Oligo-Miocene granitic magmatism in central Vietnam and implications for continental deformation in Indochina

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ABSTRACT

Two granitoid intrusions within the Bu Khang extensional complex in central Vietnam have been dated by U–Pb and Rb–Sr geochronology. A monazite U–Pb age of 26.0 ± 0.2 (2σ) Myr was obtained for the Bu Khang pluton and 23.7 ± 1.6–1.7 Myr for monazite, allanite and zircon from the Dai Loc intrusion. These ages date crystallization of magmas previously assigned Precambrian to Devonian. Rb–Sr analyses of K-feldspar and biotite fractions from the samples yield ages of 19.8 ± 0.6 (2σ) Myr and 19.6 ± 0.5 Myr, respectively. The thermal history recorded by the different geochronometers implies an average exhumation rate of ~2 mm yr−1 corresponding to ~9 km of unroofing. Magmatism was either (i) induced passively by lithospheric thinning driven by changes in regional tectonic stresses, or (ii) triggered actively by an ascending plume. Tertiary exhumation and magmatism documented elsewhere in Indochina (e.g. Ailao Shan–Red River and Wang Chao shear zones) favours a regional tectonic cause for extension and granitoid magmatism in the Bu Khang complex. On the other hand, the presence of an upwelling thermal anomaly since at least 35 Ma, causing mantle melting below Indochina, is supported by shear-wave velocity variations in the mantle, and source geochemistry of both the Bu Khang plutons and the Red River belt intrusions. In either case, Tertiary exhumation of the Bu Khang complex can account for previously undocumented NE–SW-directed extension, which is required in northern Vietnam to account for structural changes related to the opening of the South China Sea.

Terra Nova, 12, 67–76, 2000

Introduction

The kinematic, spatial, and temporal relationships between thrusting, strike-slip transpression, exhumation, and extension associated with postcollisional deformation in the India–Eurasia orogenic belt are still a matter of debate. For example, Cenozoic deformation in Indochina may have occurred diachronously from south to north (e.g. Tapponnier et al., 1986), or contemporaneously throughout the entire peninsula (e.g. Dewey et al., 1989). We address some of the general questions concerning intraplate deformation by reporting the first U–Pb and Rb–Sr dates and Pb–Sr–Nd initial signatures for the Bu Khang extensional complex of north-central Vietnam. By comparing these results with the evolution of major shear zones in Indochina, we show that extension-related magmatism in the Bu Khang dome occurred coevally with transpression-related magmatism in the Red River shear zone, and extensional deformation in Thailand.

As illustrated in Fig. 1(a), the regional geological structure of central and northern Vietnam is dominated by a series of NW-trending shear zones, extending northwards into Laos and China and terminating eastwards at the South China Sea (e.g. the Song Da, Song Ma and Song Ca shear zones).

The Bu Khang complex (Fig. 1b) is a NW–ESE-trending antiformal extensional dome composed of metamorphic and mildly deformed intrusive rocks (e.g. Jolivet et al., 1999). We have analysed two intrusive bodies from the Bu Khang Formation and the Dai Loc Complex which had been previously assigned Precambrian to Devonian ages, based primarily on the general interpretation that crystalline rocks in this region represent basement below Panerozoic cover (e.g. Tran Van Tri, 1979; Geological Survey of Vietnam, 1995). For continuity we retain the formation names given by Geological Survey of Vietnam (1995), and emphasize that the Dai Loc Complex in this study is unrelated to the Dai Loc Massif (mica age: ~245 Myr) in the Da Nang area ~500 km to the south-east (Lepvrier et al., 1997).

The roughly NW-striking, NE-dipping Quy Chau normal shear zone on the northeastern margin of the Bu Khang dome separates the igneous and metamorphic core from overlying terrigenous metasediments and marbles, all of which experienced maximum metamorphic conditions of 1.2 GPa and 670°C (Geological Survey of Vietnam, 1995; Jolivet et al., 1999). Thermometry and barometry calculations and 40Ar/39Ar synkinematic mica ages from micaceous, gneisses, and granites from the core and Quy Chau shear zone, as well as from the marble cover rocks, suggest that the major period of extension and exhumation of metamorphic rocks spanned 36–21 Ma, younging progressively from the south-west to the north-east where deformation finally localized along the Quy Chau shear zone (21 Ma; Lepvrier et al., 1997; & Lepvrier 1998; Jolivet et al., 1999). In addition to substantiating the age of magmatism, our U–Pb and Rb–Sr dating results yield further constraints on the rates of cooling and exhumation of the Bu Khang dome.

Sample description and analytical procedures

Samples were collected along the northern margin of the Bu Khang complex...
(locations in Fig. 1b) from the lower Bu Khang Formation (VGS-32), which consists of two-mica sillimanite schists and biotite-sillimanite plagiogneisses, and the Dai Loc complex (VGS-33), which consists of granite gneisses, weakly deformed plagiogneiante, and porphyric two-mica granites (Geological Survey of Vietnam, 1995). The samples plot in the granodiorite and granite fields of the total alkali vs. silica diagram (Fig. 2a) and are referred to hereafter as the Bu Khang and the Dai Loc plutons, respectively. REE patterns of these intrusions are shown in Fig. 2(b), relative to Perno-Triassic plutons in Vietnam. A sample of the Bu Khang pluton (VGS-32) was collected at an abandoned excavation site of a local ruby mine; heat carried by the intrusion may have been responsible for contact metamorphism within the marble country rocks generating the gemstones. The intrusion is gneissoid and consists of quartz, K-feldspar, plagioclase, biotite, muscovite, garnet, sillimanite, and monazite. Garnet shows evidence for static retrograde reactions resulting in a fine-grained matrix around opaque minerals. Similarly, the plagioclase shows decomposition to epidote plus albite indicative of low-temperature, retrograde metamorphism. The Dai Loc pluton (VGS-33) contains quartz, K-feldspar, biotite, plagioclase, apatite, zircon, monazite, and allanite, and exhibits mild preferential orientation of biotite (magmatic foliation). It is cut by unaltered pegmatites.

Both intrusions show petrographic evidence of brittle deformation, which produced broken grains of quartz and plagioclase oriented subparallel to the mild foliation of minerals such as primary, igneous mica. This brittle, low-temperature deformation clearly postdates the crystallization of principal magmatic phases and probably reflects an exhumation-related fabric. This low-grade event was largely static in the Dai Loc pluton, whereas it was associated with shearing in the Bu Khang pluton. There is no evidence for recrystallization associated with high-temperature metamorphism. These observations demonstrate that the high-temperature accessory minerals dated in this study (zircon, monazite, allanite) represent primary magmatic phases and not recrystallized, metamorphic minerals.

Chemical analysis of powdered whole rock from each sample was performed using Emission-ICP for major element determinations, and ICP-MS for trace and Rare Earth Element (REE) analyses (Table 1). U-Pb and Rb-Sr analyses were performed using the isotope dilution method on grain-
Fig. 2 Geochemical results illustrated by (a) total alkali-silica diagram using boundary positions after Le Bas et al. (1986), and (b) REE patterns normalized to chondritic composition (normalizing values from Anders and Ebihara, 1982). In addition to the two Oligocene–Miocene samples dated in this study, data from four local Permo-Triassic rocks are shown for comparison. The samples are from northwestern Vietnam near the Song Ma shear zone (granite from Dien Bien Phu) and the Song Ca shear zone (all others: Nagy and Schärer, unpublished data).

U–Pb and Rb–Sr geochronology

U–Pb and Rb–Sr analytical results are listed in Tables 2 and 3, respectively, and corresponding concordia and isochron diagrams are displayed in Fig. 3. All U–Pb dates were corrected for initial common Pb as determined on leached coexisting K-feldspar (Table 4). The analytical results for monazite and allanite are also corrected for excess $^{206}$Pb originating from initial disequilibrium amounts of $^{238}$Th (Schärer, 1984). To perform this correction we used the Th/U ratio measured in the rock (Table 2).

Monazites in both samples are euhe- dral, transparent, and inclusion-free grains of excellent quality. Typical yellow-coloured monazite grains are particularly abundant in the Bu Khang pluton, which lacks zircons. The Dai Loc intrusion contains dark red monazite, opaque to dark red euhe- dral allanite, and euhe- dral, transparent, short to medium prismatic zircons. Cores or overgrowths within the zircons were
Table 2 U–Pb analytical results for zircons, monazites, and allanites from the Bu Khang

<table>
<thead>
<tr>
<th>Sample description¹</th>
<th>Mass (mg)</th>
<th>Concentration (ppm)</th>
<th>206Pb/204Pb measured²</th>
<th>Radiogenic Pb in atomic %³</th>
<th>Atomic ratios³</th>
<th>Apparent ages in Myr³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bu Khang pluton (VGS-32), 17 km east of Quy Chau</td>
<td>6176</td>
<td>0.0551</td>
<td>104</td>
<td>997</td>
<td>20.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Monazite fractions:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) (M139) 6 medium to large yellow grains, transparent, abraded</td>
<td>7497</td>
<td>0.0692</td>
<td>112</td>
<td>846</td>
<td>23.4</td>
<td>1.1</td>
</tr>
<tr>
<td>(2) (M140) 8 medium to large yellow grains, transparent, abraded</td>
<td>8320</td>
<td>0.0548</td>
<td>106</td>
<td>461</td>
<td>26.9</td>
<td>1.3</td>
</tr>
<tr>
<td>(3) (M141) 5 large yellow grains, transparent, abraded</td>
<td>7271</td>
<td>0.0699</td>
<td>110</td>
<td>1117</td>
<td>23.2</td>
<td>1.1</td>
</tr>
<tr>
<td>(4) (M146) 3 large yellow grains, transparent, abraded</td>
<td>7623</td>
<td>0.0434</td>
<td>110</td>
<td>516</td>
<td>23.8</td>
<td>1.1</td>
</tr>
<tr>
<td>(5) (M147) 11 medium to large yellow grains, transparent, abraded</td>
<td>8431</td>
<td>0.0546</td>
<td>105</td>
<td>368</td>
<td>25.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Dai Loc pluton (VGS-33), 30 km east of Quy Chau</td>
<td>1459</td>
<td>0.0831</td>
<td>6.0</td>
<td>1371</td>
<td>83.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Zircon fractions:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(7) (Zm13) 4 large prismatic grains, transparent, abraded</td>
<td>3597</td>
<td>0.0525</td>
<td>13.8</td>
<td>269</td>
<td>83.8</td>
<td>4.0</td>
</tr>
<tr>
<td>(8) (Z108) 14 large prismatic grains, transparent, nonabraded</td>
<td>1417</td>
<td>0.0347</td>
<td>5.7</td>
<td>167</td>
<td>81.1</td>
<td>4.0</td>
</tr>
<tr>
<td>(9) (Z112) 7 large elongate grains, transparent, abraded</td>
<td>3957</td>
<td>0.1168</td>
<td>30.3</td>
<td>129</td>
<td>40.6</td>
<td>2.0</td>
</tr>
<tr>
<td>Allanite fraction:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 (10) (A144) 7 large elongate red to honey-brown grains, nonabraded</td>
<td>3285</td>
<td>0.1112</td>
<td>123</td>
<td>940</td>
<td>79.7</td>
<td>3.9</td>
</tr>
<tr>
<td>Monazite fraction:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(11) (M143) 3 large, short prismatic, dark red grains, nonabraded</td>
<td>1495</td>
<td>0.0170</td>
<td>23.4</td>
<td>1878</td>
<td>79.8</td>
<td>5.1</td>
</tr>
<tr>
<td>Zircon fraction:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(12) (Zm14) 26 medium to large equant grains, transparent, strongly abraded</td>
<td>7189</td>
<td>0.0680</td>
<td>38.3</td>
<td>34</td>
<td>59.4</td>
<td>2.5</td>
</tr>
</tbody>
</table>

See next page for footnote

¹ See next page for footnote.
Footnote to Table 2

1. Individual analyses were performed on euhedral, unbroken, crack free grains of highest transparency possible. Medium-size grains are 80–120 mm long, and large grains are >120 mm long. Zircons were dissolved in HCl > 50% at 220 °C for 4 days in Teflon bombs, the chemical procedure is from Krogh (1973), and abrasion was performed according to Krogh (1982). U decay constants used are those determined by Jaffey et al. (1971) as recommended by Steiger and Jäger (1977). For isotopic measurements, Pb and U were loaded together on single Re filaments with Si-gel and H2PO4 and run at 1350–1450 °C and 1450–1550 °C, respectively, on a Thomson 206 solid source mass-spectrometer. Mass-discrimination is 0.10 ± 0.05%/amu for Pb and U.

2. Ratio corrected for mass-discrimination and isotopic tracer contribution.

3. Corrected for mass-discrimination, isotopic tracer contribution, 15 pg of Pb blank, 1 pg of U blank, and initial common Pb (Table 4) as determined in leached coexisting feldspars (Schärer, 1991) from the samples. Together with mass-spectrometric precisions and uncertainties from spike calibration, such correction for initial Pb yields analytical uncertainties of 0.5–0.7% for 206Pb/238U, 0.6–1.0% for 207Pb/235U, and about 0.2–0.5% for 208Pb/232Th, dependent on 206Pb/204Pb measured.


not observed microscopically, although inherited radiogenic Pb was detected in one of the fractions analysed (Fig. 3).

Six monazite fractions from the Bu Khang pluton yield four identically concordant dates, a slightly discordant fraction, and a date plotting above concordia, even after correction for excess 206Pb (Fig. 3a). The slightly discordant fraction can be explained by the presence of a small inherited component, whereas the fraction plotting above concordia is ascribed to a substantially larger excess of initial 230Th than observed in the other fractions. Given the younger age of this fraction it seems likely that these grains crystallized at a later time when the liquid (or solid) from which the grains formed had a significantly higher Th/U ratio. The four concordant fractions give an average 206Pb/238U age of 25.9 ± 0.3 (2σ) Myr and 207Pb/235U age of 26.1 ± 0.3 Myr, yielding a mean value of 26.0 ± 0.2 Myr.

Zircon, allanite and monazite grains were measured from the Dai Loc pluton. One zircon fraction is highly discordant, whereas all other mineral fractions plot close to the concordia curve (Fig. 3b; see inset for detail). Allanite and monazite scatter around 24 Myr, and zircons plot along a regression line yielding intercept ages at 23.7 ± 1.6–1.7 Myr and 901 ± 26 Myr, with the latter approximating the age of crustal components in the magma source region. As observed for one of the monazite fractions from the other intrusion, one

### Table 3 Rb–Sr analytical results from the Bu Khang and Dai Loc plutons

<table>
<thead>
<tr>
<th>Sample</th>
<th>Concentrations (ppm)</th>
<th>Atomic ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rb</td>
<td>Sr</td>
</tr>
<tr>
<td>Bu Khang pluton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-feldspar</td>
<td>334</td>
<td>32.6</td>
</tr>
<tr>
<td>biotite-1</td>
<td>746</td>
<td>2.5</td>
</tr>
<tr>
<td>biotite-2</td>
<td>598</td>
<td>3.4</td>
</tr>
<tr>
<td>biotite-3</td>
<td>667</td>
<td>4.3</td>
</tr>
<tr>
<td>Dai Loc pluton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-feldspar</td>
<td>184</td>
<td>90.3</td>
</tr>
<tr>
<td>biotite-1</td>
<td>1000</td>
<td>3.2</td>
</tr>
<tr>
<td>biotite-2</td>
<td>1008</td>
<td>1.4</td>
</tr>
<tr>
<td>biotite-3</td>
<td>1200</td>
<td>1.8</td>
</tr>
</tbody>
</table>

A mixed spike of 85Rb-84Sr was used for the concentration measurements. Rb–Sr analyses of whole rocks and feldspars were spiked prior to dissolution, whereas micas were measured on individually spiked aliquot solutions. Analytical uncertainties on 87Sr/86Sr norm refer to the last digit given and 87Sr/86Sr is normalized to 86Sr/86Sr = 0.1194. Mass-spectrometric measurements were performed on a Thomson-206 instrument, equipped with a double Faraday collector for Sr isotope compositions, and an independent Faraday collector for Rb and Sr concentration measurements. The decay constant is 1.42·10^{-11} yr^{-1} (Steiger and Jäger, 1977).

### Table 4 Rb–Sr (K-feldspar), Sm–Nd (whole rock), and initial Pb (K-feldspar) analytical results

<table>
<thead>
<tr>
<th>Sample</th>
<th>87Rb/86Sr</th>
<th>87Sr/86Sr norm</th>
<th>143Nd/144Nd</th>
<th>147Sm/144Nd</th>
<th>143Nd/144Nd norm</th>
<th>147Sm/144Nd</th>
<th>143Nd/144Nd</th>
<th>εNd</th>
<th>εNd</th>
<th>87Sr</th>
<th>εSr</th>
<th>Initial 206Pb/204Pb</th>
<th>Initial 207Pb/204Pb</th>
<th>Initial 208Pb/204Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bu Khang Pluton</td>
<td>3.0</td>
<td>0.71970 ± 3</td>
<td>0.70862</td>
<td>0.095</td>
<td>0.512017 ± 7</td>
<td>0.51200</td>
<td>-11.8 ± 0.1</td>
<td>+ 58.9 ± 4</td>
<td>18.935</td>
<td>15.737</td>
<td>39.629</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dai Loc Pluton</td>
<td>5.98</td>
<td>0.71726 ± 2</td>
<td>0.71522</td>
<td>0.11</td>
<td>0.512117 ± 5</td>
<td>0.51210</td>
<td>-9.9 ± 0.1</td>
<td>+ 153 ± 2</td>
<td>19.186</td>
<td>15.830</td>
<td>40.007</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Rb, Sr, Sm, and Nd concentrations are given in Table 1. Nd compositions were measured on a VG-SA mass spectrometer at the University of Toulouse, France, regularly controlled by measurements of the La Jolla Nd-standard. All chemical procedures performed in Paris. Nd was separated from Sm following the technique described in Richaid et al. (1976).

1. Normalized to 86Sr/86Sr = 0.1194 and 146Nd/144Nd = 0.7219. Uncertainties for normalized values are given in the table relative to the last digit of the ratios measured.

2. Initial values calculated with t = 26 Myr for VGS-32 and t = 24 Myr for VGS-33. Decay constants are 1.42e11 yr for 87Rb (Steiger and Jäger, 1977) and 6.54e12 yr for 147Sm (Lugman and Marti, 1978).

3. 147Sm/144Nd chic = 0.1967 and 143Nd/144Nd chic = 0.512638.

4. Rb/Sr, Sr, and Nd concentrations are given in Table 1. Nd compositions were measured on a VG-SA mass spectrometer at the University of Toulouse, France, regularly controlled by measurements of the La Jolla Nd-standard. All chemical procedures performed in Paris. Nd was separated from Sm following the technique described in Richaid et al. (1976).

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allanite fraction plots above concordia (after excess $^{206}$Pb correction), which can again be ascribed to fast changes of Th/U ratios during solidification of the magma. Monazite from the Dai Loc pluton plots slightly below the concordia curve, suggesting a combined effect of minor inheritance and slight Pb-loss. A regression of all data gives intercept ages of $22.5 \pm 1.6/-1.7$ and $881 \pm 26$ Myr; both ages are identical to the intercept ages calculated exclusively from the zircons.

K-feldspar and different size fractions of biotite from the two intrusions were analysed for Rb-Sr. One K-feldspar and two biotite fractions from the Bu Khang pluton lie on a regression line, the slope of which yields an age of $19.8 \pm 0.6$ (2$\sigma$) Myr (Fig. 3c), whereas a third biotite fraction plots slightly above. This deviation may have resulted from minor loss of Rb during fluid circulation, as supported by the relatively high volatile loss of 5 wt% in the rock (LOI, Table 1) and abundant ore mineralizations (Sn and As) in the region (e.g. United Nations Publications, 1990). A regression of all four analyses gives an age of $21.1 \pm 0.5$ Myr. Minor disequilibrium is similarly apparent in the Dai Loc pluton (Fig. 3d). K-feldspar and two biotite fractions define an isochron age of $19.6 \pm 0.5$ Myr, whereas a third biotite fraction, lying above the line, is again ascribed to minor Rb loss due to fluid circulation. Such loss was perhaps facilitated by the high Rb concentrations.
of these biotites (in excess of 1000 ppm; Table 3). Regressing all four mineral analyses from the Dai Loc pluton yields an isochron age of 21.2 ± 0.5 Myr.

**Geochemistry and thermal history**

Although the plutons plot in the granite and granodiorite fields in a total alkali–silica diagram as described above (Fig. 2a), major, trace, and REE analyses (Table 1) show that the rocks are different from typical subduction-related, calc-alkaline series. For example, there is an absence of Mn and Mg, very low Ca, and high K, all of which contrast with the expected chemical differentiation of calc-alkaline rocks. In addition to the original nature of melted crustal material, chemical exchange during later hydrothermal activity may have contributed to the geochemical patterns of the plutons. This could also account for the relatively low Na and Nb/Ta concentrations in our samples (e.g., Harris et al., 1983). As mentioned, widespread Sn and As mineralizations in the Bu Kang region substantiate the occurrence of such hydrothermal activity.

The two samples are LREE-enriched (Fig. 2b), and the Dai Loc pluton is particularly enriched overall relative to chondrites as well as Permian-Triassic granites from the region. Both samples have significant Eu anomalies, suggesting plagioclase fractionation either in the magma source rocks, the parent magma, or during differentiation of the ascending magma; this is also supported by low Sr concentrations in both samples.

Sr and Nd initial isotope signatures (Table 4), for the time of magma crystallization, were calculated using the U–Pb ages determined in this study. Initial Pb ratios were measured directly in K-feldspar because this mineral is devoid of U (also used to correct for common Pb). The Bu Kang and Dai Loc intrusions have significantly negative initial εNd values of −11.8 and −9.9, respectively, and initial ⁸⁷Sr/⁸⁶Sr values (I₀) of 0.7086 and 0.7152. In contrast to these whole rock values, initial isotope ratios deduced from the mineral isochrons of the same samples lie at 0.7112 and 0.7156 (Fig. 3c,d). These slightly higher initial radiogenic ratios can be ascribed to radiogenic ⁸⁷Sr produced in the Rb-rich biotites between 26–24 Ma and 20 Ma (Table 4).

The two granitoid intrusions require a significant contribution from older crustal material, mixed to different degrees with a much less evolved magma component. Such mixing is required to explain the different I₀ of the two intrusions (0.7086 vs. 0.7152). As illustrated in Fig. 4, their initial isotopic values closely resemble Oligocene alkaline intrusions from the Ailao Shan–Red River shear belt, rather than those from the few Precambrian country gneisses measured in Indochina, which are very radiogenic compared to the values of the Bu Kang plutons (0.74 vs. 0.71). From U–Pb dating and Hf isotope tracing on single zircon and baddeleyite grains from large rivers it has been shown that major crustal growth periods in southeast Asia occurred during Precambrian times (Bodet and Schärer 2000). If the Bu Kang plutons were derived from such rocks, they should have significantly more evolved signatures, similar to those of the gneisses.

Involvement of older lower crust (e.g. low Rb/Sr, high Sm/Nd) in magma genesis is also permissible; however, the actual composition of Precambrian lower crust, or any Precambrian basement rocks in this and most regions of southeast Asia, is unconstrained due to the presence of thick Palaeozoic to Cenozoic cover rocks which obscure the underlying rock units. It is therefore difficult to speculate about the chemistry of potential source rocks for magmatism in the Bu Kang area. On the other hand, insight into lower crustal compositions of the Vietnam region is provided by significantly younger (~ 250 Myr old) lower crustal rocks identified in the Kontum massif in south-central Vietnam (Nagy et al., submitted). These charnockitic and granulitic rocks yield present-day ⁸⁷Sr/⁸⁶Sr values in excess to 0.711, which is higher than the value found for the Bu Kang plutons, after only 250 Myr of in situ ⁸⁷Rb decay. Such lower crustal rocks are therefore not the source of the Bu Kang magmas. These results from the Kontum complex also imply that the lower crust is not necessarily depleted in Rb, and enriched in Nd, as generally assumed.

Given the relatively low I₀ values for the Bu Kang and Dai Loc plutons, the lack of evidence for little evolved crustal source rocks in the region, and the isotopic similarities with alkaline intrusions from the Ailao Shan–Red River shear belt, it seems that a contribution from a mantle source is likely to have participated in magma generation. The Bu Kang complex intrusions could therefore represent a mixture of highly evolved crust and Oligocene mantle-derived magmas.

A potential thermal history for the northern Bu Kang dome is shown in Fig. 5. The U–Pb ages imply crystallization of zircons, monazites, and probably also allanite in the magma at 26–24 Ma, occurring most likely above 700–800 °C (although the exact magma temperatures are not known). Thermobarometric constraints indicate that the adjacent country rocks (meta-pelites)

![Fig. 4 εNd–I₀ isotope correlation diagram showing calculated initial values of the Oligo-Miocene plutons dated in this study. Isotopic data from the Red River shear zone (RRSZ) alkaline intrusions (open squares) and the country gneisses (full triangles) are shown for comparison (Schärer et al., 1990, 1994; Zhang and Schärer, 1999).](https://example.com/fig4.png)
in the core of the dome were at $600^{\circ} \pm 50 ^{\circ} C/1.1$-1.2 GPa at the time of magma emplacement ($\sim 23$ Ma; Jolivet et al., 1999). Micas from foliated granites and gneisses near the Quy Chau shear zone yield $^{40}$Ar/$^{39}$Ar ages as young as 21 Ma (Jolivet et al., 1999). Our Rb–Sr results imply that the intrusions reached $300 ^{\circ} C$ at about 20 Ma (Fig. 3b,c). These time-temperature constraints yield a relatively constant postemplacement cooling rate of $\sim 80 ^{\circ} C$ Myr$^{-1}$ (Fig. 5). Using an intermediate value for the geothermal gradient (35 $^{\circ} C$ km$^{-1}$), this cooling rate suggests $\sim 9$ km of exhumation during a period of 4–6 Myr, corresponding to an average exhumation rate of $\sim 2$ mm yr$^{-1}$.

Cenozoic deformation and magmatism in central Vietnam

In order to place the Oligocene–Miocene magmatic event identified in the Bu Khang complex into a geodynamic context, it is useful to make comparisons with nearby regions that have experienced contemporaneous exhumation and magmatism. About 200–300 km to the north, sinistral transpressional shear along the NW-striking Ailao Shan–Red River shear zone occurred from at least 35 to 20 Ma, accompanied by syntectonic emplacement of basaltic to acidic alkaline magmas and leucogranites (Schärer et al., 1990, 1994; Leloup et al., 1995; Harrisson et al., 1996; Zhang and Schärer, 1999). By about 20 Ma this mechanism of absorbing plate convergence ceased along the Ailao Shan–Red River belt, and some portions of the belt experienced exhumation. Re-activation in the reverse sense to a dextral strike-slip system occurred only recently ($\sim 5$ Ma; Leloup et al., 1995). Sinistral shear also occurred in Thailand along the NW-striking Three Pagodas (36–33 Ma) and Wang Chao (33–30 Ma) faults, which experienced subsequent rapid uplift during E–W extension (25–23 Ma) prior to reverting to dextral fault systems (23 Ma to present; Lacassin et al., 1997). Further east, sea-floor spreading in the South China Sea occurred along an E–W-oriented ridge at a rate of $\sim 50$ mm yr$^{-1}$ between 32 and 27 Ma, at which time a NE–SW-oriented ridge propagated southwestwards and spread at a rate of $\sim 35$ mm yr$^{-1}$ from 27 to 16 Ma, with ridge propagation ending $\sim 20$ Ma (Brais et al., 1993).

Emplacement of the Bu Khang and Dai Loc plutons 26–24 Ma was clearly contemporaneous with late phases of syntectonic magmatism along the Ailao Shan–Red River shear zone. On a broader scale, the major period of NE-directed extension and exhumation of the metamorphic rocks in the entire Bu Khang complex, which began 36 Ma and peaked at 21 Ma (Lepvrier et al., 1997; Jolivet et al., 1999), also overlaps with (i) the Oligocene–Miocene phases of transpressional sinistral deformation and partial exhumation in the Red River shear zone, (ii) extension in Thailand, and (iii) all but the final phases of sea-floor spreading in the South China Sea.

Our results conform with the kinematic model of Jolivet et al. (1999) for the Bu Khang complex which involves deformation within a broad shear zone encompassing most of the Indochina peninsula, similar to scenarios proposed in earlier studies which require coeval bookshelf-style block rotations throughout a large region to accommodate India–Eurasia convergence (e.g. Dewey et al., 1989; England and Molnar, 1990). Alternatively, given the proximity of the Bu Khang complex and the Ailao Shan–Red River shear zone compared to the entire Indochina peninsula, the ages do not contradict the theory of a diachronous, S–N migration of deformation on a larger scale (e.g. Tapponnier et al., 1986; Leloup et al., 1995; Lacassin et al., 1997).

Oligocene–Miocene magmatism in the Bu Khang complex, and cessation of sinistral strike-slip motion along the Ailao Shan–Red River and Wang Chao shear zones, may be related to the docking of the Philippine Sea plate against the Eurasian plate $\sim 20$ Ma, which forced kinematic reorganization along the previously free boundary on the Eurasian plate’s eastern margin (e.g. Rangin et al., 1990; Northrup et al., 1995). It is debatable whether the opening of basins in the South China Sea was (i) linked to propagation of the sinistral Red River fault and the extrusion of Indochina (e.g. Brais et al., 1993), (ii) bounded by the submerged dextral N-striking Vietnam fault (e.g. Marquis et al., 1997), (iii) controlled partly by slab pull from forces along the Sunda trench (e.g. Rangin et al., 1990), or (iv) some combination of these processes. In any case, Tertiary strike-perpendicular, NE–SW-directed extension, predicted at the south-east end of the Ailao Shan–Red River shear zone (Brais et al., 1993), may have partitioned onto structures in the Bu Khang complex instead. We note that there is evidence for Tertiary (35–20 Ma) exhumation via transpression along the Ailao Shan–Red River shear zone (e.g. Tapponnier et al., 1990; Leloup et al., 1995), but not strike-perpendicular extension until latest
Miocene (~5 Ma) times (Harrison et al., 1996).

The relationship between exhumation and granitic magmatism within the Bu Khang complex bears similarities to processes documented in the well-exposed core complexes of the western North America Cordillera. For example, extension in the Ruby Mountains core complex in Nevada was accompanied by mafic underplating in the lower crust which stimulated syn-deformational granitic magmatism, enhancing mid-crustal flow and compensating for some of the upper crustal thinning (MacCready et al., 1997). Isotopic studies indicate that the plutons that form the core of the complex originated from a mixing of mantle and crustal reservoirs (Wright and Snoke, 1993), which is supported by the presence of mantle-derived mafic material intruded at the base of the crust, as inferred from wide-angle seismic data (Stoerzcl and Smithson, 1998). The onset of exhumation in the Bitterroot metamorphic core complex in Idaho was also accompanied by granitic intrusions that supplied heat to maintain elevated footwall temperatures (House et al., 1997). Crustal melting can also be enhanced in core complex settings by regional scale flow within the lower crust (Block and Royden, 1990). Our U–Pb and Rb–Sr results substantiate the theory that extension in the Bu Khang complex included crustal, and possibly mantle, melting during the younger phases of exhumation 26–24 Ma. It is possible that syn-extensional magmatic emplacement occurred through the entire period of exhumation. Alternatively, it may have taken 10–12 Myr (from 36 to 26–24 Ma) for lithospheric thinning to advance to the stage where adiabatic decompression of the mantle and related melting of crust could occur and granitic melts were produced.

The above discussion suggests that the Bu Khang complex may have experienced the early stages of core-complex-like extensional deformation and lithospheric thinning as a result of far-field plate motion kinematics, thereby triggering magmatic emplacement in the latest Oligocene–early Miocene. Alternatively, the presence of vertical pressure gradients (e.g. Hutton, 1997) along the pre-Cenozoic Song Ma shear zone (Fig. 1a) may have facilitated the ascent of actively upwelling mantle-derived magma, thereby localizing extension.

Shear-wave velocity variations modelled beneath present-day East Asia show a concentration of slow-velocity anomalies to depths of 400 km centred beneath Indochina, corresponding to hot, partially melted regions (Zhang, 1998). The palaeo-position of the Indochina peninsula prior to and during the history of India–Asia collision is controversial (e.g. Tapponnier et al., 1986; Dewey et al., 1989) and beyond the scope of this discussion; however, we note that even if the peninsula experienced 700–900 km dextral motion along the Red River shear zone (e.g. Leloup et al., 1995), its restored position would still be well within the region overlying the low velocity anomaly, which has a map-view diameter of about 1200–1500 km at a depth of 50 km presently centred below northwestern Vietnam (Zhang, 1998).

An upwelling thermal anomaly in the asthenospheric or lithospheric mantle (i.e. mantle plume) has previously been proposed for the Ailao Shan–Red River shear zone in Yunnan to explain both the source signatures of amphibole-bearing alkaline intrusions and crustal melting (Zhang and Schärer, 1999). The same anomaly may be responsible for mantle melting and related crustal magmatism in the Bu Khang complex.

Acknowledgements

We thank François Bodet for rewriting the data processing programs and providing generous assistance during many stages of analysis. We are particularly indebted to Luisa de la Cruz for help in the analytical tasks, to Mireille Polvé and Pierre Brunet for performing the Nd mass spectrometric analyses in Toulouse, and to Pat Bickford, Marin Clark, Eric Kirby, Françoise Roger, and Nicole Santarelli for helpful discussions. For review and constructive comments we thank Henri Maluski, K. Wemmer, Albrecht Steck, and an anonymous reviewer. We also thank Claude Lepvrier for critical reading and many useful suggestions. This work was partially funded by the Bourse Châteaubriand program in France and an NSF International Research Fellowship to E.A.N. We acknowledge the PICS-Vietnam (INSU-CNRS) program for logistic support in Vietnam.

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Jolivet, L., Maluski, H., Beyssac, O. et al., 1999. Oligocene–Miocene Bu Khang


Received 18 January 2000; revised version accepted 7 June 2000.

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