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Sequential kinetic modelling: A new tool decodes pulsed tectonic patterns in early hot orogens of Earth

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ABSTRACT

Tectonic styles in an early hot Earth were different from the present-day situation governed by plate tectonics. Processes in such hot settings remain poorly understood because they often occur on timescales that are below the resolution of conventional isotopic clocks, the rock records are fragmentary, and these have been superposed by later high-temperature events. We have developed a tool based on diffusion kinetics to overcome these difficulties and reconstruct sequences of short-lived episodes. Application of the method to a rock from the ultra-hot c.1.6 Ga orogenic domain of the Central Indian Tectonic Zone, where additional data are available to verify the results, shows that pulses of approach and roll-back of colliding plates preceded the final closure and collision. We demonstrate that cooling from ultra-high temperature metamorphic conditions in the orogen took place in multiple pulses that occurred with a periodicity of about 10 Myr at rates that vary between 100's to 10's °C/Myr, and burial-/exhumation-rates that vary between 30 and 2 km/Myr, respectively. Such details of tectonic processes in the Precambrian, with quantification of variable heating-, cooling-, burial-, and exhumation-rates of individual stages, have not been accessible until now. Application of this method to other regions would provide a means of exploring the thermal viability of the inferred long durations (>100 Myr) for some ultra-high temperature orogenies.

1. Introduction

One of the central questions in the Earth sciences is when and how the present style of plate tectonics emerged. To answer this question it is necessary to identify and quantitatively characterize tectonic processes that occurred in the early hot Earth. As conventional ideas (e.g., England and Richardson, 1977; Thompson and England, 1984) about the duration of metamorphic – tectonic events are refined it has become essential to resolve processes that occur on short timescales of a few million years (Baxter et al., 2002; Anczkiewicz et al., 2014). Such timescales are below the resolution of conventional geochronometers applied to old rocks [e.g., zircon dating: ∼20–30 million years (2σ value) (Condie, 2013), although recent developments are bringing this resolution to about a million year (e.g., Condon et al., 2015). New tools are required that (a) have a time resolution of well below a million years, (b) are independent of the age of the rocks, and (c) can see through multiple, superposed thermal/tectonic events even at ultra-high temperature (UHT) conditions. Here we develop such a tool based on diffusion chronometry, and apply it illustratively to a Proterozoic sample from the Central Indian Tectonic Zone (CITZ) to reveal a pulsed tectonic style of alternating collision and extension within a single orogenic cycle. Although the rock is Proterozoic in age it comes from an UHT setting and thereby illustrates applicability of the tool in early, hot tectonic settings. In the process, we quantify the rates of cooling, burial and exhumation of each stage, and verify the integrated overall duration using available zircon and monazite dates. The approach provides a much more detailed quantitative record of the dynamics of ancient orogenic processes than has been accessible until now.

1.1. Geological setting and previous work

We have chosen a partially hydrated garnet + orthopyroxene granulite sample from the Bhandara–Balaghat granulite (BBG) terrain at the southern margin of the Central Indian Tectonic Zone (CITZ) (Fig. 1) to demonstrate the new technique. The BBG terrain is a 190-km long and 4–20-km wide granulite–gneiss belt at the southern margin of the E–W trending CITZ, which lies at the heart of the Indian Peninsula between North and South Indian cratonic blocks (NIB and SIB respectively) (Fig. 1). Supracrustal and metaig-

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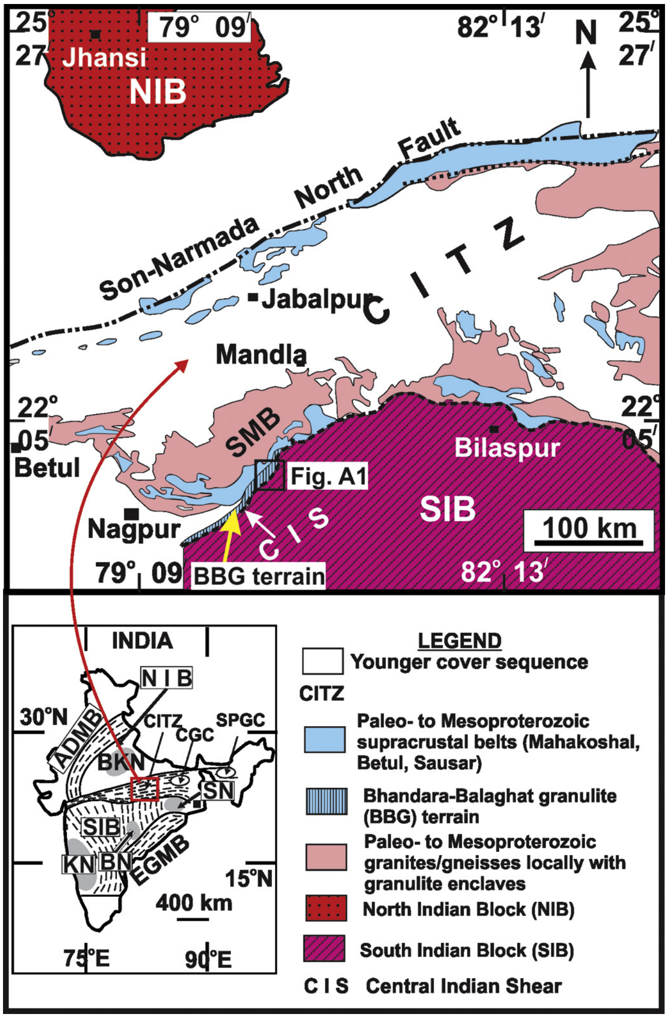

Fig. 1. Simplified geological map of the Central Indian Tectonic Zone (CITZ), showing the location of the Bhandara–Balaghat granulite (BBG) terrain (after Bhowmik et al., 2005). The black square box marks the study area, shown in detail in Fig. A1. Inset shows the location of the CITZ in the tectonic framework of the Archean cratonic blocks [North Indian Block (NIB) and South Indian Block (SIB)] and Proterozoic mobile belts [Aravalli–Delhi Mobile Belt (ADMB) in the west; the CITZ in the centre; the Chhotanagpur Gneissic Complex (CGC) in the east; the Shillong Plateau Gneissic Complex (SPGC) in the NE; the Eastern Ghats Mobile Belt (EGMB) in the SE] of India. The NIB and SIB contain the Archean nuclei of Bundelkhand (BKN) and Singhbhum (SN)–Bastar (BN)–Karnataka (KN), respectively.

neous granulites, which occur as discontinuous pods and lenses within felsic gneisses of granitic to granodioritic compositions (see Fig. A1 in Appendix) record three episodes of superposed granulite facies metamorphism (M_1–M_3) (see Basu Sarbadhikari and Bhowmik, 2008; Bhowmik et al., 2014 for metamorphic conditions and P–T paths). In several localities, the M_1 metamorphism in the supracrustal granulites reached lower crustal UHT metamorphic conditions (Bhowmik et al., 2005, 2014; Bhowmik, 2006) (locations 1–3, Fig. A1). Metaigneous granulites are represented by a suite of metamorphosed, coarse-grained, gabbro–norite rocks (now two pyroxene granulites) and different generations of mafic dykes (see Bhowmik et al., 2005; Basu Sarbadhikari and Bhowmik, 2008 for detailed field relationships). Previous studies have correlated the different phases of mafic magmatism with different periods of granulite facies metamorphism (Bhowmik et al., 2005; Basu Sarbadhikari and Bhowmik, 2008). Recent studies have developed chronological constraints for three separate high-grade metamorphic pulses in the BBG terrain: (1) at 1658 Ma, (2) between 1612 and 1574 Ma and (3) between 1572 and 1539 Ma (Bhowmik et al., 2014 and references therein). Pulses 2 and 3 are the most pervasive in the rock record, and are correlated with the M_1–M_3 metamorphic stages (Bhowmik et al., 2014). The investigated granulite sample (Sample B37A) occurs at the outermost zone of a metasomatically banded ultramafic body within the host psammo-pelitic granulite.

2. Methods of study

In the first part of this study we establish the polyphase metamorphic evolution (M_1–M_2–M_3 metamorphic pulses) in the investigated sample and reconstruct a composite metamorphic P–T path of evolution involving these pulses. In the second part we apply the garnet–orthopyroxene sequential kinetic modelling technique to this composite P–T path to obtain the duration and rates of heating/cooling and burial/exhumation of the individual metamorphic pulses. In the following we present the analytical protocols for measurements of mineral compositions that are used in metamorphic reconstructions, the methods of thermobarometry, and the approach for diffusion chronometry that were used.

2.1. Analytical techniques

Major-element mineral chemical analyses were carried out using a CAMECA SX-100 electron microprobe fitted with four spectrometers at the Department of Geology and Geophysics, Indian Institute of Technology (IIT), Kharagpur. Analyses were carried out at 15 kV accelerating voltage and 15 nA beam current. Natural mineral standards were used for calibrations which included orthoclase (for K and Si), jadeite (Na), wollastonite (Ca), hematite (Fe), corundum (Al), rhodonite (Mn), chromite (Cr). Analytical variation for primary standards was kept at or below ∼1.5 wt% for primary standards and ∼3 wt% for secondary standards.

Rare earth elements of representative garnet and orthopyroxene were analysed using Laser Ablation Inductively Coupled Plasma Mass spectrometry (LA-ICP-MS) at the same department using a Cetac 213 nm Nd YAG laser-ablation system connected to a Varian 820 quadrupole ICP-MS. The Laser ablation was done at 5 Hz pulse frequency, 60 μm spot size and 730 V energy. Analyses were performed in peak hopping mode with each analysis consisting of a 20 s background measurement with the laser turned off and 40 s peak signal measurement with the laser turned on. Calibration was done using NIST 610 and NIST 612 glass standards. Data reduction was done applying the Glitter software and using Si and Ca concentrations as internal standards. Prior to and during analytical sessions, analyses of the NIST standards were carried out periodically to monitor short-term systematic errors and to check for overall accuracy and reproducibility of results between the sessions. Typical uncertainties as estimated from repeated analyses of NIST 610 and NIST 612 glass standards are <11% and <4% respectively.

2.2. Methods of determination of metamorphic pressures (P) and temperatures (T) and P–T histories

We have adopted a conventional thermobarometric approach to obtain P–T conditions of metamorphism of the 3 metamorphic cycles (see Fig. 2 for a brief summary). This approach utilizes micro-domainal-scale equilibration of mineral assemblages and compositions to obtain P–T constraints of the different metamorphic stages that are recorded in the polymetamorphic garnet + orthopyroxene granulite.

Peak P–T conditions for each metamorphic stage (e.g., M_{1P}, M_{2P}, M_{3P}, where P refers to metamorphic peak) have been computed following the approach of simultaneous solutions of