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PALEOPROTEROZOIC S-TYPE GRANITES FROM LESSER HIMALAYA, INDIA: COMPOSITION, ZIRCON GEOCHRONOLOGY, ND-SYSTEMATICS AND GEODYNAMIC SETTING

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The Proterozoic granites and gneisses of the Himalayan orogen, particularly those exposed in the Lesser Himalaya, provide essential insights into the geodinamics of the northern Indian craton. Here, we investigate the Toneta granites of the Garhwal Himalaya using whole-rock geochemistry, zircon U–Th–Pb geochronology, and whole-rock Sm–Nd isotope systematics to constrain their petrogenesis, source characteristics, and tectonic significance. Zircon U–Th–Pb dating yields a crystallization age of 1845 ± 19 Ma, with inherited zircon cores at 3.52, 2.78, 2.62, and 2.10 Ga, indicating recycling of Paleoarchean to Paleoproterozoic crustal components. Sm–Nd isotopic data further support a significant contribution from ancient Archean crust. The granites are strongly peraluminous (A/CNK = 1.01–2.40) and characterized by high SiO_2, Al_2O_3, and K_2O contents, together with depletion in Ba, Sr, Nb, and Ti and enrichment in Rb, Th, U, and Pb, supporting their S-type affinity. Chondrite-normalized REE patterns show LREE enrichment, relative HREE depletion, and pronounced negative Eu anomalies, indicating significant feldspar involvement during partial melting and/or magmatic differentiation. The combined geochronological, geochemical, and isotopic characteristics suggest that the Toneta granites formed predominantly through partial melting of metasedimentary crust containing an Archean component. Their emplacement at ca. 1.85 Ga is interpreted to reflect crustal thickening and thermal reworking during a Paleoproterozoic convergent tectonic episode. These features are consistent with an accretionary–collisional tectonic setting associated with the assembly of the Columbia (Nuna) supercontinent at ca. 1.85 Ga. The Toneta granites thus provide important evidence for Paleoproterozoic crustal recycling and stabilization of the northern Indian continental crust.

Keywords: S-type granites; Paleoproterozoic; Garhwal Himalaya; Archean crustal recycling; Columbia Supercontinent; Continental collision; Crustal evolution

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С. Мишра[1, 2], А. Слабунов[2]*, М. Ф. Серка Руиз[3], В. Сингх[4], Э. Гонзалез-Партида[3]. ПАЛЕОПРОТЕРОЗОЙСКИЕ S-ГРАНИТЫ МАЛЫХ ГИМАЛАЕВ (ИНДИЯ): СОСТАВ, ГЕОХРОНОЛОГИЯ ЦИРКОНА, ND-СИСТЕМАТИКА И ГЕОДИНАМИЧЕСКИЕ РЕКОНСТРУКЦИИ

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Протерозойские граниты и гнейсы Гималайского орогена, особенно широко представленные в пределах Малых Гималаев, являются важным источником информации о палеогеодинамике северной части Индийского кратона. В настоящей статье подводятся итоги исследования гранитов Тонета Гарвальских Гималаев с использованием геохимии пород, U–Th–Pb геохронологии циркона и изотопной системы Sm–Nd для определения их петрогенезиса, характеристик источника и тектонической обстановки формирования. U–Th–Pb датирование циркона определяет возраст кристаллизации 1845 ± 19 млн лет, тогда как унаследованные ядра циркона характеризуются возрастными популяциями 3,52; 2,78; 2,62 и 2,10 млрд лет, что свидетельствует о переработке палеоархейского–палеопротерозойского континентального материала. Данные Sm–Nd также подтверждают значительный вклад древней архейской коры в формирование гранитов. Граниты характеризуются резко перлюминиевым составом (A/CNK = 1,01–2,40), повышенными содержаниями SiO_2, Al_2O_3 и K_2O, обеднением Ba, Sr, Nb и Ti и обогащением Rb, Th, U и Pb, что подтверждает их S-типовую природу. Нормализованные по хондриту спектры редкоземельных элементов характеризуются обогащением легкими РЗЭ, относительным обеднением тяжелыми РЗЭ и выраженными отрицательными Eu-аномалиями, указывающими на существенную роль полевых шпатов в процессе частичного плавления и/или последующей магматической дифференциации. Совокупность геохронологических, геохимических и изотопных данных свидетельствует о том, что граниты Тонета сформировались преимущественно в результате частичного плавления метаосадочной коры, содержащей архейский компонент. Их внедрение около 1,85 млрд лет интерпретируется как результат утолщения коры и ее термической переработки в ходе палеопротерозойского конвергентного тектонического эпизода. Эти особенности согласуются с аккреционно-коллизионной тектонической обстановкой, связанной со сборкой суперконтинента Колумбия (Нуна) около 1,85 млрд лет назад. Таким образом, граниты Тонета предоставляют важные свидетельства палеопротерозойской переработки и стабилизации континентальной коры северной части Индии.

Ключевые слова: S-гранит; палеопротерозой; Гархвальские Гималаи; рециклинг архейской коры; Суперконтинент Колумбия; коллизия; эволюция земной коры

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1. Introduction

Paleoproterozoic granitoids of the Lesser Himalayan Crystalline Sequence (LHCS) provide important evidence for the early evolution and reworking of the northern Indian continental crust (Fig. 1). Regional studies in Himachal Pradesh, Garhwal–Kumaun, and adjoining sectors have documented widespread granitoids associated with metasedimentary and gneissic rocks [Valdiya, 1980; Sharma, 1983, 1998]. Early Rb–Sr studies established ages around 1.84 Ga in Himachal Pradesh [Frank, 1977], while subsequent zircon geochronology demonstrated widespread ca. 1.80–1.87 Ga felsic magmatism in the Lesser Himalaya [Miller et al., 2000; Gupta and Kumar, 2023]. This database has been further expanded by recent studies that have recognized Paleoproterozoic

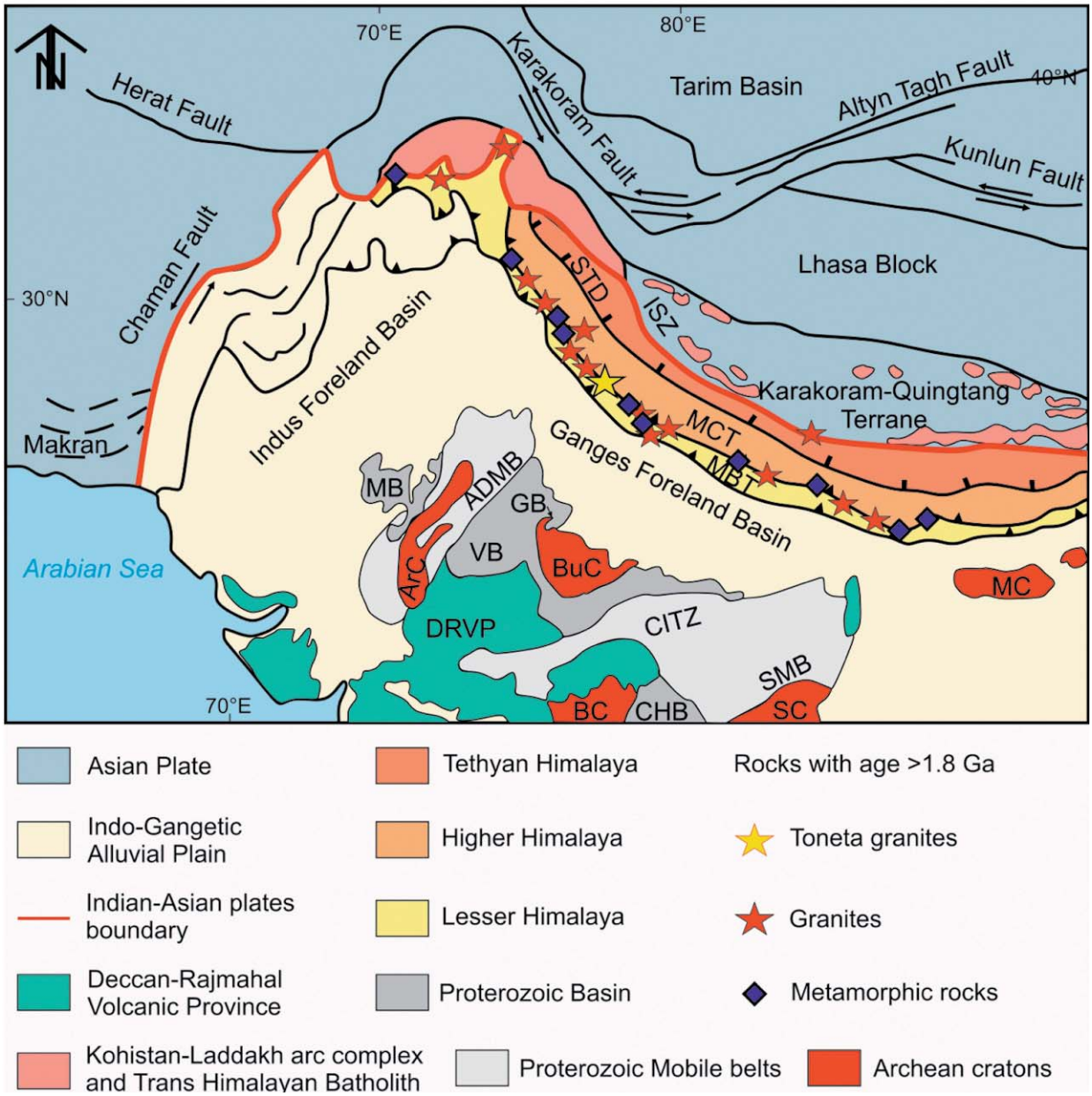


Fig. 1. Schematic map of structural divisions of the Himalaya and the adjacent part of the Indian Shield [Butler, 2019; Jain et al., 2020; Mishra et al., 2022 and references therein]. ADMB – Aravalli-Delhi Mobile Belt; ArC – Aravalli Craton; BC – Bastar Craton; BuC – Bundelkhand Craton; CHB – Chattisgarh Basin; CITZ – Central Indian Tectonic Zone; DRVP – Deccan-Rajmahal Volcanic Province; GB – Gwalior Basin; ISZ – Indus Suture Zone; MB – Marwar Basin; MB – Meghalaya Craton; MBT – Main Boundary Thrust; MCT – Main Central Thrust; SC – Singhbhum Craton; SMB – Singhbhum Mobile Belt; STD – South-Tibetan Detachment; VB – Vindhyan Basin

granitoids and orthogneisses throughout the Himalayan belt and highlighted both ancient crustal reworking and juvenile magmatic contributions [Yang et al., 2022; Imayama et al., 2023]. The tectonic significance of this magmatism is still debated. Geochemical and isotopic studies have interpreted Paleoproterozoic magmatism in the Lesser Himalaya as related to subduction, active continental margins, rifting, or crustal extension [Yang et al., 2022; Gupta and Kumar, 2023]. Recent work in the Arun sector also suggests that ca. 1.85–1.78 Ga magmatism may represent a regionally extensive crustal system, although a rift- or plume-related origin has been proposed for parts of this complex [Imayama et al., 2025].

The Toneta granite of the Garhwal Himalaya provides an important example of Paleoproterozoic S-type magmatism. Zircon U–Th–Pb dating yielded a crystallization age of 1845 ± 19 Ma, with inherited zircon populations at 3.52, 2.78, 2.62, and 2.10 Ga [Mishra et al., 2021]. The strongly peraluminous composition and Sm–Nd isotopic characteristics suggest a major contribution from the ancient crust as well [Mishra et al., 2022]. In this paper, we integrate these data to assess the source and petrogenesis of the Toneta granite and its implications for the Paleoproterozoic crustal evolution.

2. Geological Setting and Field Characteristics

The Lesser Himalaya is characterized by vast exposures of Precambrian crystalline and metasedimentary rocks recording a protracted pre-Himalayan crustal evolution. Paleoproterozoic granitoids occur as leucocratic, felsic, locally porphyritic, and variably foliated bodies associated with gneisses and metasedimentary rocks [Valdiya, 1980; Sharma, 1983, 1998]. The Toneta granite occurs within the crystalline domain of the Garhwal Himalaya (Fig. 1), where it forms resistant, generally massive to weakly foliated exposures. Close-up exposures show a leucocratic, medium- to coarse-grained granite with locally inequigranular or porphyritic textures.

The granite is mainly composed of quartz and feldspar with minor muscovite and biotite and accessory zircon, monazite, apatite and tourmaline [Mishra et al., 2021, 2022]. The zircon grains are oscillatory zoned and contain quartz, monazite and apatite inclusions, suggesting a magmatic origin [Mishra et al., 2021]. The mineral assemblage and strongly peraluminous composition are consistent with an S-type affinity.

The Toneta granite forms part of a broader ca. 1.8–1.9 Ga magmatic episode recognized throughout the Lesser Himalaya. In the outer Kumaun Himalaya, zircon U–Pb data indicate ca. 1.80–1.87 Ga felsic magmatism with crustal reworking, magma mixing and juvenile input [Gupta and Kumar, 2023].

3. Geochemical, Geochronological and Isotopic Characteristics

The Toneta granite is strongly peraluminous, with A/CNK values of 1.01–2.40, SiO_2 contents of approximately 73–76 wt.%, Al_2O_3 of 12–14 wt.%, and K_2O of 4.5–6.2 wt.% [Mishra et al., 2022]. Low CaO, MgO, TiO_2, and P_2O_5, together with enrichment in Rb, Th, U, and Pb and depletion in Ba, Sr, Nb, and Ti, characterize an evolved crust-derived magmatic system. Chondrite-normalized REE patterns show LREE enrichment relative to HREE, with $(La/Yb)_N = 1.61–15.08$ and pronounced negative Eu anomalies ($Eu/Eu^* = 0.12–0.31$). These characteristics indicate a heterogeneous ancient crustal source, rather than dominantly juvenile Paleoproterozoic crust. Negative εNd (t) values and T_{DM} model ages of ~2.5–2.7 Ga from the Sm-Nd data independently support considerable Archean crustal residence [Mishra et al., 2022]. Inherited zircon cores at 3.52, 2.78, 2.62 and 2.10 Ga indicate the magma interacted with much older crustal material. Zircon U-Th-Pb geochronology results in a crystallization age of 1845 ± 19 Ma [Mishra et al., 2021]. These characteristics imply important feldspar control during partial melting and/or magmatic differentiation.

New data from the Wangtu Gneissic Complex also indicate granite-gneiss crystallization at 1872.1 ± 2.5 and 1861 ± 13 Ma, confirming the regional significance of this age interval [Hifzurrahman et al., 2026]. In addition, the age of metamorphic processes in the schists hosting the granites was estimated using monazite. Metamorphism under upper amphibolite-facies conditions occurred between 1851 ± 20 and 1839 ± 22 Ma [Hifzurrahman et al., 2026] – that is, synchronously with the collisional granites.

4. Petrogenesis and Geodynamic Significance

The strongly peraluminous composition, S-type geochemical characteristics, and mineral assemblage indicate that the Toneta granite was generated predominantly from crustal material. Its low P_2O_5, high Rb, and depletion in Sr and Ba are compatible with melting of metasedimentary protoliths followed by feldspar-controlled evolution. The inherited zircon populations demonstrate that the source region contained Archean and Paleoproterozoic components, while the Nd model ages indicate long-lived Archean crustal residence.

We therefore interpret the Toneta granite as the product of partial melting of metasedimentary crust containing a substantial Archean component. Crustal thickening and thermal reworking provide plausible mechanisms for generating such melts during Paleoproterozoic tectonothermal activity. However, the available evidence does not uniquely distinguish a continental arc from other convergent or extensional settings. This caution is important because recent studies from the Lesser Himalaya have produced contrasting interpretations, including subduction-related [Yang et al., 2022], rift-related [Gupta and Kumar, 2023], and plume- or rift-related models [Imayama et al., 2025].

The 1845 ± 19 Ma age of the Toneta granite falls within a major interval of Paleoproterozoic magmatism broadly associated with Columbia–Nuna assembly. Recent studies from the Wangtu Gneissic Complex identify ca. 1.87–1.86 Ga magmatism and interpret the northern Indian margin in an active-margin framework, whereas other regional studies favour extension or rifting during this period [Gupta and Kumar, 2023; Hifzurrahman et al., 2026]. Thus, the Toneta granite is best interpreted as evidence for Paleoproterozoic crustal melting and recycling during a major tectonothermal episode, rather than as unequivocal evidence for one specific tectonic setting.

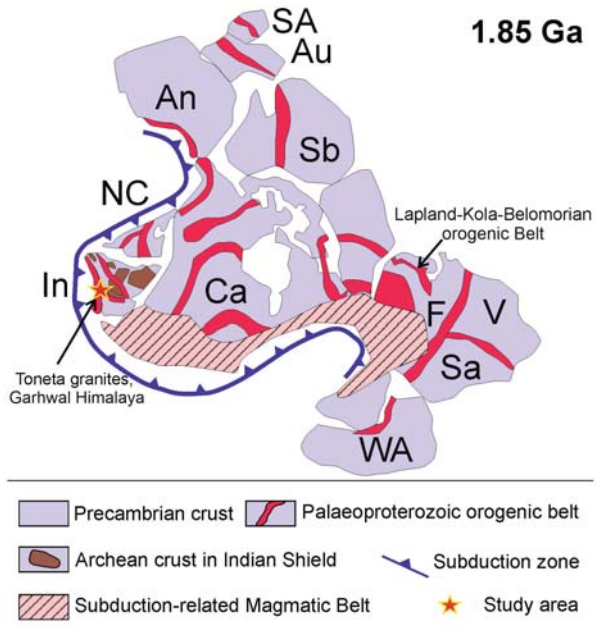


Fig. 2. Locations of the study area on the supercontinent Columbia (Nuna) model at ca. 1.85 Ga [Hou et al., 2008]. An – Antarctic Craton; Au – Australian Shield; Ca – Canadian Shield; F – Fennoscandia segment of the East European Craton (EEC); In – Indian Shield; NC – North China Craton; Sa – Sarmatia of the EEC; SA – South Africa Craton; Sb – Siberian Craton; V–Volgo-Uralia segment of the EEC; WA – West Africa Craton

The ca. 1.85 Ga age is also broadly comparable with Paleoproterozoic magmatism identified across the Himalayan crystalline domains (Fig. 2). Imayama et al. (2023) documented zircon U–Pb–Hf–O evidence from Garhwal basement rocks, while recent work from eastern Nepal identified ca. 1.85–1.81 Ga orthogneisses and suggested a broadly coherent Paleoproterozoic Himalayan crustal domain [Imayama et al., 2023, 2025]. The Toneta granite therefore contributes to the growing evidence for extensive Paleoproterozoic crustal reworking along the northern Indian continental domain of the Columbia (Nuna) Supercontinent (Fig. 2).

5. Conclusions

The Toneta granite represents a Paleoproterozoic, strongly peraluminous S-type granite with a crystallization age of 1845 ± 19 Ma. Inherited zircon populations at 3.52–2.10 Ga and Nd model ages of 2.5–2.7 Ga demonstrate substantial involvement of ancient Archean crust. Its geochemical characteristics indicate derivation predominantly from metasedimentary rocks, with significant feldspar control during magma evolution. We interpret Toneta magmatism as the result of Paleoproterozoic crustal melting and thermal reworking during a major tectonothermal episode. Its ca. 1.85 Ga age broadly coincides with Columbia (Nuna) assembly and contributes to evidence for extensive Paleoproterozoic crustal recycling and stabilization along the northern Indian continental domain.

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