

## **CHAPTER-8**

### **TECTONO-METAMORPHIC EVOLUTION**

This chapter attempts to discuss the tectono-metamorphic evolution considering petrographic evidence, geochemical signatures, P-T path, and geodynamic conditions. The metamorphic evolution of the study area around Betul Belt reveals of a wide variety of rocks, which are affected by three stages of metamorphism (M1 to M3).

#### **8.1. Metamorphic condition**

Various approaches are employed to extract the geological history of the Betul Belt (BB), yielding essential facts that constrain its evolution. The evolutionary explanations for granulite are documented through various mineral assemblages and associations found in different rock types, as well as through the examination of fabrics and textural relationships.

In addition to the significance of the physical mineral textures, other imperative components such as major, trace and rare earth elements and their isotopic composition provide crucial information about the rock's genesis and evolution. The objective of estimating P-T and calculating mineral equilibria is to decipher relevant information on granulitic rocks which provides reliable information relating to their burial and exposure on the surface through the geologic time.

The areas around Betul Belt has been studied based on different tools such as petrography, mineralogy, phase petrology, geothermobarometry, phase equilibria modelling, and geochemistry, based on this, construction of P-T path was done to divulge its metamorphic evolution.

### **8.1.1 Petrographic evidences**

The field of metamorphic petrology has been utilised to interpret the mineral composition and microstructural evidence of burial/exhumation and heating/cooling events that have affected pre-existing sedimentary, igneous, and metamorphic rocks. These processes include subduction, accretion, and collisional orogenesis. Petrologists engage in a range of investigations, including the examination of the pressure-temperature-time history of rocks across different spatial and temporal contexts. The utilisation of quantitative P-T-t routes offers valuable insights for the parameterization of subduction zone dynamics and collisional orogenesis. By incorporating the provided pressure-temperature-time (P-T-t) data, valuable insights can be obtained on the geodynamic and tectono-metamorphic evolution, hence shedding light on the historical development of the lithosphere.

#### **8.1.1.1 Mafic granulite**

##### **8.1.1.1.a Prograde assemblage**

An inclusion of clinopyroxene + amphibole + plagioclase + ilmenite + quartz present within garnet porphyroblast as the earliest distinct mineral phase (Fig.4.2b and 4.3c-d). The recrystallization of clinopyroxene develops this early assemblage; amphibole and plagioclase further maintain the equilibrium phase after the garnet formation. This prograde metamorphic association was developed from the pre-existing mineral assemblage presumed to derive from the older metamorphic or magmatic origin. At this stage, a stable mineral association indicates upper-amphibolite facies.

##### **8.1.1.1.b Peak assemblage**

The peak metamorphic assemblage is characterized by the Hbl+ Opx + Cpx + Plg + Ilm + Qz. This peak stage is characterized by coexisting matrix of coarse-grained

clinopyroxene, amphibole, plagioclase and quartz along with sporadic remnant garnets. It is suggested that orthopyroxene and clinopyroxene formation at an equilibrium state of the peak stage along with plagioclase.

#### **8.1.1.1.c Post-peak assemblage**

Clinopyroxene + orthopyroxene + plagioclase symplectite assemblages represented as the first retrograde stage of post-peak assemblages. Reaction texture and petrographic association (Fig.4.2c) delineate the metamorphic evolution of mafic granulite, and consequently, it consists of the retrograde assemblages under which opx along with cpx and plagioclase breaks in several stages. The amphibole mineral dominates this late-retrograde assemblage at this stage hydrous phase dominated over the anhydrous mineral phases. These are the amphibolite facies assemblage Amp + Ilm + Qz and this is inferred to be cooling stage. Textural association shows that opx and cpx are replaced by the amphibole (Fig.4.4a).

#### **8.1.1.2 Pelitic granulite**

##### **8.1.1.2.a Pre-peak assemblage**

Fine-grained aggregates of opx, quartz, plagioclase, biotite and ilmenite minerals are present as enveloping material of porphyroblastic garnet (Fig.4.2c). The presence of these minerals outside the garnet suggests that opx formation has occurred through the assimilation of garnet. Hence, these mineral phases are referred to as a pre-peak assemblage of the M0 metamorphic stage.

##### **8.1.1.2.b Peak assemblage**

The peak metamorphic stage of pelitic granulite shown by the appearance of opx + cordierite by the disappearance of garnet and quartz, this reaction texture is

represented by the inclusion of garnet and quartz in the granular aggregates of opx and cordierite where Sillimanite laths are observed in close proximity to the garnet porphyroblast. (Fig.4.3d).

#### **8.1.1.3.c Post-peak assemblage**

The visual characteristics of the orthopyroxene phase are a consequence of isothermal decompression, as evidenced by the post-peak composition of pelitic granulites. The most elevated attainable compositions of pelitic granulites have manifested, including garnet, cordierite, sillimanite, plagioclase, biotite, K-feldspar, melt, ilmenite, and quartz. Two potential responses can be identified regarding the texture of cordierite as observed in Betul pelitic granulites. The textural evidence reveals the occurrence of cordierite grains surrounding the garnet grains within the corona. (Fig.4.3e).

#### **8.1.2 P-T-t Path**

Three types of thermodynamics methods were used to compute P-T conditions, i.e., conventional (mono-equilibrium) geothermobarometry, multi-equilibrium geothermometry, and forward modelling. These methods yielded more or less same results for granulites of the Betul Belt. P-T-t paths represent a rock or a terrain through P-T space with time. It is the sequence of P-T conditions experienced by a rock unit during regional metamorphism. The P-T path can be grouped into two types viz., the clockwise and anti-clockwise path. Peak temperatures follow the peak pressures in clockwise P-T path and the peak temperature is succeeded by peak pressures in anti-clockwise path. To formulate the tectonic models for the evolution of granulite terrains, the proper evolution of P-T paths is essential. P-T paths can be inferred using estimates of pressure and temperature from the minerals' paragenetic sequence. The data provided

by geothermobarometry for the metamorphic rocks of the study area suggest that these high-grade rocks have witnessed and undergone various geodynamic processes through a various degree of change in pressure and temperature along with the Earth's history, this metamorphic evolution of granulites concerning time represents a P-T-t path of the rock. The determination of the pressure-temperature path of metamorphic rocks is one of the most critical aspects in understanding the rocks' evolution since it can reveal many constraints such as the heat and pressure achieved during peak metamorphism, local structural setting and tectonic process. Many workers have derived the P-T path in investigating the evolution of Orogenic belts through time [478-485]. Qualitative and quantitative methods can estimate the pressure and temperature experienced by metamorphic rocks during metamorphism and subsequent cooling or decompression during upliftment.

P-T path has been constrained for Betul Belt (BB), using two different rock types such as pelitic granulites and mafic granulites. A combination of micro-textures, mineral prograde and retrograde reactions, and the P-T estimates derived from mineral chemistry data of coexisting mineral pairs have been utilized to evaluate the different metamorphism grades P-T-t paths. Based on geological, petrographic and micro-textural studies, it is inferred that the various rock types in the study area have undergone a granulite facies metamorphism and suggest a distinct near Isothermal Decompression (ITD) path.

#### **8.1.2.1 Mafic granulite**

The metamorphic assemblages and textural relationship have been described with special emphasis for non-garnetiferous mafic granulites of Betul Belt. The mafic granulites have a distinctive mineral assemblage orthopyroxene + clinopyroxene +

plagioclase + amphibole + biotite + ilmenite + quartz. P-T pseudosection modelling shows mineral assemblage opx- cpx- amp- plg- bt- ilm- qz to be stable at the P-T range between >6.5 to 8.5 kbar and ~600 to 850°C. Bulk rock composition modelling provides significant knowledge about mineral nucleation, development, and ingestion in multivariate mineral assemblages, as well as regarding alleged microstructures with prograde metamorphism until achieving the peak condition, it can be shown by comparative changes in the expected mineral abundances (in mol% ) ([486] and references therein).

The study demonstrated that the mafic granulite underwent metamorphism inside the pentavariant stability field (opx, cpx, amp, plg, bt, ilm, qz) in the NCKFMASHTO system. The estimated pressure-temperature (P-T) conditions for this metamorphism ranged from 6.0 to 7.5 kbar and 700 to 850°C. The  $PT_{av}$  (pressure-temperature average) was limited by the internally consistent dataset of a specific type of rock called two-pyroxene mafic granulite. This rock was found at a pressure of 8.66 kilobars and a temperature of 900°C. It was observed that a pressure value of around 8.99 kilobars corresponds to a crustal thickness of approximately 24 kilometres, with a gradient of 3.5 kilometres per kilobar. The mafic granulites likely underwent exhumation to the Earth's surface as a result of tectonic activity. Subsequently, they would have been subjected to various geological processes, which manifested as enclaves within the surrounding granitic gneisses. The emplacement of the mafic granulite occurred during the Neoproterozoic period, as documented by previous studies ([74] and references therein). This phenomenon has been attributed to the collision of continents during the amalgamation of the Rodinia supercontinent.

### 8.1.2.2 Pelitic granulite

The pseudosection of pelitic granulite was constructed using the NCKFMASHTO thermodynamic system as depicted in Figure 7.5. The pelitic granulite exhibited pre-peak metamorphism (M0), followed by peak metamorphism (M1), and thereafter underwent an isothermal decompression (ITD) course (M2). The pre-peak metamorphism is characterized by a pressure-temperature (P-T) condition of around 3.2 kilobars and 620°C. During this stage, the sample under investigation consists of diminutive cordierite and biotite crystals, and quartz grains which enclose a larger garnet porphyroblast, resulting in the disintegration of garnet. The primary metamorphic event (M1) is distinguished by the presence of garnet, sillimanite, plagioclase, biotite, K-feldspar, ilmenite, melt, and quartz as a stable mineral assemblage. This event exhibits a limited temperature range but a significant pressure range. However, determining the precise pressure-temperature conditions necessitates the use of  $X_{Mg}$  isopleths for different minerals. The isopleths representing the ratio of magnesium (Mg) to the sum of magnesium, iron (Fe), and calcium (Ca) in the mineral Grt, as well as the ratio of Mg to the sum of Mg and Fe in the mineral Bt, have been graphed in order to approximate the maximum pressure-temperature (PT) conditions during metamorphism. These conditions vary between 6.8 and 7.2 kilobars of pressure and 650 to 800°C, as depicted in Figure 8.9b. Based on the aforementioned interpretations, it was hypothesised that the pelitic protolith had a constrained deposition time, thereafter becoming buried within the lower crust and undergoing metamorphism to form pelitic granulites at the peak metamorphic event (M1). The cordierite included in this pelitic granulite is believed to have originated as a result of increased pressure during the peak metamorphic event. This transformation is thought to have occurred through the interactions of garnet and quartz, which produced cordierite and orthopyroxene.

Sillimanite is observed to occur in metamorphic assemblages throughout both the pre-peak and peak stages of metamorphism. These assemblages commonly include garnet and cordierite, which exist in different stable phases. The abundant presence of large quantities of alumina in pelitic granulite is conducive to the development of sillimanite. Cordierite is observed to form at pressures below 6.8 kilobars. The isopleth lines of Crd ( $X_{Mg}$ ) and Grt ( $X_{Mg}$ ) are utilised to depict the isothermal decompression stage, occurring at around 5.5 kbar pressure and 800°C temperature. These lines indicate the ratio of Mg to the sum of Fe and Mg for Crd, and the ratio of Mg to the sum of Mg, Fe, and Ca for Grt. The felsic magmatism intruded pre-existing pelitic granulites, subsequently becoming an enclave.

## **8.2 Geodynamic condition**

The lithospheric evolution and Earth's thermal evolution is a response to geodynamics. There are significant variations recorded in the geological and tectonic style between Archean and post-Archean crust. Tonalite–trondhjemite–granodiorite (TTG) and grey gneisses suites are dominated in the Archean terrains with volcano-sedimentary greenstone belts forming a minor component [487]. However, the Earth's thermal evolution is poorly constrained [488-492], it is likely that prior to Archean (3.0 Ga) heating was mainly due to decay of radioactive substances that would lead to surface heat loss, whereas post-Archean (ca 2.5 Ga) period was dominated by secular cooling [493].

### **8.2.1 Mafic granulite**

Even though the CITZ in the central India is a famous mobile metamorphic belt containing three prominent supracrustal belts, the mafic granulites of Betul Belt have not been studied in detail. The different geotectonic setting has been suggested for the

evolutionary trajectory of the Betul Belt in relation to the CITZ which are as follows:

(i) The process of northward subduction of the Bastar craton (BC) beneath the southern Bundelkhand craton (BKC) resulted in the convergence of the South Indian block (SIB) with the North Indian block (NIB). This tectonic event led to the formation of rift basins and the emplacement of granitic intrusions, such as the Dongargarh and Malanjhand granitoids, within the Bastar craton. Ultimately, this geological process culminated in a collision between two continental masses. [222], (ii) The Mahakoshal belt was formed as a back-arc rift basin during the initial stage of northward subduction approximately 2.2 Ga [208], (iii) The basin underwent closure approximately 1.8 Ga, accompanied by the occurrence of extensive calc-alkaline magmatism, low pressure metamorphism, and reverse slip ductile shearing along the Son Narmada South Fault [15,216], and (iv) The Betul belt, situated to the south of Mahakoshal, underwent development as an intra-arc basin characterised by the presence of sediments and bimodal volcanics. It is hypothesised that this basin may have experienced closure around approximately 1.5 Ga. The process of subduction resulted in the collision of two continents, resulting to the formation of the RKG belt approximately 1.5 Ga. This collision caused the suturing of the BC and BKC regions. [70].

Mafic magma within the continental setting is generally linked to the lithospheric mantle extension [494-497]. Some of the workers have set up the relationship of generated magma due to the continent-continent collision between the Bundelkhand craton and Bastar craton [210, 253]. The subducted slab of Bastar craton beneath the CITZ was promoted to mantle upwelling, partial melting and further generation of mafic magma [74] around 1450 Ma and simultaneously another felsic gneiss protolith emplaced [73]. Th/Yb vs Nb/Yb discrimination diagram [341], the basaltic eruption is directly linked with volcanic arc setting. Basalt is calc-alkaline and

their generation related to island arc as well as subduction-related setting. Our study's result emplacement of the basaltic protolith was during the orogenic (compressive) tectonism at active margins of island arcs, and their regime was subduction-related and enrichment of lithospheric-mantle source region. The basaltic magma was formed at the orogenic tectonic environment; it resulted from the Bundelkhand- Bastar cratonic convergence, where the Bastar craton underwent subduction beneath the Bundelkhand craton and suffered breakdown into the lower lithosphere. The La/Yb vs Nb/La ( $Nb/La < 0.5$ ) discrimination diagram [333] is deduced the source of magma generated from the lower lithospheric mantle. Partial melting of subducted materials in the lithospheric mantle was formed as a basaltic magma rich in LREE and LILE but depleted in Nb, Sr, and Ti. In the study area, mafic granulites occur as enclaves within older gneisses which were the metamorphic product (granulite facies) of basaltic protolith [22, 23, 70, 73, 128-130, 210].

### **8.2.2 Pelitic granulite**

The geotectonic setting model suggests two Archean cratons; Bundelkhand craton and Bastar craton with the process of subduction and suturing occurred during the late Archean to Paleoproterozoic epoch. This led to the development of the sedimentary arc basin. The rift portion developed as a sink basin for sedimentation which arrived from the different sources as older Craton and Mobile Belt. The geochronological age of detrital zircon demarcates the protolith of pelitic granulites and their origin source ([22, 249], and in this study). The clockwise P-T path is inferred that peak P-T condition ranges from 6.8 to 7.2 kbar and 750 to 800°C and post-peak decompression P-T conditions varies from 5.60 to 6.50 kbar/ 790 to 820°C. A nearly isothermal decompression P-T path characterized the continental collision or overthrusting ([498] and references therein). The CITZ pelitic granulite underwent a

progressive phase of tectonothermal processes where initially occurrence of crustal thickening (M1) followed by quick exhumation of the crustal lithosphere (M2), these both processes indicate that collision or subduction-related tectonic processes. The subduction process reported by the emplacement of calc alkaline magmatism along the northern part of the CITZ (1.76–1.66 Ga: [253], and substantial magmatic emplacement recorded in Mahakoshal Belt (~1.8–1.7 Ga: [4]), which indicated that tectonothermal evolution of adjacent terrain of CITZ vis a vis Betul Belt basin during the late Paleoproterozoic time. Before the ~1.65 Ga age, there was a development of oceanic environment and deposition of the sediments from the adjacent terrain which contains the Paleoproterozoic volcano-sedimentary rocks.

Moreover, it was a great chance to develop an arc type basin or oceanic basin among the Bundelkhand and Bastar cratons during the period of 1.86–1.65 Ga [249]. Various categories of sediments were deposited within this oceanic basin, contributing to the development of high-pressure/middle-temperature pelitic granulites at ~1.63 Ga; it was due to subduction of the oceanic lithosphere. Pelitic granulite is the only rock type that consists of the first stage of metamorphism. The provided block diagram illustrates the sequential phases involved in the sedimentation of the protolith of pelitic granulites, as well as the initial stage of metamorphism (M1) of pelitic granulite. These granulites are observed as localized patches within the larger granitic gneisses found in the CITZ region (Fig 8.1).

### **8.3 Tectonometamorphic evolution of the Betul belt vis-à-vis the CITZ (Geochronological significance)**

The U-Pb zircon ages from the granite gneiss, rhyolite, and granites, and monazite ages from pelitic and mafic rocks of the Betul belt were reported for the first time by [350, 351, 352, 498, 500, 501, 502, 503, and 504]. The zircon and monazite ages and the whole-rock Sm-Nd isochron ages point to major geological events at ca. 2167-2051; 1715-1671, 1326 and 1120-954 Ma, involving several episodes of magmatism and metamorphism in the Betul belt (Fig 8.1). Despite more than three decades of research, the tectonometamorphic evolution of the CITZ is still a matter of contention, and numerous hypotheses have been put forth to account for its geological past. Based on the extant age, structural, and thermobarometric evidence, it can be inferred that the CITZ underwent a polyphase geological evolution throughout the Proterozoic period. This history encompassed numerous cycles of volcanic sedimentary deposition, deformation, metamorphism, and magmatism [501, 504]. The U-Pb zircon, monazite, and whole-rock Sm-Nd isochron ages range between 2167 Ma and ca. 934 Ma attesting to the protracted geological evolution of the Betul belt. The major age peaks retrieved represent the imprints of magmatism and tectonothermal events from the Paleoproterozoic to the Neoproterozoic in diverse tectonic settings. The A1-type nature of 1715 Ma rhyolites and the 1671 Ma Morkha granite imply within plate emplacement in an anorogenic environment. The deposition of clastic sedimentary rocks followed volcanic activity, as evidenced by the presence of shales and phyllites in the central part of the Betul Belt. The igneous activity culminated with the emplacement of the Navegaon granite in a post-orogenic setting between ca. 1079 and 954 Ma. The ~1.0 Ga event recorded in the Betul belt is also seen in the rocks of the Ramakona– Katangi granulite and the Balaghat–Bhandara granulite belts [504]. The

1026-954 Ma ages in the Betul belt can be correlated with the 1.0–0.9 Ga Sausar Orogeny [351, 504] and 1.0–0.9 Ga ages of tectonometamorphism in the Mahakoshal belt [502, 504].

### **8.3.1. Proterozoic geodynamics in the Betul belt and their regional and global significance**

The rocks of the Betul belt have undergone multiple significant tectono-magmatic events, as indicated by the field observations, petrographic analysis, geochemical/isotopic data, and geochronological constraints mentioned earlier. Many of these events occurred at the same time as geological events in the CITZ and other continents. The U-Pb ages and trace element chemistry of zircon from the Betul granite gneiss indicate that it developed by intracrustal melting around 2167 Ma. The existence of inherited zircon from 2720 Ma within the gneisses constrains the age of the felsic protoliths. Similar ages have been reported for the Bundelkhand gneisses, implying that they could have been protoliths. By 2167 Ma, the Bundelkhand Craton had merged with the Bastar Craton after a lengthy process including the accretion of multiple crustal blocks ([504] and *references therein*).

The geological evolution of the Betul orogenic belt can give key constraints on the CITZ's geological history and its relationship to the assembly and disintegration of former supercontinents. Columbia was one of the first supercontinents to exist. The Columbia supercontinent formed and disintegrated between 2.2 and 1.3 billion years ago. Global collisional events and subduction-associated accretion at continental margins characterized its assembly phase. The creation of rift valleys and anorogenic magmatic activity accelerated the fragmentation phase ([504] and *references therein*). The accretionary processes that led to the assembly phase of continental fragments

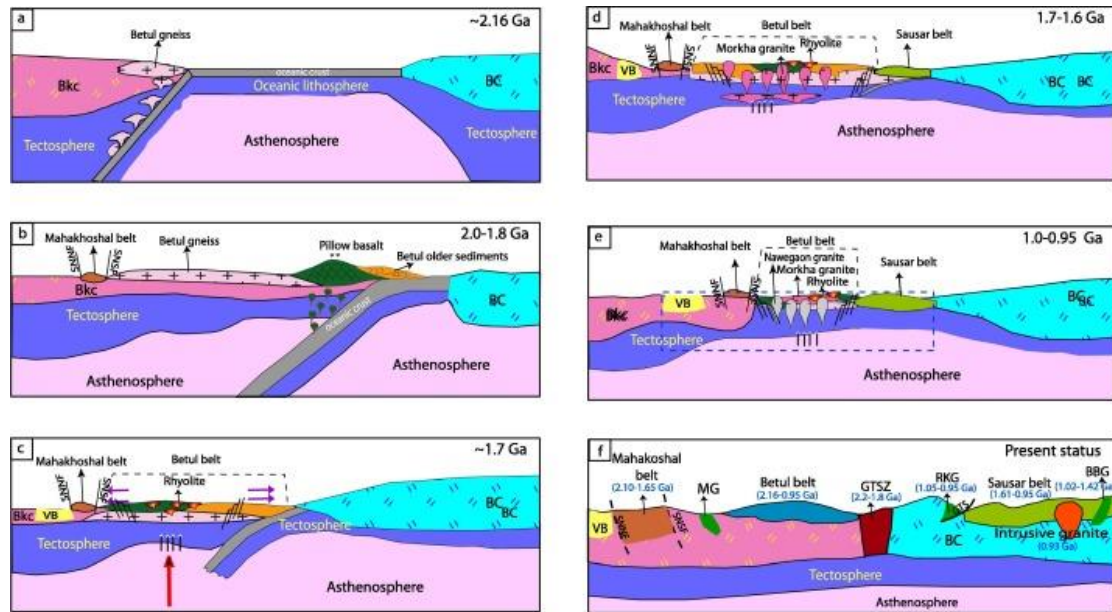
culminating in the Paleoproterozoic Columbia supercontinent can be linked to the amalgamation of the Bastar and Bundelkhand cratons around 2167 Ma and the formation of 2051 Ma arc-related pillow lavas in the Betul belt [504-506]. The ca. 2167 Ma granitoid activity in the Betul belt is correlatable with global orogenic events [507,508], which have also been reported elsewhere, including in South America, Africa [509-510], Canada [511], Baltic shield [512], Gawler Craton [513], Western Australia [504, 514,515] China [516] and India [517].

The extrusion of rhyolite and the emplacement of anorogenic granite in the Betul belt show evidence of anorogenic magmatism around 1750-1650 Ma. This occurrence coincided with Western Australia's Capricorn orogeny within the Columbia supercontinent [518-519]. The Late Paleoproterozoic extensional magmatism in the Betul belt can be linked to global anorogenic magmatism in the Columbia supercontinent framework. These Paleoproterozoic geological processes are also linked to regional events in other parts of peninsular India, such as the North Singhbhum Orogenic Belt (ca. 1850 Ma) [501,504], the Mahakoshal belt, the Satpura belt (ca. 1850-1800 Ma), and the Chhotanagpur Gneissic complex [504,520,521].

The emplacement of gabbroic rocks in the Betul belt between ca. 1320-1240 Ma represents the next stage of evolution in the CITZ and can also be linked to crustal extension during the breakup of the Columbia supercontinent. This phase also opened up the Sausar sedimentary basin between 1.54 Ga and 1.06 Ga in the middle Proterozoic, and is roughly coeval with 1.45 Ga extensional tectonics in the nearby Chhotanagpur Gneissic Complex [352, 504 *and references therein*].

The deposition of granite rocks at 1079-954 Ma marks the end of evolution in the CITZ, as evidenced by U-Pb zircon and U-Th monazite geochronology. Laurentia,

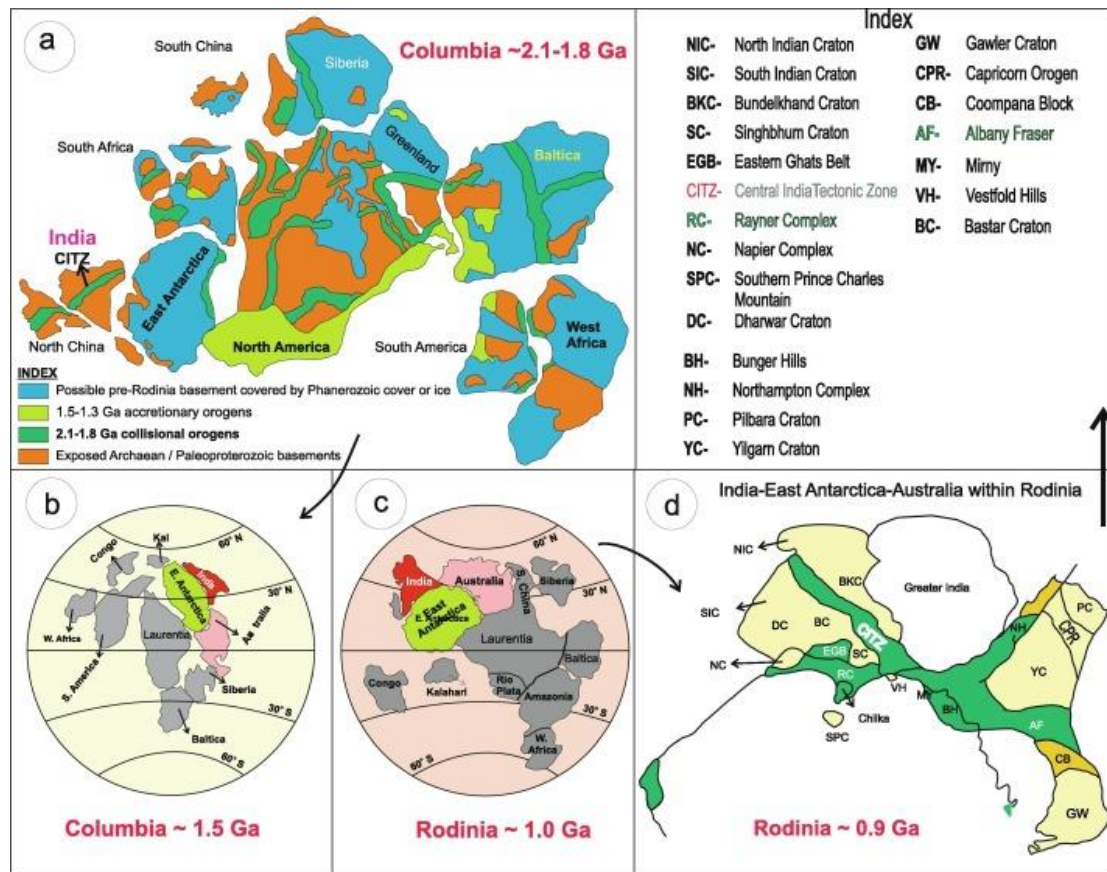
Baltica, Australia, India, east Antarctica, and many other continents were influenced by the 1.3-0.9 Ga global orogenic event [504, 522 and references therein]. It is related to the formation of the Rodinia supercontinent [523 and references therein].



**Fig 8.1** Sequence of cartoons (not to scale) illustrating the geodynamic evolution of the Betul Belt involving multiple episodes of accretion, arc magmatism and extension due to the Northward subduction of the southern block (Bastar Craton—BC) under the northern block of Bundelkhand Craton (BKC) and development of the Betul Belt along with other supracrustal belts such as Mahakoshal belt and Sausar belt (after [504]).

[504] attempted to link the location of the CITZ in the detailed configuration of the Columbia and Rodinia supercontinents (Fig 8.2). Although the precise placement of Indian landmass within the Rodinia supercontinent is unknown [524, 525] the Greater Indian Landmass, which is divided by a network of interconnected c.1.0 Ga orogenic belts, resembles a tiny Rodinia [352, 504 and references therein]. Here, the CITZ is also shown as proposed by [518 and 519], in which the North China Craton (NCC) was linked to the India Shield based on the Archean to Paleoproterozoic correlations between the two cratons as well as between the Trans-North China Orogen and the Central Indian Tectonic Zone [526-528]. The Betul belt is an important crustal unit that has the potential to help unravel the large scale tectonic processes associated

with the Columbia and Rodinia supercontinents because it preserves geological evidence of multiple collisional, accretionary, and extensional tectonics (ca. 2.16-0.95 Ga) within the timeframe of the assembly and breakup of these two supercontinents.



**Fig 8.2** Reconstruction of the Columbia supercontinent showing the proposed position of India, including the CITZ, between 2.1 Ga and 1.5 Ga, and that of Rodinia at 1.0-0.9 Ga (c-d). Fields were redrawn from [518, 529-532]. The tectonothermal events identified in the Betul belt largely coincide with the events associated with the assembly and dispersal of the Columbia and Rodinia supercontinents (after [504]).