Geochronology and Geochemistry of the Kuwei Mafic Intrusion, Southern Margin of the Altai Mountains, Northern Xinjiang, Northwest China: Evidence for Distant Effects of the Indo-Eurasia Collision

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ABSTRACT

The Kuwei mafic intrusion, consisting of hornblende gabbro, gabbro, gabbro norite, and olivine norite, lies in the southern Altai Mountains, northern Xinjiang. A combined field, geochronological, and geochemical study of the Kuwei intrusion is reported here. This study provides the first reliable SHRIMP U-Pb zircon dating results for the intrusion, and these yielded an age of 47 ± 1 Ma, which is the first documented report of Eocene magmatism in the region. The chondrite-normalized rare earth element patterns for the Eocene intrusions are flat, and most of the incompatible elements are comparably depleted. Thus, geochemical data suggest that the Kuwei mafic intrusion was produced by partial melting of asthenospheric mantle that was slightly contaminated by lithospheric material. We interpret the 47-Ma magmatism to result from asthenospheric mantle upwelling following the progressive India-Eurasian collision. Although the Kuwei intrusion is laterally beyond the limit of Eocene deformation normally attributed to the India-Asia collision, the timing of magmatism in the intrusion suggests that lateral extension may have initially affected a wider region than the area later thickened by convergence in the Tibetan Plateau. The Kuwei intrusion and other plutons likely related to it may have been emplaced into dilational jogs in fault systems activated by the India-Asia collision. The emplacement depth is estimated to be ∼6 km, based on geobarometric determinations. Erosion was imperceptible before 25 Ma but has worn away an average of 0.024 cm of uplift every year since 25 Ma. The 6 km of exhumation since the late Oligocene is also attributed to far-field effects of the India-Asia collision.

Online enhancement: table.

Introduction

The 2000-km-long southeast-northwest trending Altai Mountains [fig. 1a] are part of the Central Asian orogenic belt (CAOB), which is one of the world's largest active intracontinental orogenic systems yet remains one of the most poorly un-derstood regions of the continental crust. The CAOB has a continuously growing data set of active tectonic and seismic information [e.g., De Grave et al. 2007] that is helping to alleviate this problem, but many years of interdisciplinary research are needed to fully understand this orogen and its significance. The history of the mountains can be traced back to the early Paleozoic and a series of subduction-accretion events associated with the convergence between the Kazakhstan-Junggar plates and the Siberian Craton (see reviews in Windley et al. 2001; Li et al. 2003; Şengör and Natal’ín 2004; Xiao et al. 2004; Natal’ín and Şengör 2005) and production of juvenile crust during un-
Figure 1.  

a. Topographic map of Tibet and central Asia showing the tectonic framework and geotectonic units.  
b. Regional geological sketch map showing location of the Kuwei district (modified from Wang et al. 2002).  
c. Geological sketch map showing the outcrop of mafic rocks in the Kuwei district. The black bar represents the section for d.  
d. Geological section of the Kuwei mafic intrusion showing different lithologies. Sampling locations are also shown.
derplating of mantle-derived basaltic magmas near or at the crust-mantle interface and its subsequent differentiation processes (Wu et al. 2000; Chen and Jahn 2002, 2004). However, the origin of the mountains as we know them today is unclear. Are the mountains a long-lived feature or a more recent development? It is widely accepted that the modern Altai Mountains reactivation is attributed to the Cenozoic India-Eurasia collision and ongoing indentation of India into Eurasia (Molnar and Tapponnier 1975, 1977; Tapponnier and Molnar 1979; Peltzer and Tapponnier 1988). The India-Eurasia collision and continued convergence dominated much of Asia's Cenozoic geological, tectonic, geodynamic, and even climatic evolution. However, other models have also been proposed to explain the uplift of the Altai, including [1] a mantle plume or hotspot (Logatchev 1984; Zorin and Lepina 1985; Windley and Allen 1993), [2] thermal blanketing caused by collision of continental plates (Petit et al. 2002), [3] the combined effect of collision between India and Asia during the Eocene with secondary input from a mantle plume (Khain 1990), and [4] an asthenospheric mantle upwelling (Barry et al. 1998, 2003). One of the reasons for the disparity in views is the lack of any record of ~50-Ma magmatism linked to the India-Eurasia collision, as previous studies have suggested that the oldest magmatism in the Altai Mountains occurred at ~33 Ma in Gobi Altai, which cannot easily be interpreted in terms of the progressive Indo-Eurasia collision (Barry et al. 1998).

Recently, we determined a 47 ± 1-Ma SHRIMP U-Pb zircon age on a mafic intrusion in the Altai Mountains, Xinjiang, northwest China, which provides key evidence for the distant effects of the progressive Indo-Eurasia collision on the Altai Mountains. In this article, we report the dating results and geochemical data for the intrusion and discuss the relationships between petrogenesis and geodynamics.

Tectonic Setting

The Altai Mountains lie between the east European craton in the west, the Siberian craton in the east, and the Tarim and Karakum Precambrian blocks in the south (Li et al. 2003). The mountains were formed mainly through a complex series of subduction and terrane accretion events, although multiple openings and closings of small continental marginal basins are sometimes also invoked as important tectonic events (Dobretsov et al. 2004; Xiao et al. 2004; Ota et al. 2007). Deformation in the area is mainly manifested as a series of northwest-striking faults. During Mesozoic-Cenozoic times, older structures were overprinted by Alpine-Himalayan deformation (Zonenshain et al. 1991; Şengör et al. 1996).

The Paleozoic basement of the present-day Altai Mountains formed between the rigid Siberian craton in the north and the amalgamated Kazakhstan continent in the south. Many smaller blocks are trapped in between. They include microcontinents (e.g., Altai-Mongolia), with Precambrian basement, and “oceanic” units such as fore- and back-arc basins (e.g., West Sayan block), turbidite sequences, island arcs (e.g., Gorny Altai block), and seamount arrays (Buslov et al. 2001). Main accretion stages are Ediacaran–Early Silurian and Devonian-Carboniferous (Bachtadse et al. 2000; Buslov et al. 2001; Kravchinsky et al. 2001). Devonian to Carboniferous volcanic rocks are considered to represent a volcanic arc associated with subduction of Junggar oceanic crust. Final closure of the Paleo-Asian ocean with collision between the Kazakhstan and Siberian plates occurred by the Late Carboniferous. During the Permian, the tectonic regime was predominantly collisional, although Allen et al. (1995) proposed a Late Permian transtensional phase. The basement was intruded by large volumes of magma in the middle and late Paleozoic (fig. 1b), building extensive igneous complexes that added to the crustal growth of Eurasia (Şengör et al. 1993; Dobretsov and Vladimirov 2001).

The Altai area shows signs of minor Mesozoic activity as well. Several small Triassic-Jurassic plutons were emplaced in the Paleozoic basement (fig. 1b; Dobretsov and Vladimirov 2001; Wang et al. 2002, 2004), while remnants of small Jurassic intramontaine basins are found in several areas within the Altai orogen. These basins are filled mainly with coarse, continental, and typically coal-bearing Jurassic sediments atop relict Triassic red beds. This might imply regional Jurassic denudation-sedimentation, which is also seen in the sedimentary profiles of the large adjacent Junggar-Zaisan basin and the Mongolian basins (e.g., Johnson 2004).

In the Cenozoic, the Altai Mountains were converted to an active transpressional mountain belt between the rigid Junggar and Kazakhstan basement in the southwest and Siberia and Mongolia in the northeast (fig. 1). A current transpressional tectonic regime is demonstrated by strike-slip and thrust movements along major faults (e.g., Irtysh fault zone; fig. 2; Cunningham et al. et al. 1996; Buslov et al. 1999). Late Cenozoic deformation in the Altai Mountains is also evident in the Oligocene-Mio-
cene, but the main, still-active deformation is clearly constrained to the Pliocene-Quaternary. This modern deformation involves various smaller Paleozoic tectonic units and is manifested mainly along the older, inherited Paleozoic structures (Buslov et al. 1999). Various geological, seismological, and geomorphological indicators show that the Altai are still being affected by active tectonics (e.g., Cunningham et al. 1996; Owen et al. 1999; Philip and Ritz 1999).

**Geology and Petrology of the Intrusion**

The Kuwei mafic intrusion lies along the southern margin of the Altai Mountains (47°25’05”N, 89°26’16”E). Dozens of northwest-trending mafic-ultramafic intrusions in the region are recognized [fig. 1c] and are probably related to each other. The Kuwei intrusion is the largest one and consists of several rock types. It has an elliptical shape and is elongate in a west-northwest direction; it is 3.5 km long and 1 km wide and has a surface area of approximately 3.3 km² [fig. 1c]. It intrudes middle-upper Ordovician strata that include garnet schist and quartz schist. The intrusion consists of hornblende gabbro, gabbro, gabbro norite, and olivine norite [fig. 1d]. The hornblende gabbro contains an assemblage of hornblende (70%) and plagioclase. Minor magnetite occurs in the marginal zone of the pluton, which accounts for 20% of the whole exposed surface area of the pluton. The hornblende gabbro intrudes the other rock types, suggesting that it formed later than the other rock types. Gabbro, gabbro norite, and olivine norite change gradually from the margin to the center of the intrusion. Locally, gabbro and olivine norite are intercalated and exhibit zoned structure with 30–70-cm-wide zones. Poikilitic texture is dominant in gabbro, gabbro norite, and olivine norite, all of which are composed of similar mineral assemblages, that is, olivine (Fo70–76, 5%–10%), hypersthene (Wo3.5En71.1Fs27.5, 5%–20%), augite (Wo29.4En44.8Fs22.7, 20%–40%; table 1), hornblende (5%–10%), and calcium plagioclase (20%–30%) and minor magnetite, pentlandite, chalcopyrite, and pyrite. However, hornblende gabbro consists chiefly of hornblende (~60%) and plagioclase (~35%) but no olivine or pyroxene. KW-9 appears to contain exceptional accessory minerals. It contains relatively abundant sphene and rutile. All rock types were very slightly altered, with olivine and hypersthene replaced by serpentine and cummingtonite.

**SHRIMP U-Pb Zircon Dating and Results**

Thirteen zircon grains were separated from about 20 kg of gabbro norite [sample KW-1], using conventional heavy liquid and magnetic techniques. They were handpicked, mounted on an epoxy resin disk, and then polished. Internal structure was examined using cathodoluminescence and backscatter electron images at the electron microprobe laboratory of the Institute of Mineral Resources, Chinese Academy of Geological Sciences (CAGS). The U-Pb analyses were performed using the sensitive high-resolution ion microprobe (SHRIMP-II) at CAGS in Beijing. Operation and data processing procedures closely followed those of Compston et al. [1984] and Williams [1992]. The U-Pb ages were normalized to a value of 417 Ma, determined by conventional U-Pb analysis of zircon standards (SL13). Common Pb was corrected using the methods of Compston et al. [1984]. The 206Pb/238U and 207Pb/235U data were corrected for uncertainties associated with the measurements of the SL13 standards. The ages quoted in this article are 206Pb/238U ages [weighted means at the 95% confidence level].

The U and Th contents of the zircon grains range from 450 to 2878 ppm and from 410 to 2153 ppm, respectively [table 1]. The grains’ Th/U ratios vary from 0.53 to 1.67, indicating a magmatic origin [Belousova et al. 2002], which is also indicated by their morphological characteristics [fig. 3]. Eight analyses were obtained using the Beijing SHRIMP II [table 2]. Except for one analysis [KW-8.1] that yielded
<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Spot</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>Cr₂O₃</th>
<th>NiO</th>
<th>Total</th>
<th>End members</th>
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<td>37.89</td>
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<td>12.09</td>
<td>1.18</td>
<td>.00</td>
<td>.00</td>
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<td>13.41</td>
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<td>98.29</td>
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</table>

Note. TSi 6.73 represents the cation number of Si in the T site occupancy of amphibole. Others can be inferred in the same way.
an older age of around 147 Ma, all analyses yielded a single age. One analysis (KW-1.1) had a large error and was omitted from the mean. The remaining six analyses yielded a mean $^{206}\text{Pb}/^{238}\text{U}$ age of $47 \pm 1$ Ma, with MSWD = 1.3 [fig. 2]. All six grains are from a single-age population of zircons, and there is no evidence of any disturbance since 47 Ma. The 47-Ma age of the zircons from sample KW-1 is therefore considered to be the best estimate of the crystallization age for the Kuwei intrusion. One zircon has an older concordant age (147 Ma) and may represent the inherited zircon age, which is consistent with the ages of nearby granitic plutons [Wang et al. 2002].

**Major and Trace Element Results**

Samples were collected from the best-exposed and least-altered outcrops. The analyzed samples are believed to be representative of the major lithologies in the intrusions. Samples were reduced to chips after any altered surfaces were cleaned. The chips were then pulverized into powders using alumina mortars. Major element abundances were obtained using x-ray fluorescence (XRF) on fused glass beads. The trace elements Sc, V, Cr, Ni, Cu, Zn, Zr, and Hf were also determined by XRF on pressed powder pellets. Other trace elements, including rare earth elements (REEs), were analyzed on a VG Elemental Plasma-Quad 3 inductively coupled plasma-mass spectrometer (ICP-MS) at the Institute of Rock and Mineral Analyses, CAGS. We used pure elemental standards for external calibration and BHVO-1 as reference materials. Accuracies of the XRF analyses were estimated as ±2% for major elements present in concentrations >0.5 wt% and ±5% for trace elements (table A1, available in the online edition or from the *Journal of Geology* office). The ICP-MS analyses yield accuracies better than 5%.

The mafic rocks have a wide range of compositions. They have variable SiO$_2$ ranging from 39 to 46 wt%. Except for one sample (KW-9) with relatively high TiO$_2$ content (1.57%), the samples have narrow ranges of TiO$_2$ (0.15%–0.31%), which are the lowest TiO$_2$ contents for the mafic intrusions in the Altai orogenic belt (Zhang et al. 2003; Yang et al. 2004). High TiO$_2$ in the sample KW-9 could be interpreted by presence of sphene and rutile in the thin section. The rocks have a wide range of MgO content, ranging from 6.6 to 20.1 wt%. Compared with other mafic intrusions in the region, the Al$_2$O$_3$ contents are much higher, from 13.21% to 25.8%, which reflects the fact that there is much more plagioclase in the intrusion. Similarly, the rocks’ CaO contents are also relatively high, ranging from 8.2% to 14.2%. In contrast, K$_2$O and Na$_2$O contents are low, from 0.02 to 0.15 wt% and from 0.40 to 1.12 wt%, respectively.

There is a roughly negative correlation of MgO
Table 2. SHRIMP U-Pb Zircon Dating of the Kuwei Gabbro Norite

| Sample no. | U (ppm) | Th (ppm) | $^{206}\text{Pb}/^{238}\text{U}$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | $^{208}\text{Pb}/^{238}\text{U}$ | $^{207}\text{Pb}/^{207}\text{Th}$ | Isotopic ratios |
|------------|---------|----------|----------------------|------------------|----------------------|------------------|----------------
| KW-5.1     | 1523    | 2153     | 1.46                 | 9.93             | 48.2 ± 1.40          | 45 ± 180         | 48.0 ± 1.70    |
| KW-6.1     | 2878    | 1823     | 0.65                 | 18.2             | 47.1 ± 1.40          | 54 ± 130         | 45.5 ± 2.20    |
| KW-7.1     | 518     | 470      | 0.94                 | 3.49             | 48.6 ± 1.50          | -704 ± 670       | 48.4 ± 4.00    |
| KW-8.1     | 532     | 282      | 0.55                 | 10.7             | 146.8 ± 4.20         | -111 ± 170       | 134.0 ± 7.90   |
| KW-4.1     | 968     | 1613     | 1.72                 | 6.40             | 49.2 ± 1.40          | 228 ± 130        | 48.9 ± 1.70    |
| KW-1.1     | 450     | 410      | 0.94                 | 3.18             | 52.1 ± 1.60          | -17 ± 310        | 43.1 ± 3.10    |
| KW-2.1     | 733     | 912      | 1.29                 | 4.61             | 46.3 ± 1.40          | -598 ± 320       | 44.0 ± 1.90    |
| KW-3.1     | 628     | 938      | 1.54                 | 3.88             | 43.8 ± 1.90          | -90 ± 1900       | 45.3 ± 7.10    |

Discussion

Mantle Sources. The low total REE abundances and flat chondrite-normalized REE patterns, as well as low incompatible element abundances, in the Kuwei intrusion (fig. 5) suggest that the primary magmas were generated by extensive melting of depleted mantle or primitive mantle, although there is no isotopic evidence to support or refute this idea. Sample KW-9 has distinctive trace element characteristics. Its high TiO$_2$ content can be attributed to sphene and rutile in the rock, which is consistent with petrographic observations and with the relatively high REE abundances (table A1; fig. 5a) because accessory minerals usually contain high REE abundances (Green and Pearson 1987; Klemme et al. 2004).

Incompatible element ratios can provide some constraints on source regions. Ormerod et al. (1991) regarded the ratio Zr/Ba as an index of whether primary magma is derived from asthenospheric mantle or lithospheric mantle. All analyzed samples had Zr/Ba ratios >0.2 (table A1), suggesting that they resulted from melting of asthenospheric mantle, although Ba contents might have been slightly changed by a low-temperature alteration effect. Furthermore, low Zr/Y (1.9–6.2) and (La/Yb)n ratios (1.1–3.8) also indicate that they were derived from asthenospheric mantle (Sato et al. 2007). As described above, the Fo contents of olivines in the intrusion are too low for them to be in equilibrium with mantle minerals (Wilson 1989), so the intrusion should have formed by processes within the magma chamber (e.g., fractional crystallization and assimilation). It is impossible to estimate the composition of primary magma. Thus, the degree of partial melting, the proportion of the residual minerals, could not be estimated by major elements. In contrast, incompatible elements, especially their ratios, could be used to infer the mineralogy and degree of melting because of their similar partitioning coefficients. In addition, partial melting of either garnet or spinel peridotite will preferentially enrich light REEs, such as La, which are more incompatible in most mantle phases than are middle REEs, such as Sm. However, the degree of enrichment of middle REEs relative to heavy REEs such as Yb depends greatly on whether garnet exists as a residual phase during melting, because the heavy REEs are preferentially retained by garnet during melting but not in most other mantle phases. Furthermore, fractional crystallization will produce only modest changes in La/Sm and Sm/Yb.
Figure 4. MgO versus major oxides and Cr and Ni contents of the Kuwei intrusion.

ratios, compared with variations caused by changes in melt fraction or source mineralogy. Enrichment in La/Sm and Sm/Yb produced by batch melting of spinel and garnet peridotite are shown in figure 6. Four samples fall in the melting curve of primitive garnet peridotite, and three samples plot the melting curves between primitive garnet peridotite and primitive spinel peridotite. Thus, the Kuwei mafic intrusion appears to have been generated through high degrees of melting of a mix of depleted and primitive peridotite (fig. 6). The primary melt may have been generated by melting of garnet peridotite or transitional mantle facies between spinel and garnet. This is consistent with the characteristics of chondrite-normalized REE patterns and primitive mantle-normalized trace element patterns (fig. 5a, 5b). Hence, we infer that the primary magmas were derived from asthenospheric mantle, not lith-
osheric mantle. Although a 147-Ma zircon is probably derived from nearby Jurassic granites, the contribution from the lithosphere could be limited, which is reflected by the slightly positive Pb anomalies and Nb anomalies on the primitive mantle-normalized patterns. Consequently, the Kuwei mafic intrusion was generated by partial melting of asthenospheric mantle, probably triggered by decompression.

Age of Mafic Intrusion and Uplift of Central Asian Mountain Belt. In the Chinese Altai Mountains, there has been only one age determined of Cenozoic magmatism, that is, 17.59 ± 0.59 Ma, dated by the 40Ar/39Ar method for nearby basalts (Huang et al. 2006). The age of the Kuwei mafic intrusion cannot be well constrained by its relationships to the wallrocks, since it intruded Lower Devonian metamorphic rocks and is not overlain by any strata.

The zircon grains are fine (10–40 μm) and exhibit zoning, characteristic of basic magmatic zircons. Although we dated only eight grains (others were too small to be dated), six analyses fall within one group that spreads along the concordia, yielding a mean 206Pb/238U age of 47 ± 1 Ma. Consequently,
the mean age of $47 \pm 1$ Ma is believed to represent the crystallization age.

Much geologic evidence shows that the CAOB was formed under conditions of horizontal contraction, for example, widespread thrusts, consistent fold-thrust dislocations, and widespread systems of contiguous diagonal wrench faults [Windley et al. 2001; Şengör and Natal’ïn 2004; Xiao et al. 2004; Natal’ïn and Şengör 2005; De Grave et al. 2007]. In general, such contraction is attributed to convergence between the Eurasian, Arabian, and Indian lithospheric plates [Molnar and Tattonnier 1975; Yin and Harrison 1996]. Thus, the plate-tectonic concept of the origin of CAOB gives an adequate explanation of its Paleozoic formation as the result of convergence and collision of the Indian and Eurasian lithospheric plates. However, as discussed above, the Kuwei mafic intrusion resulted from partial melting of asthenospheric mantle by decompression, which might have been caused by extension. Although the exact timing of collision is still being debated, most researchers believe that the collision started at 45–58 Ma (e.g., Burtman 1994; Rowley 1998; Yin and Harrison 2000; Aitchison et al. 2002). Thus, from the point of view of the tectonic regime, it seems unlikely that emplacement of the Kuwei intrusion could be linked to India-Eurasian collision, despite the similar timing. However, an extension setting can also be caused by strain relaxation following compression or by the localization of plutons in structural settings, such as jogs or dilational bends in strike slip faults, or in fault systems oriented at high angles to the compressional direction (see review and references in Kusky et al. 2003). Thus, the two events between 47-Ma magmatism and 50-Ma India-Eurasian collision can be plausibly interpreted as related to one of two phenomena, which require further testing: [1] after the India-Eurasian collision around 50 Ma, the Altai area was under extension in response to strain relaxation following (presumed) compression caused by India-Eurasian collision, or [2] the plutons intruded into dilational jogs in fault systems activated by the India-Asia collision. If the former model is correct, then extension gave rise to asthenospheric mantle up-welling, and decompression caused partial melting of asthenospheric mantle. The Kuwei mafic intrusion was formed by emplacement of a series of evolved magmas produced by fractional crystalli-
zation, with minor granitic contamination of primary magma that resulted from a high degree of partial melting of asthenospheric mantle.

The emplacement depth can be constrained by the amphibole geobarometers. Although several amphibole geobarometers have been proposed, many of them may not be suitable for mafic-ultramafic intrusions. Ernst and Liu’s (1998) calibration is relatively new and has been tested with analyzed Ca-amphiboles from a variety of plate-tectonic settings; thus, it is currently the best measure for mafic-ultramafic intrusions. They proposed that Al contents in amphibole are controlled by temperature, whereas Ti contents are a function of temperature and pressure under crustal or uppermost mantle conditions, based on experiments. Thus, based on the Al$^{IV}$ (table 1), the temperature is estimated to be 870°–890°C (fig. 7a), and then the pressure can be estimated to be 1.84–1.92 kbar, corresponding to ~6-km depth, on the basis of the average Ti content and estimated temperature (table 1; fig. 7b). This estimate suggests that the erosional unroofing has been ~6 km since 47 Ma; that is, the uplift has been up to 6 km since 47 Ma. This estimate is also consistent with Cunningham’s (2001) conclusion for >3500-m uplift in the same time period. However, apatite fission track data and sedimentation history from the Chinese part of the Altai Mountains (Yuan et al. 2006; De Grave et al. 2007) show that hardly any erosion was taking place before 25 Ma. There is regional evidence for uplift afterward; that is, a large amount of regional surface uplift started around 25 Ma. Thus, it can be inferred that 0.024 cm surface uplift per year has occurred since 25 Ma.

**Concluding Remarks**

The new SHRIMP U-Pb dating for the Kuwei mafic intrusion in the Altai Mountains shows that there was magmatic activity at ~47 Ma in the CAOB, which is temporally coincident with the initial point of the India-Eurasia collision (~50 Ma). The geochemical characteristics of the Kuwei mafic intrusion suggest that the primitive magma was generated by partial melting of asthenospheric mantle caused by extension, either in response to strain relaxation following India-Eurasia collision or in local extensional settings in jogs along regional fault systems activated by the collision. Large-scale surface uplift may have started around 25 Ma, and 0.024 cm of surface uplift per year is estimated to have occurred since then.

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