981; Gorsh-
kov, 1981; Gorshkov et al., 1984; Whit-
ford-Stark, 1987; Tu et al., 1991, 1992; Flow-
er et al., 1991; Fedorov and Koloskov, 2005;
Hoang et al., 2014; An et al., 2017; Hoang-
Thi et al., 2018). The volcanism occurred long
after the cessation of East Vietnam Sea open-
ing tectonics (32-16 Ma) (Li et al., 2014 and
references therein). The latter, termed as ex-
trusion tectonics, has been viewed as a conse-
quence of India - Eurasian hard collision
about 60-40 Ma (Tapponnier et al., 1982;
Briais et al., 1993; Lee and Lawver, 1995),
igniting left lateral strike slip along the Ailao
Shan - Red River fault zone and counter-
clockwise rotation of the Indochina block, and
might lead to the opening of East Vietnam Sea
(Tapponnier et al., 1982, 1990). The extrusion
concept of marginal sea opening is controver-
sial (e.g., Cung et al., 1998; see summaries in
Li et al., 2014, 2015); however, this is out of
our scope to debate.

Like many Cenozoic volcanic fields in the
Western Highlands and elsewhere in south-
Central region of Vietnam, the basaltic rocks
in Nghia Dan (and Nhu Xuan) (thereafter
Nghia Dan center) occur along or at the inter-
section of the regional fault systems. The vol-
canism appears as monogenetic volcanoes,
forming lava covers with varying thicknesses,
from a few meters to hundreds of meters. De-
pending on the size of volcanoes, the lava
cover varies from a few square kilometers to
tens of square kilometers in area. Volcanoes
being tens of meters to more than 250 meters
high are scattered in Nghia Son (Mt. Nui
Tien), Nghia Lam (Mt. Nui Hang), Nghia My
(Mt. Doi Tro, Doi Troc, Ke Lui), and Xuan
Binh (Mt. Nui Ro), etc. The basalt occurs as
massive or porous. Rectangular- and penta-
gon-columnar basalts are seen at Mt. Ke Lui
(Hoang et al., 2014) (Figure 2). Heavily po-
rous basaltic rocks (up to 50 vol.% vesicles
from several millimeters to more than one
centimeters in diameter) are subject to strong
weathering, forming a crust that is widely
used as cement additive for many local ce-
ment factories. Two basaltic samples collected
along the Ho Chi Minh trail in the Nghia My
The Nghia Dan basalts are low in SiO$_2$ (wt.%), very high in TiO$_2$ (wt.%) and high in the total alkali (K$_2$O + Na$_2$O) that they plot in the alkaline field in the classification diagram (Hoang et al., 2014). Nghia Dan Pliocene basalts Nghia Dan have high abundances of incompatible and rare earth elements, they are even higher as compared with those in young (<1 Ma) alkaline basalts in Pleiku, Western Highlands, used to view as the most enriched Cenozoic basalts in Vietnam (Hoang et al., 2014). Using Nghia Dan trace element abundances along with their corresponding Sr, Nd and Pb isotopic compositions for mantle
source modelling, Hoang et al. (2014) con-
cluded that the Nghia Dan alkaline basalts were produced by partial melting of spinel
peridotites in the asthenosphere (e.g. Johnson
et al., 1990; Workman and Hart, 2005).

As reported elsewhere in the world, in
Vietnam mantle xenoliths are found only in
highly alkaline basalts (Ne-
normative
> 5vol.%). Mantle xenoliths are discovered at
two locations around Thai Hoa township, at
Nghia My (Mt. Ke Lui) and Nghia Loi com-
munes (Figure 2a). The mantle xenoliths oc-
cur in various sizes, from a few centimeters
up to 15 cm by 10 cm. They are coarse-
grained, massive, comprising mostly olivine,
up to 2 mm by 1 mm in size. The xenoliths,
clearly distinguishable on the dark basalt
background, are dark green to light green,
some turned to brown as an effect of weather-
ing (Figure 2b).

Mantle xenolith samples were collected in
alkaline basalt at two locations in Nghia My
and Nghia Loi communes for this study. The
whole rock samples were processed for petro-
graphic study and electronic probe microana-
lysis (EPMA) for rock-forming minerals. The
trace element and Sr-Nd isotopic analysis
were performed on clinopyroxenes separated
from the xenolith samples. The data were in-
terpreted in terms of petrological and geo-
chemical characteristics of the lithospheric
mantle and its associated major regional geo-
dynamic processes.

2. Sample processing and analytical proce-
dures

The samples were processed for petro-
graphic study under a polarizing microscope,
also for acquisition of rock-forming mineral
geochronological data. The samples were pro-
cessed for EPMA for acquisition of rock-forming mineral
geochemical compositions using electron
probe microscopic analysis (EPMA). The
mantle xenoliths are spinel-lherzolites, coarse-
grained, xenogranular or metamorphic te-
xtured. The crystals are compacted with
smooth rims, or round-shaped, certainly re-
reflecting melting experience. The most repre-
sentative mineral assemblage is (in vol.%) olivine (Ol): 70-80, orthopyroxene (Opx): 19-
25, clinopyroxene (Cpx): 3-5, and spinel (Sp):
<2. The modal data were collected in thin sec-
tions and counting >500 points on a 1mm grid
(Figure 3). The olivine is lemon yellow, or
green to brightly green, coarse-grained (up to
2 by 2mm), partially corroded. The orthopy-
roxene is grayish dark, glassy black. The crys-
tals with clear cleavages are tablet, elongated
with sizes up to 2 by 1mm, anhedral or semi-
euhedral. The clinopyroxene is dark green, ir-
regular-shaped, small-sized (<0.5 by 0.2mm), distributed between the co-existent orthopyroxene grains. The spinel is darkish red, dark brown, irregularly shaped, distributed in the interstices between, or included in, large olivine crystals (Figure 4).

Five representative samples were chosen among the collected samples in the Nghia My and Nghia Loi communes. The samples were processed to measure for major elements of the rock-forming minerals using a JEOL 8800 Electron Probe Microanalyzer (EPMA) at the Geological Survey of Japan (Tsukuba, Japan). The accuracy of the analysis was estimated between ±2 and ±3% based on the repeated measurements of JEOL standards using natural minerals such as jadeite (Na), albite (K), kyanite (Al), wollastonite (Ca, Si), forsterite (Mg), rutile (Ti) and manganese ferrite (Fe) etc. Data for coexisting pyroxenes were used to calculate for crystallization temperatures using two pyroxene geothermometer by Wells (1977), Brey and Kohler (1990), Putirka et al. (2003), and Putirka (2008, 2017). The data are shown in Table 1.
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Table 1: Major element concentrations (wt.%) of rock-forming minerals of Nghia Dan mantle xenoliths.
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213
The trace element and Sr-Nd isotopic compositions were acquired on separated clinopyroxenes from two representative large (5×10×10 cm) spinel-lherzolite samples collected from Mt. Ke Rui and Nghia Loi (Figure 2). The clinopyroxene separation was treated as follows. About 50 g of the mantle xenoliths were crushed and ground, followed by 1 mm sized sieving. The sieved particles were cleaned ultrasonically for about 30 minutes, followed by multiple rinse with clean water. The cleaned samples were dried in an oven at 90°C for about 1 hour. The samples were left to cool. Clinopyroxenes were then hand-picked under a stereo binocular microscope. The clinopyroxene separates were again roughly ground, ultrasonically cleaned, dried and hand-picked to eliminate any other minerals than clinopyroxene.

About 100 mg of clinopyroxene separates were weighed in 15 ml Teflon beakers, ready for dissolution. For sample dissolution, a mixture of 1 ml and 2 ml, respectively, of concentrated HNO₃ and HF was added to the beakers, capped and left on a hotplate at about 140 °C for two days, followed by complete evaporation. The dried samples were added with 3 ml of 7 M HNO₃, capped and left on a hotplate at about 80 °C for an overnight to ensure the samples were dissolved completely. The samples were evaporated, weighed, then diluted with 6 ml of 0.3 M HNO₃. An aliquot of about 3 ml (ca. 50 mg) of the sample was taken for trace element concentration determination using a Neptune Elemental quadrupole inductively coupled plasma mass spectrometer (Q-ICP-MS) at the Department of Physics and Earth Sciences, University of the Ryukyus, Okinawa, Japan. The trace element compositions are shown in Table 2.

The remaining sample solutions were treated for chromatographic work to extract Sr and Nd elements. The ⁸⁷Sr/⁸⁶Sr, ¹⁴³Nd/¹⁴⁴Nd isotopic ratios were acquired using a VG Sector 54 Thermo- ionization Mass Spectrometer (TIMS) at the Geological Survey of Japan, Tsukuba, Japan. The data are shown in Table 2.

### Table 2. Trace element and Sm-Nd-Sr isotopic compositions of clinopyroxene separates from Nghia Dan spinel-lherzolite xenoliths

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<th>Location</th>
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<th>Longitude</th>
<th>Sm (ppm)</th>
<th>Nd (ppm)</th>
<th>⁰⁷Sm/⁰⁹Nd</th>
<th>⁰⁴Nd/⁰⁴Nd</th>
<th>¹⁴⁷Sm/¹⁴⁴Nd</th>
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3. Analytical results

3.1. Geochemistry of the mantle xenoliths

Note that most of the mantle xenoliths are spinel lherzolites. Geochemical compositions of their rock-forming minerals are relatively uniform regardless of being collected from two sites about 10 km apart. Geochemical similarity is also seen in alkaline basalts sampled from the two sites (Table 2).

3.1.1. Spinel and olivine relationship

Geochemically compositional characteristics of mantle xenoliths are reflected by the geochemistry of their rock-forming minerals (Figure 4). The olivine content in the Nghia Dan mantle xenoliths varies from about 70 to 80 vol.%, with forsterite composition \([100 \times (\text{Mg}/(\text{Mg}+\text{Fe}^2\text{+}))]\) ranging from 89 to 90.5 (Table 1). The spinel content varies from (about) 0.5 to 1.5 vol.\% having relatively low Cr-number (Cr/Cr+Al), about 8.5 (Table 1). Having low Cr-number (e.g. high \(\text{Al}_2\text{O}_3\) content) and relatively high forsterite component, Nghia Dan mantle xenoliths plot in the field of (intraplate) oceanic hotspot peridotites believed to be fertile and enriched for experiencing low degrees of partial melting as compared to peridotite residues in the ocean ridges, arc settings or ancient cratons (Figure 5, after Arai, 1994).

3.1.2. Orthopyroxene

The orthopyroxene content in Nghia Dan mantle xenoliths ranges from 19 to 25 vol.\% (Figure 3). The mineral is an enstatite showing a compositional range of \(\text{En}_{88.2-88.7}\text{Fs}_{5.5-6.4}\text{Wo}_{1.3-1.4}\). The Mg-number varies in a narrow range, from 89.3 to 90, about the range of co-existing olivine. The \(\text{Cr}_2\text{O}_3\) contents are low, from 0.27 to 0.33 wt.\%. The \(\text{Cr}_2\text{O}_3\) increase...
with increasing Al$_2$O$_3$, from 4.68 to 5.1 wt.%. The variation of Cr$_2$O$_3$, Al$_2$O$_3$ and TiO$_2$ concentrations (from 0.12 to 0.22 wt.%) may be small to notice the change in their corresponding Mg-number (Table 1).

Figure 5. Olivine - Spinel Mantle Array (OSMA) showing distribution fields of peridotites from various tectonic settings. Residual peridotites produced by high degrees of partial melting are refractory (and depleted), having high Cr-numbers and forsterite contents. Redrawn after Arai (1994), data for oceanic ridges and intraplate oceanic hotspots are from Choi et al. (2005), Workman and Hart (2005) and Warren (2016).

3.1.3. Clinopyroxene

The clinopyroxene is a diopside which constitutes 3 to 5 vol.%, in some rare cases up to 8-10 vol.% among the spinel lherzolite-forming minerals, showing a range of chemical compositions of En$_{47.9-48.9}$Fs$_{5.2-6.1}$Wo$_{45.1-46.1}$. The Mg-number increases with increasing enstatite component, from 88.9 to 90.4. The TiO$_2$ and Cr$_2$O$_3$ contents are moderate, from 0.6 to 0.7 wt.%, and from 0.65 to 0.74 wt.%, respectively. The Al$_2$O$_3$ concentrations vary from 7.1 to 7.5 wt.%, which are slightly higher as compared with those in Jeju mantle spinel-lherzolite and elsewhere in East Asia (Choi et al., 2001, 2008). Despite minor differences in geochemical composition, the Nghia Dan clinopyroxene is very much similar to clinopyroxene in mantle xenoliths in Cenozoic alkaline basalts in east and northeast China (Tatsumoto et al., 1992, Qi et al., 1995), the Japan Sea (Choi et al., 2001, 2008), and elsewhere in the Western Highlands, south-Central Vietnam, and southeastern continental shelf of East Vietnam Sea (Gorshkov, 1981; Fedorov and Koloskov, 2005; Malinovsky and Rashidov, 2015). The Nghia Dan mantle xenolith separated clinopyroxenes, however, have slightly higher wollastonite (Ca$_2$Si$_2$O$_6$) and (clino)-ferrosilite (Fe$_2$Si$_2$O$_6$) components, shifting more toward the hedenbergite field as compared to clinopyroxenes separated from mantle xenoliths in the (mid-)ocean ridges (after Johnson et al., 1990; Workman and Hart, 2005; Warren, 2016). Al$_2$O$_3$ and TiO$_2$ concentrations in Nghia Dan orthopyroxene and clinopyroxene are higher as compared with mid-ocean ridge mantle xenolith separated clinopyroxene (e.g. Workman and Hart, 2005; Warren, 2016). Experimental data suggested that the higher Al$_2$O$_3$ content in pyroxenes the higher melting temperature and pressure of the minerals (Kushiro, 1996).

3.2. Elemental geochemistry of Nghia Dan separated clinopyroxene

The trace element compositions of Nghia Dan clinopyroxene are given in Table 2. The data are normalized to the primitive mantle value (after Sun and McDonough, 1989), illustrated in Figure 6. Data of mantle xenolith separated clinopyroxenes from 1 Ma alkaline basalt in the Dat Do district (Ba Ria-Vung Tau) (Hoang unpublished data) are plotted for reference. The trace element distribution pattern of Nghia Dan clinopyroxene is relatively smooth, showing a gradual decrease from heavy, less mobile elements to lighter, highly incompatible elements. The observation suggests that the Nghia Dan mantle xenoliths may have experienced small melting degrees, and that, other than the effect of melting and
crystallization, Nghia Dan mantle peridotite residues may not undergo any significant post-melting process, such as melt addition or removal (as compared to, for example, the mantle xenolith in Dat Do alkaline basalt). In summary, the trace element distribution pattern of Nghia Dan clinopyroxene reflects typical geochemical characteristics of clinopyroxenes in alkaline basalt-borne mantle xenoliths (e.g. Embey-Isztin et al., 2001).

Figure 6. Trace element primitive mantle normalization of Nghia Dan clinopyroxene separate showing relatively smooth trend from moderately immobile to highly mobile elements (normalizing data are after Sun and McDonough, 1989). Shown are data for the host alkaline basalt and mantle xenolith-separated clinopyroxenes from Dat Do (Ba Ria - Vung Tau) for comparison. See text for details.

3.3. Isotope geochemistry of Nghia Dan mantle xenolith separated clinopyroxene

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios vary from 0.70249 to 0.70269, and $^{143}\text{Nd}/^{144}\text{Nd}$ range from 0.51322 to 0.51329 (Table 2). They plot in the depleted mantle field (DMM) along with several other Vietnamese separated clinopyroxenes, although most of the latter are more enriched than the Nghia Dan clinopyroxenes and plotting in the field of oceanic island basalts (Figure 7). In general, most (if not all) of the mantle xenolith separated clinopyroxenes in Vietnam are isotopically depleted and plot in the upper corner of the depleted quadrant differentiating from their host-basalts, suggesting that they are not genetically related. However, the isotope trending between depleted (e.g. N-MORB: mid-ocean ridge basalt) and enriched mantle (EM1, EM2) may suggest possible interaction of depleted mantle-derived melts with enriched sources in the lithospheric mantle (Figure 7). The isotopic characteristics of Nghia Dan mantle xenolith separated clinopyroxenes (and elsewhere in Vietnam) are mostly similar to clinopyroxenes separated from mantle xenoliths in alkaline basalts in northeast China (Tatsumoto et al., 1992) and Jeju island (Choi et al., 2005, 2008).

In summary, the elemental and radiogenic isotopic characteristics of the mantle xenolith and their host alkaline basalt are vastly different, implying, most certainly, that they are not genetically related. Moreover, thermal contacts between host basalt and mantle xenolith are commonly observed, suggesting that the mantle xenolith is brought to the surface by alkaline basaltic melt formed at deeper levels.
The basaltic melt must move up at a speed that is fast enough to tear off the mantle xenolith from its bed in the lithospheric mantle to bring to the surface (see Nixon (Editor), 1987; Qi et al., 1995; Choi et al., 2001; Embey-Isztin et al., 2001).

**Figure 7.** Plots of $^{87}$Sr/$^{86}$Sr versus $\varepsilon_{Nd} = \left(\frac{\text{Nd}}{\text{Nd}_{0}}\right) \times 10000$ of Vietnam alkaline basalt-borne mantle xenolith separated clinopyroxenes (empty circles; Hoang unpublished data) including Nghia Dan (red filled diamond) (Table 2) and host basalts (cross). Shown are fields of Depleted Mid-Ocean Ridge Basalt Mantle (N-MORB), Enriched Mantle type 1 and 2 (EM1 and EM2) (after Zindler and Hart, 1986); field of continental crust (CC) (after Taylor and McLennan, 1981) and Oceanic Island basalt (OIB Hawaii, after Norman and Garcia, 1999) for reference.

**4. Discussion**

**4.1. Mantle peridotite melting**

Compiled data of mantle peridotites from oceanic ridges and other tectonic settings worldwide showed that an upper mantle peridotite is averagely composed of (in vol.%) olivine (Ol: 57), orthopyroxene (Opx: 28), clinopyroxene (Cpx: 13) and spinel (Sp: 2). Partial melting of a peridotite having the above mentioned mineral assemblage to produce basaltic melt, according to a number of recent experimental studies (e.g. Takahashi and Kushiro, 1983; Takahashi, 1986; Johnson et al., 1990; Hirose and Kushiro, 1993; Kushiro, 1996, 1998), would occur in the following proportion (in vol.%) Ol: 10, Opx: 20, Cpx: 68, and Sp: 2. Moreover, the melting process is fractional rather than batch melting (Johnson et al., 1990).

Basic fractional melting equation to show the change in concentration of an element in clinopyroxene with melting was developed by Gast (1968) and Shaw (1970) as follows:

$$
\frac{C_i}{C_0} = \frac{\left(\frac{1}{1-F}\right) \left(1 - \frac{P_{f}}{D_{0}^{i}}\right)^{1/p}}{1^{1/p}} \quad (1)
$$

Where $C_i$ is the concentration of element $i$ in the residue ($s$) as a function of partial melting degree ($F$), $C_0$ is initial concentration of element $i$ and $D_{0}^{i}$ is bulk solid partition coefficient of element $i$. $P$ weighted partition coefficient of liquid:

$$
P = \Sigma p_{a} D_{a}^{i} = p_{\text{oliv}} D_{\text{oliv}}^{i} + p_{\text{opx}} D_{\text{opx}}^{i} + p_{\text{cpx}} D_{\text{cpx}}^{i} + p_{\text{spin}} D_{\text{spin}}^{i} \quad (2)
$$
\( D_i^\alpha \): partition coefficient of element \( i \) in \( \alpha \) mineral phase;

\( p_{\alpha} \): proportion of mineral phase entering liquid.

Because the bulk trace element abundance of upper mantle peridotite is mainly incorporated in clinopyroxene, Equation (1) therefore may be changed to (3) (e.g. Johnson et al., 1990):

\[
\frac{C_i^{\text{cpx}}}{C_i^{\text{bulk}}} = \left( 1 - \frac{P_F}{D_i^\alpha} \right)^{m-1} \tag{3}
\]

To apply equation (4) it needs to change bulk rock variable to clinopyroxene as follows:

\[
\frac{C_i^{\text{bulk}}}{C_i^{\text{cpx}}} = \left( \frac{D_{\text{bulk}}}{D_{\text{cpx}}} \right) \tag{4}
\]

\[
D_{\text{bulk}} = \sum x_\alpha D_i^\alpha - x_{\text{oliv}}D_i^{\text{oliv}} + x_{\text{opx}}D_i^{\text{opx}} + x_{\text{cpx}}D_i^{\text{cpx}} + x_{\text{spin}}D_i^{\text{spin}} \tag{5}
\]

Where \( x_\alpha \) is weight fraction of mineral phase.

Using equations 4 and 5, the trace element abundance of a peridotite can be interpolated from the trace element concentrations in clinopyroxene separated from the peridotite.

Applying equation 5 to the trace element concentration of Nghia Dan separated clinopyroxene (Table 2), trace element abundance of parental mantle peridotites can be determined. Depending on the bulk partition coefficient of elements in individual rock-forming minerals (Table 3), their constituents in a given peridotite and proportion of mineral entering the liquid (Table 4), and the melting degrees, the interpolated trace element abundances may be differently acquired. The computed data are shown in Table 4 and illustrated in Figures 8a, b.

**Table 3.** Elemental liquid/solid partition coefficients \( (D_{\text{liquid}}^{\alpha}) \) for rock-forming minerals of mantle peridotite

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**Table 4.** Mineral modal constituents of Nghia Dan alkaline basalt-bearing mantle xenoliths and rare earth element concentrations estimated for related mantle xenolith whole rock

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</tr>
<tr>
<td>La (ppm)</td>
<td>0.055</td>
<td>0.078</td>
<td>0.062</td>
<td>0.099</td>
<td>0.079</td>
</tr>
<tr>
<td>Ce</td>
<td>0.097</td>
<td>0.133</td>
<td>0.113</td>
<td>0.169</td>
<td>0.139</td>
</tr>
<tr>
<td>Pr</td>
<td>0.133</td>
<td>0.185</td>
<td>0.152</td>
<td>0.235</td>
<td>0.191</td>
</tr>
<tr>
<td>Nd</td>
<td>0.203</td>
<td>0.279</td>
<td>0.234</td>
<td>0.354</td>
<td>0.290</td>
</tr>
<tr>
<td>Sm</td>
<td>0.343</td>
<td>0.460</td>
<td>0.400</td>
<td>0.577</td>
<td>0.483</td>
</tr>
<tr>
<td>Eu</td>
<td>0.394</td>
<td>0.522</td>
<td>0.463</td>
<td>0.652</td>
<td>0.552</td>
</tr>
<tr>
<td>Gd</td>
<td>0.401</td>
<td>0.524</td>
<td>0.474</td>
<td>0.649</td>
<td>0.556</td>
</tr>
<tr>
<td>Tb</td>
<td>0.504</td>
<td>0.647</td>
<td>0.596</td>
<td>0.795</td>
<td>0.691</td>
</tr>
<tr>
<td>Dy</td>
<td>0.574</td>
<td>0.724</td>
<td>0.681</td>
<td>0.882</td>
<td>0.776</td>
</tr>
<tr>
<td>Ho</td>
<td>0.627</td>
<td>0.777</td>
<td>0.744</td>
<td>0.937</td>
<td>0.836</td>
</tr>
<tr>
<td>Er</td>
<td>0.714</td>
<td>0.869</td>
<td>0.845</td>
<td>1.038</td>
<td>0.938</td>
</tr>
<tr>
<td>Tm</td>
<td>0.675</td>
<td>0.821</td>
<td>0.798</td>
<td>0.980</td>
<td>0.887</td>
</tr>
<tr>
<td>Yb</td>
<td>0.787</td>
<td>0.928</td>
<td>0.923</td>
<td>1.085</td>
<td>1.002</td>
</tr>
<tr>
<td>Lu</td>
<td>0.803</td>
<td>0.934</td>
<td>0.937</td>
<td>1.082</td>
<td>1.007</td>
</tr>
</tbody>
</table>
Figure 8a, b. Chondrite normalized computed rare earth element abundance produced by fractional melting (Eq. 1); A%M and A%R: rare earth element composition of melt (M) or residue (R) produced by A melting degree (8a, left); rare earth element chondrite normalized distribution pattern of Nghia Dan clinopyroxene (thick, red line) and corresponding residual parental peridotite (thin, red lines) according to different mineral constituents (8b, right). Shown for comparison are clinopyroxene separate and their residual peridotite from Dat Do (Ba Ria- Vung Tau), and clinopyroxene (DM_Cpx) separated from the representative depleted mantle peridotite (Computing template is after Workman and Hart, 2005; Warren, 2016). Normalizing data are after Anders and Grevesse (1989).

By interpolation, the trace element contents of Nghia Dan clinopyroxene may be obtained by melting degree between 8 to 12% (Figures 8a, b) of a mantle peridotite which is relatively depleted (and refractory). The Nghia Dan clinopyroxene is more depleted in light rare earth element concentrations as compared to an average mid-ocean ridge peridotite separated clinopyroxene (DM-Cpx) (Figure 8b), suggesting that the Nghia Dan mantle xenolith may have experienced multiple melting events (Takahashi, 1986; Hirose and Kushiro, 1993). Note that clinopyroxenes separated from Dat Do mantle xenoliths (Ba Ria - Vung Tau) show strong geochemical heterogeneity, suggesting mantle peridotites in the lithospheric mantle may undergo various melting events and/or melt addition or removal (Carlson and Irving, 1994) (Figure 8b).

4.2. Thermal state of the lithospheric mantle under Nghia Dan

A number of geothermometers for applicable mineral assemblages of mantle peridotite xenoliths have been introduced over the years. Equilibrium temperatures may be estimated using geothermometers based on (1) enstatite component of coexisting two pyroxenes (Wells, 1977; Brey and Kohler, 1990), (2) Al-solubility in orthopyroxene coexisting with olivine and spinel (Sachtliche and Seck, 1981; Webb and Wood, 1986); (3) Mg-Fe²⁺ exchange between olivine and spinel (Ballhaus et al., 1991); (4) concentration of Group II elements (Cr, Al, Sc, Ca and Na) in mantle peridotite olivine (De Hoog et al., 2010). Brey and Köhler (1990), following many testing combinations of geothermobarometers, suggested that the geobarothermometer of Köhler and Brey (1990) may provide a reasonable T-P estimate for spinel peridotite.

Experimentally, Putirka et al. (1996), followed by Putirka et al. (2003) developed equations (1) and (2) two-pyroxene pressure and temperature estimates. Equation (2) has been improved from a previous equation by Putirka (2008, 2017).

\[
P(kbar) = -88.3 + 2.82 \times 10^{-3} T(K) \ln[Jd^{Cpx}]/
\]
\[ [\text{Na}^{\text{liq}} \text{Al}^{\text{liq}} (\text{Si}^{\text{liq}})^2] + 2.19 \times 10^{-2}T(\text{°K}) - 25.1 \ln[\text{Ca}^{\text{liq}} \text{Si}^{\text{liq}}] + 7.03[\text{Mg}^{\text{liq}}] + 12.41 \ln[\text{Ca}^{\text{liq}}] \]

\[ P(\text{kbar}) = -26.3 + 39.2 \times 10^{-4}T(\text{K}) \left( \frac{X_{\text{Cpx}}^{\text{cpx}}}{(X_{\text{Na}^{0.5}}^{\text{liq}})(X_{\text{AlO}^{1.5}}^{\text{liq}})(X_{\text{SiO}^{2}}^{\text{liq}})^2} \right) - 4.22\ln[\text{DiHd}^{\text{Di}] + 78.4\text{X}_{\text{AlO}^{1.5}}^{\text{liq}} + 12.41\text{X}_{\text{Na}^{0.5}}^{\text{liq}} + 7.03\text{M}_{\text{MgO}^{\text{liq}}} + 7.03\text{M}_{\text{MgO}^{\text{liq}} + \text{Fe}^{\text{liq}}}] \]  

The temperature is in Kelvin, pressure is in kbar, \(J_{\text{Cpx}}\) is molecule component of jadeite in clinopyroxene, number of cations in pyroxene are calculated based on 6 oxygen atoms. \(D_{\text{DiHd}}\) is molecule component of diopside and hedenbergite in clinopyroxene. \(A_{\text{Di}}\) is \(\text{AlO}_{1.5}\) cation content in melts, \(\text{MgO}^{\text{liq}}\) is cation content of \(\text{MgO}^{\text{liq}}/ (\text{MgO}^{\text{liq}} + \text{Fe}^{\text{liq}})\). See Putirka et al. (1996, 2003) and Putirka (2008) for more details.

The computed pressure and temperature of mineral assemblages in Nghia Dan mantle peridotites basing on coexisting pyroxenes using equations (1) and (2) (Putirka et al., 1996, 2003; Putirka, 2008, 2017) are shown in Table 5. The estimated data are compared with the temperatures calculated using approaches by Wells (1977) and Brey and Köhler (1990). The temperatures estimated for coexisting pyroxenes in Nghia Dan mantle xenoliths using equations of Putirka et al. (1996, 2003) and Putirka (2008, 2017) are about 30°C lower as compared to those using equations of Wells (1977), Brey and Kohler (1990) and De Hoog et al. (2009) (Figure 9).

**Table 5.** Two-pyroxene temperature - pressure estimates and observed \(K_{\text{D}}(\text{Fe-Mg})\) values for Nghia Dan mantle xenoliths (computed after Putirka, 2008). Shown for comparison are two-pyroxene crystallization temperatures by Brey and Kohler (1990) method

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Temperature (°C)</th>
<th>Pressure (kbar)</th>
<th>(K_{\text{D}}(\text{Fe-Mg}))</th>
<th>Brey &amp; Kohler (1990) °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>B040313-16Cpx/1</td>
<td>1023.5</td>
<td>13.1</td>
<td>1.053</td>
<td>1079.1</td>
</tr>
<tr>
<td>B040313-16Cpx/2</td>
<td>1029.3</td>
<td>13.9</td>
<td>1.053</td>
<td>1081.0</td>
</tr>
<tr>
<td>B040313-16Cpx/3</td>
<td>1011.3</td>
<td>13.4</td>
<td>0.948</td>
<td>1051.7</td>
</tr>
<tr>
<td>B040313-16Cpx/4</td>
<td>1023.9</td>
<td>13.6</td>
<td>1.014</td>
<td>1076.9</td>
</tr>
<tr>
<td>B040313-16Cpx/5</td>
<td>1034.4</td>
<td>14.1</td>
<td>1.070</td>
<td>1067.7</td>
</tr>
<tr>
<td>A040313-7Cpx/1</td>
<td>1016.9</td>
<td>14.1</td>
<td>0.927</td>
<td>1072.9</td>
</tr>
<tr>
<td>A040313-7Cpx/2</td>
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<td>13.6</td>
<td>1.051</td>
<td>1051.3</td>
</tr>
<tr>
<td>A040313-7Cpx/3</td>
<td>1009.0</td>
<td>13.8</td>
<td>1.050</td>
<td>1048.0</td>
</tr>
<tr>
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<td>14.1</td>
<td>1.121</td>
<td>1076.7</td>
</tr>
<tr>
<td>A040313-7Cpx/5</td>
<td>1027.2</td>
<td>14.2</td>
<td>1.050</td>
<td>1071.2</td>
</tr>
</tbody>
</table>

(*) www.minsocam.org/MSA/RIM/RiMG069/RiMG069_Ch03_two-pyroxene_P-T.xls

Figure 9. Plots of temperature estimates for equilibrium two-pyroxenes in Nghia Dan mantle xenoliths using geothermometers of Wells (1977), Brey and Kohler (1990) versus Putirka (2008, 2017). Data for Pleiku (Western Highlands) and Tro Islet (Ile des Cendres, East Vietnam Sea) mantle xenoliths (Hoang unpublished data) are shown for reference.

### 4.3. Geotherm beneath Western Nghe An

Cenozoic basaltic volcanism in the Western Highlands of Vietnam was driven by the regional thermally anomalous mantle fol-
followed by lithospheric extension (e.g. Garnier et al., 2005; Izokh et al., 2010, and references therein). Using primitive melt compositions computed for Cenozoic basalts from the Western Highlands, and elsewhere in the offshore and coastal areas of Vietnam to interpolate melting temperatures and pressures of the basalts by correlating with experimental mantle peridotite melting data (e.g. Takahashi and Kushiro, 1983; Kushiro, 1990, 1996, 1998; Hirose and Kushiro, 1993) Hoang et al. (2014) reported that mantle beneath Vietnam is hotter than normal (e.g. 1280°C), reaching up to 1380°C. The thermally anomalous mantle has been viewed as a consequence of the India- Eurasian collision that led to the Tethys closure, uplift of Himalaya and Tibet, subduction initiation under the Himalaya (Tapponnier et al., 1982, 1990), and collision-induced east-west mantle injection (Tamaki, 1995). The extrusion (injection) of deep, (thus) hot mantle flow to east and southeast Asia was the main cause of mantle perturbation and temperature upsurge, leading to mantle melting and wide-spread basaltic volcanism in the region regardless of the regional lithospheric extension factor is small (after Latin and White, 1990).

The crystallization temperature was estimated for various mineral assemblages in alkaline basalt-bearing spinel-lherzolites in the Western Highlands and Southeastern region of Vietnam using the geothermometer of De Hoog et al. (2009), showed a temperature range of 850-1150°C and pressure varying from 14 to 25 kbar (Hoang unpublished data). A geotherm constructed for Western Highlands, Southeastern region and Nghia Dan is shown in Figure 10, lying between two conductive geothermal lines in post-Phanerozoic continental lithosphere for heat flow of 80 to 90 mW/m², respectively (after Pollack and Chapman, 1977). The Nghia Dan geothermal gradient (1020-1045°C corresponding to pressure range of 13-14.2 kbar, Table 1) is higher than that of conductive model and even higher as compared with that of Western Highlands and Southeastern region of Vietnam (Figure 10), suggesting a perturbation of thermal structure in the lithospheric mantle under the relating region (e.g. Hoang et al., 2014).

![Figure 10. A geotherm for Nghia Dan determined by spinel lherzolite (thick dashed line) using two-pyroxene geothermobarometers by Putirka et al. (1996, 2003) and Putirka (2008, 2017). Thin solid lines are model conductive geotherms of continental areas with surface heat flows from 30 to 90mW/m² (Pollack and Chapman, 1977). Thin dashed line (tm) thermally normal mantle adiabatic line ca. 1280°C, Thick continuous line (TM) continuous line, elevated temperature adiabatic, ca. >1380°C (Hoang unpublished. Shown for comparison are mantle xenoliths from Pleiku: red filled diamonds, Tro islet (Ile des Cendres): white filled square (Malinovsky and Rashidov, 2015), Western Highlands and Southeastern region of Vietnam: filled rectangle (Hoang unpublished data). 4.4. Lithospheric mantle dynamics under Western Nghe An

Any process causing isotope disequilibrium, for example, melt extraction, source mixing or crustal assimilation to the isotopic systems such as Sm-Nd, Lu-Hf, Rb-Sr… can be traceable and determined, especially for the systems that are durable to secondary alteration such as Sm-Nd and Lu-Hf (Carlson and Lugmair, 1979, 1981; DePaolo and Wasserburg, 1976; DePaolo, 1981).
Determination of Sm-Nd model age for alkali basalt-borne mantle xenolith is one of the ways to understand geodynamic processes causing isotope disequilibrium to the isotopic system before the xenolith being brought to the surface. Suppose the lithospheric mantle was formed about 3 Ga following the mantle melting to form the crust. Any major geodynamic event having occurred in the lithospheric mantle after the 3 Ga time causing isotopic perturbation and changing the evolutional trend of the isotopic system may be determined using basic isotopic parent-daughter relationship (see footnote in Table 2). The model age for Nghia Dan spinel lherzolites varies between 122 and 127 million years (Table 2). Assuming the computed the age could be significant, it would mean that there was a major geodynamic event having occurred in the lithospheric mantle in the mid-Early Cretaceous (Aptian).

**Figure 11.** Plots of \(^{143}\text{Sm}/^{144}\text{Nd}\) vs. \(^{143}\text{Nd}/^{144}\text{Nd}\) of Nghia Dan spinel lherzolite separated clinopyroxene (red filled diamond); shown for reference are clinopyroxene separated from mantle xenoliths collected in the Western Highlands (Pham Tich Xuan, personal communication). Host basalts (cross) are shown for comparison

### 5. Conclusions

From the above descriptions the following conclusions may be drawn:

The mantle xenoliths in Pliocene alkaline basalts in Nghia Dan (West Nghe An) are geochemically depleted spinel lherzolites. They are residual entities of mantle peridotite melting from 8 to 12% that became basic components of the lithospheric mantle before being brought to the surface by basaltic melt.

Temperature and pressure estimates for mineral assemblages in Nghia Dan mantle xenoliths by various geothermobarometers vary from 1020 to 1050°C and 13 to 14.2 kbar (ca. 40 to 43 km), having much higher geothermal gradient as compared to that of the conductive model. This observation is supported by previous studies of mantle thermal state under Western Highland and elsewhere in Vietnam that the mantle in the region is anomalously higher than normal by 50 to 100°C.

Sm-Nd model age calculated for Nghia Dan mantle xenolith separated clinopyroxene yielded 127 and 122 Ma (mid-Early Cretaceous). Assuming the model age is meaningful there would be a major geodynamic event having occurred under Western Nghe An during this period, large enough to cause perturbation in the Sm-Nd isotopic system.

### Acknowledgments

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