

to standard 'pump-and-treat' processes for cleaning up contaminated groundwater^{25,39}.

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A precise U–Pb zircon/baddeleyite age for the Jasra igneous complex, Karbi–Analong District, Assam, NE India

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Five Cretaceous alkaline–carbonatite igneous complexes are reported from the Assam–Meghalaya Plateau. These alkaline intrusions have been interpreted to be coeval and associated with the 117–105 Ma Rajmahal–Sylhet flood basalt province. With the existing age information it is possible that this alkaline magmatism may be a late magmatic stage of the Rajmahal–Sylhet large igneous province. Therefore, it is essential to determine high-precision ages for these alkaline complexes in order to understand the detailed temporal evolution and genesis of this basaltic and alkaline magmatism. Out of five igneous complexes, Sung Valley, Swangkre and Samchampi have been dated, but the emplacement ages of the other two, i.e. Jasra and Barpung, are poorly constrained. The present communication reports a new, high-precision U–Pb zircon/baddeleyite age for a differentiated portion of gabbro phase of the Jasra igneous complex.

THE majority of carbonatite occurrences worldwide are associated with alkaline, mafic and ultramafic rocks and

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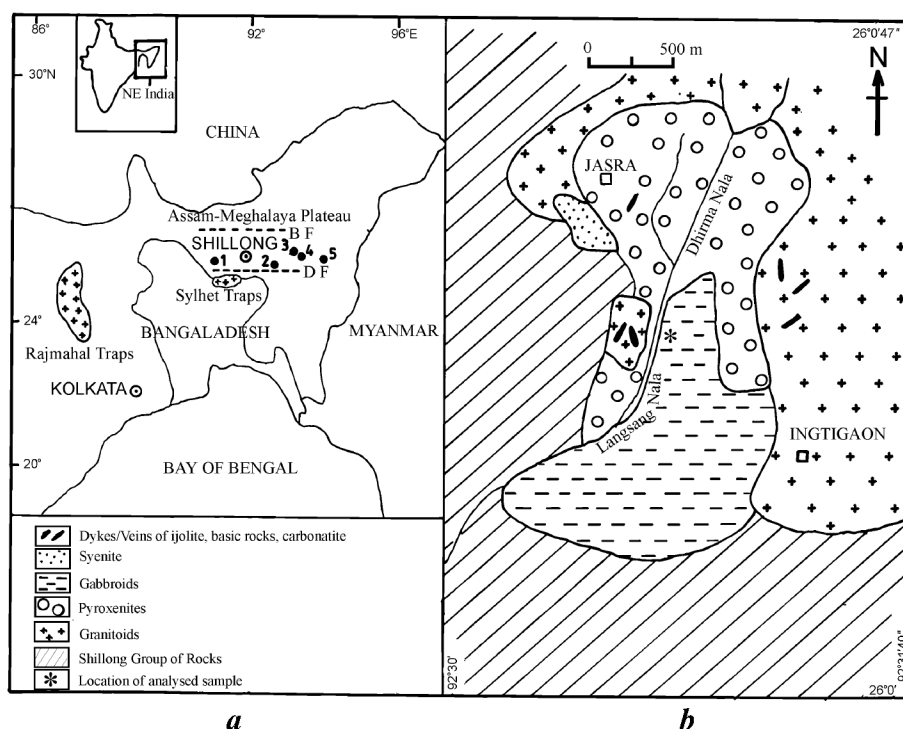


Figure 1. *a*, Map of NE India showing location of alkaline-carbonatite igneous complexes and Sylhet and Rajmahal traps. 1, Swangkare; 2, Sung Valley; 3, Samchampi; 4, Jasra; and 5, Barpung. DF, Dauki fault; BF, Brahmaputra fault; *b*, Geological map of the Jasra igneous complex (modified after Mamallan *et al.*¹²).

together form alkaline-carbonatite igneous complexes (ACICs). The coincidence of such complexes with major crustal structures (faulting and rifting) is well established^{1,2}. Woolley¹ has also correlated alkaline-carbonatite magmatism, in space and time, with major orogenic and tectonic events. A similar effort has also been attempted for the Indian alkaline-carbonatite complexes², but high-precision age constraints are generally not available for the latter. Several alkaline-carbonatite igneous complexes are reported from northeastern India³, viz. Swangkare, Sung Valley, Samchampi, Jasra and Barpung (see Figure 1 *a*). These igneous complexes are also associated with an uplifted horst-like feature, the Assam-Meghalaya Plateau (AMP), bounded by the E-W trending Dauki and Brahmaputra faults^{2,4}. Another deep fault, the N-S trending Nongcharam fault, is also associated with AMP⁵. Out of these five igneous complexes, only the Sung Valley intrusion has been studied in detail⁶⁻¹⁰. Considering all the age determinations reported in Table 1 for the Sung Valley intrusion, there exists a large range of emplacement ages between 90 and 150 Ma. But if we considered the geochronological study of Ray *et al.*^{9,10}, who used a variety of material to date the emplacement age of the Sung Valley ACIC by different methods (see Table 1), one can obtain a good estimate of the emplacement age for this intrusion of around 107 Ma. This age is well supported by ages of other ACICs^{7,11} as all these complexes were probably emplaced within a short span of time⁹. The 107 Ma

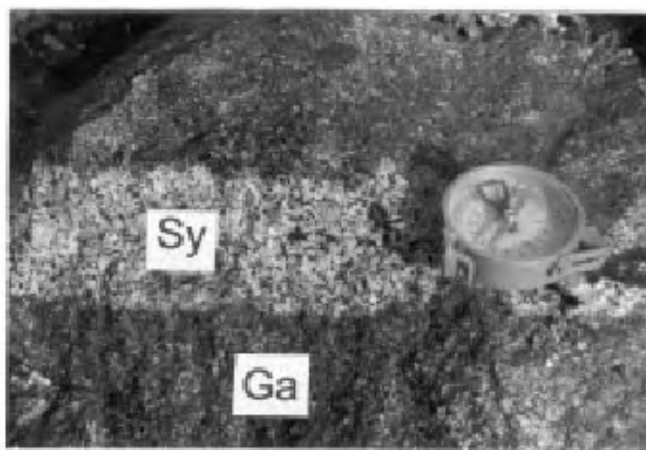
Swangkare⁷ and ~ 105 Ma Samchampi¹¹ intrusions have been dated using K-Ar and fission track methods, respectively (see Table 1). There is currently no age data available for the Jasra and Barpung igneous complexes. Another important point is that all these NE Indian ACICs have similar petrologic and geochemical characteristics³; it could be interpreted that they all are derived from a single magmatic episode at around 107 Ma (ref. 7).

The Jasra igneous complex comprises ultramafic (different types of pyroxenite), mafic (olivine gabbro and basic dykes) and alkaline (syenite, trachyte, carbonatite and ijolite) rocks and associated fenite¹². Pyroxenites and gabbros form the main body of the complex, which mainly intrudes the Proterozoic Shillong group represented by quartzite, phyllite and amphibolite. In places, rocks of Shillong group show an intrusive relationship with Neoproterozoic granitoids. Other associated rock units of the complex display an intrusive relationship with pyroxenites and gabbros. Carbonatite occurs as very thin veins. A geological map of the area¹² is presented in Figure 1 *b*.

In order to determine a high-precision U-Pb zircon/baddeleyite age for the Jasra complex, we have selected a differentiated gabbro sample. This 0.5 kg sample was collected from the Langsang Nala gabbro (Figure 2). It shows a central differentiated part (syenite) bordered by gabbro. The sample was selected for the U-Pb study because felsic differentiated portions of mafic complexes often contain zircon and/or baddeleyite in sufficient quantities for age-dating. Un-

Table 1. Geochronological data on northeastern India ACICs

Complex	Method	Material	Age (in Ma)	Reference
<i>Sung Valley ACIC</i>				
	Fission track	Apatite	90 ± 10	6
	K–Ar	Phlogopite from carbonatite	149 ± 5	7
	Pb–Pb	Carbonatite (WR)	134 ± 20	8
	Ar–Ar	Pyroxenite (WR) and phlogopite from carbonatite	107.2 ± 0.8	9
	Rb–Sr	Carbonatite (WR), pyroxenite (WR) and phlogopite from carbonatite	106 ± 11	10
<i>Swangkre ACIC</i>				
	K–Ar	Lamprophyre	107 ± 3	7
<i>Samchampi ACIC</i>				
	Fission track	Apatite	~ 105	11

**Figure 2.** Field photograph showing differentiated central part (Sy, syenite) of a gabbroic body (Ga).

der the microscope, this sample is primarily equigranular hypidiomorphic, but in places panidiomorphic and allotriomorphic textures are also present. This textural variation is related to a range in crystal shapes, although most crystals show subhedral characteristics. The main mineral constituents are orthoclase, nepheline, hypersthene, biotite, ilmenite, apatite, augite/aegirine–augite, titanite, sulphide, zircon and baddeleyite. Euhedral crystal morphologies are exhibited by titanite, apatite, nepheline and ilmenite.

The differentiated portion of this gabbro sample selected for the study (JS-5) was pulverized using a jaw crusher and disk mill. Zircon and baddeleyite were separated by a series of mineral separation steps that include the use of a Wilfley table, Frantz isodynamic separator and heavy liquids (methylene iodide). All mineral grains selected for analysis were carefully examined at high magnification using a stereomicroscope. The grains were first washed in 4N HNO₃, H₂O and acetone. All crystals were weighed and placed into 10 ml TFE Teflon dissolution vessels together with a mixture of HF and HNO₃ (10:1) and a measured amount of mixed ²⁰⁵Pb–²³⁵U tracer solution. After a dissolution period of 5 and 7 days at a temperature of

220°C, uranium and lead were isolated using standard anion exchange chromatography¹³ closely following the procedure outlined in Heaman and Machado¹⁴. All analyses were performed on a VG354 thermal ionization mass spectrometer at the Radiogenic Isotope Facility, University of Alberta. The uranium decay constants used in this study are $1.55125 \times 10^{-10} \text{ yr}^{-1}$ (²³⁸U) and $9.8485 \times 10^{-10} \text{ yr}^{-1}$ (²³⁵U).

The heavy mineral fraction isolated from sample JS-5 consisted of apatite, augite, zircon, titanite and a minor amount of baddeleyite and sulphide. Titanite occurs as straw-yellow fragments with abundant mineral inclusions and veining. Zircon occurs as colourless skeletal grains and fragments with rare crystal face development. Baddeleyite occurs as tiny tan to brown parts of blades.

The U–Pb results for two multi-grain zircon fractions and one multi-grain baddeleyite fraction are shown in Figure 3 (baddeleyite is denoted by a shaded ellipse) and Table 2. The zircon fractions have moderate uranium content (430 and 362 ppm, respectively) and high Th/U (> 2) which, combined with the skeletal habit, is typical of zircon that rapidly crystallizes from a mafic magma. The single baddeleyite analysis has a moderate to high uranium content of 1040 ppm and low Th/U (0.04), also typical of baddeleyite that crystallizes directly from a mafic magma. The model ages reported in Table 2 for all three analyses are quite similar and plot on (as in the case of analysis #1) or very close to the concordia curve. The ²⁰⁶Pb/²³⁸U ages for zircon fraction #1 and baddeleyite fraction #3 are identical (105.2 ± 0.6 and 105.2 ± 0.8 Ma, respectively) and the weighted average ²⁰⁶Pb/²³⁸U age of 105.2 ± 0.5 Ma (2 sigma) for these two fractions is considered the best estimate for the emplacement age of the Jasra gabbro. The slightly older age for zircon fraction #2 could reflect the presence of a small inherited Pb component.

The precise U–Pb zircon/baddeleyite age of 105.2 ± 0.5 Ma obtained in this study for the Jasra gabbro is similar to slightly less-precise ages obtained for other alkaline complexes in northeastern India. These

Table 2. U–Pb results for a differentiated gabbro phase (JS-5) of the Jasra igneous complex

Description	Weight (μg)	U (ppm)	Th (ppm)	Pb (ppm)	Th/U	TCPb (pg)	Atomic ratio						Model age (Ma)	
							$^{206}\text{Pb}/^{204}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{207}\text{Pb}/^{206}\text{Pb}$	%Disc
1–z, lg irreg frags col trans 6M (30)	163	430.0	1028.6	11.4	2.39	39	1852	0.01645 ± 5	0.1092 ± 4	0.04816 ± 7	105.2 ± 0.3	105.2 ± 0.3	107.1 ± 3.2	1.8
2–z, irreg frags col-tan trans n/incl 6NM (29)	163	362.2	787.8	9.2	2.17	12	5167	0.01657 ± 4	0.1104 ± 3	0.04831 ± 4	105.9 ± 0.3	106.3 ± 0.3	114.4 ± 2.0	7.4
3–b, brown trans frags 10M, 6M, 6NM (33)	37	1040.2	42.0	15.9	0.04	13	2991	0.01646 ± 6	0.1098 ± 4	0.04838 ± 6	105.2 ± 0.4	105.8 ± 0.4	118.1 ± 2.8	11.0

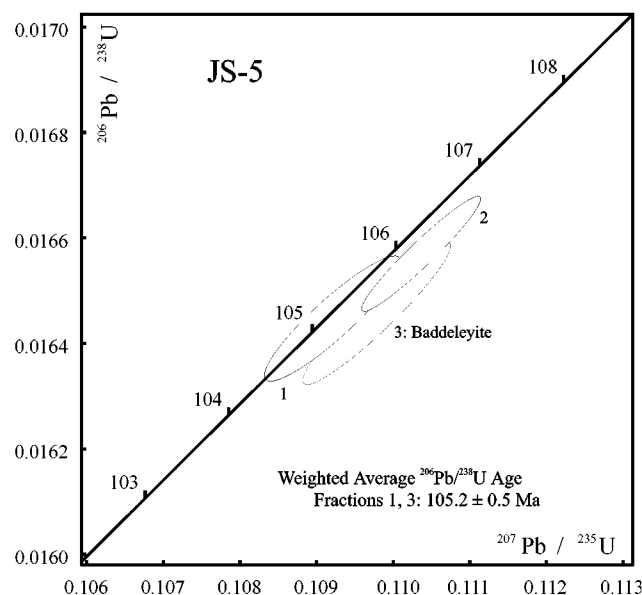
Notes: Mineral analysed: b, baddeleyite; z, zircon.

Col, colourless; frags, fragments; incl, inclusions; irreg, irregular; lg, large; trans, transparent; M, magnetic fraction; NM, non-magnetic fraction.

6M refers to a magnetic fraction from a Frantz isodynamic separator at full field strength (1.8 Amps) and 6° side tilt/10° forward tilt.

Concentration estimated from amount of ^{208}Pb in analysis. Numbers in parentheses refer to crystals analysed.

All errors reported at 1 sigma and reflect the uncertainty in the last decimal position.

**Figure 3.** The U–Pb results. Empty ellipses (1 and 2) are of multi-grain zircon fraction and shaded ellipse (3) is of multi-grain baddeleyite fraction.

include the 107 ± 3 Ma K–Ar age obtained for the Swangkri lamprophyre⁷, the 107.2 ± 0.8 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age obtained for the Sung Valley pyroxenite/carbonatite⁹ and the ~ 105 Ma apatite fission track age obtained for Samchampi complex¹¹. The similarity in the emplacement age for these alkaline complexes indicates that this period of alkaline magmatism is generally a late magmatic pulse related to the 117–105 Ma Rajmahal–Sylhet flood basalt province^{9,15,16}, considered by many to be a product of the Cretaceous Kerguelen plume^{8,10,17}.

Many other mafic alkaline–carbonatite complexes worldwide are also reported to have both a temporal and genetic association with continental flood basalt (CFB) provinces^{18–20}. This inference is well supported by the similarity in their stable and radiogenic isotope compositions. Ray *et al.*⁹ have discussed these isotope data in detail and suggested that the alkaline–carbonatite igneous complexes of northeastern India, similar to many other complexes worldwide (< 200 Ma), show an OIB mantle source signature.

An interesting feature of many mafic alkaline–carbonatite complexes is their emplacement during the latest stages of CFB magmatism¹⁸. Some excellent examples are – (i) Parana CFB (133–129 Ma)²¹ and associated Ponta Grossa ACIC (130 ± 5 Ma)¹; (ii) Etendeka CFB (132–129 Ma)²² and associated Angolia/Namibia ACIC (120 ± 2 Ma)¹; (iii) Deccan CFB (69–63 Ma)^{23,24} and associated Chhota Udepur ACIC (65 ± 0.2 Ma)²⁰. In the present case, we also observed a similar temporal relationship between the Rajmahal–Sylhet CFB (117–105 Ma)^{9,15,16} and Jasra ACIC (105.2 ± 0.5 Ma). But at the same time it is also observed that not all alkaline magmatism occurs late. For example, the MRC alkaline magmatism¹⁴, including carbonatites occurs at the onset of

CFB magmatism. Thus it is important to work on the temporal relationship between ACICs and CFBs, which may certainly play an important role for understanding the origin of ACICs.

The majority of carbonatite occurrences worldwide are Cretaceous in age (< 200 Ma)¹ and are temporally linked to the formation of large igneous provinces immediately prior to the break-up of the supercontinent Pangea. The exact timing of this alkaline-carbonatite magmatism globally is critical in evaluating the details of magmatic processes operating within mantle plumes and could provide a detailed record of the break-up history of the supercontinent Pangea.

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Estimates of coseismic displacement and post-seismic deformation using Global Positioning System geodesy for the Bhuj earthquake of 26 January 2001

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The $M_w = 7.6$ Bhuj earthquake of 26 January 2001 that occurred in the Kachchh Rift Basin (KRB) was felt over a wide area in the country. Global Positioning System (GPS) measurements were made at eleven sites in the epicentral area and at Jamnagar, south of the KRB to estimate the total residual displacements at these sites as a result of this earthquake. During the survey, seven Great Trigonometrical Survey (GTS) points (1857) were reoccupied using GPS. An additional five GPS points were established by C-MMACS for post-seismic studies. The Jamnagar site was measured earlier in 1997 while the seven GTS sites are those established during the GTS, 144 years ago. Comparison of GPS (1997) and GPS (2001) coordinates at Jamnagar gives the coseismic displacement vector of 16 ± 8 mm at $N35^\circ E$ for the four-year period (1997–2001); this is the only GPS–GPS based estimate of coseismic slip of the Bhuj earthquake. Comparison of GTS (1857) and GPS (2001) coordinates at 7 GTS sites yields upper bounds on the displacements suffered by these sites as a result of the co-seismic slip of major events that occurred in the intervening period. GTS (1857)–GPS (2001) baselines oriented at low angles to the NNE–SSW compression or transport direction have shortened in length, while those oriented at high angles have been elongated. The two epochs of measurements at the five GPS sites in KRB and Jamnagar during February and July 2001, yield post-seismic displacement rates averaging about 1 mm/month at these sites. GPS (February 2001)–GPS (July 2001) baselines, on the other hand, have shortened in length irrespective of their orientation relative to the NNE–SSW transport direction.

AN earthquake of moment magnitude $M_w = 7.6$, rocked the Rann of Kachchh and adjoining areas at 8 h 46 min (IST) on the morning of 26 January 2001 (Figure 1). This is the second catastrophic earthquake to have occurred in Kachchh, 181 years after the M 7.5 (ref. 1) earthquake of June 1819 which destroyed the towns of Bhuj and Anjar and created an 80-km-long fault scarp and a natural dam (Allah Bund) uplifted at its crest by

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