ISSN 0972-2173

SGAT Bulletin

Journal of the Society of Geoscientists and Allied Technologists

Volume 27 • No. 1 • June 2026

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ISSN 0972-2173
RNI Regd. No: ORIENG/2000/2296

SGAT bulletin
Bi-annual

Vol. 27 o No. 1 o June 2026

Publication of the Society of Geoscientists and Allied Technologists
Complementary for Members of the Society

SGAT Bulletin

Vol. 27	No. 1	June 2026

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EDITOR'S COLUMN

"You can never cross the ocean until you have the courage to lose sight of the shore."

- Christopher Columbus

During the Last Glacial Maxima (LGM), consequent to the lowering of the sea level to 122 m below present sea level (psl), about 18 ka to 14 ka B.P., the entire continental shelf went subaerial and was subjected to aeolian process giving rise to formation of massive dunes with relief of 10 to 45 m, along Kerala, Tamil Nadu, Andhra Pradesh and Odisha coastal tracts. Subsequently, the deglaciation set transgressive phase in motion and the sea level rose and nearly stabilised at present see level (psl) since about 6 ka B.P., barring an episodic rise and fall of 5 m above psl during the Late Holocene. This led to the formation of present foredunes which are now seen fringing the present shoreline and beaches. The older dunes, formed during LGM, have developed a red coat, due to chemical weathering and leaching of iron bearing minerals, on the predominantly detrital particles and thus all the older dunes display various shades of red, which are referred to as Red Dunes and termed as *Teri* Sands in Tamil Nadu and *Erra Matti Dibbalu* in Andhra Pradesh. The top portion of the coastal Tamil Nadu Red dunes gave Optically Simulated Luminescence (OSL) age of 11 ka. While majority of the Teri sands are the products of aeolian processes, there are some inland red dunes which carry the signatures of fluvial processes and date between 2.3 and 4.1 ka (Jayangonda Perumal, 2014).

The red dunes have developed rather massive form in Tamil Nadu from Puducherry to Thoothukodi on the eastern side, Manavalakurichi-Muttam to Edavai on the western coast. It has been mapped by GSI on the leeward side of the present foredunes in Kerala, Tamil Nadu and also in Andhra Pradesh, between Rishikonda and Bhimunipatnam. Further northeast the older red dunes appear in smaller form and have been seen sporadically in the stretch of beach to the northwest of Gopalpur-Aryapalli and after a gap of nearly 60 km as small mounds south of Satpada, on Chilika Lagoon. While no detailed study was ever done on the red dunes of either Satpada or Aryapalli, quite a few publications have appeared on the red sand dunes of Tamilnadu and Andhra Pradesh, which describe the presence of heavy minerals-sillimanite, garnet, magnetite, ilmenite, rutile, zircon and monazite- though in lesser proportion than the heavy mineral concentration in the younger fore dunes. The Red dunes of Gopalpur and Satpada, from field relationship, appear to be older than the foredunes and contain small percentage of heavy minerals. The age of the red dunes, in Odisha sector, needs to be confirmed. However, it can be conjectured to have been formed during the Last Glacial Maxima and contain all the six heavy minerals present in foredunes. One of the heavy minerals, Monazite, is a phosphate of Cerium, Lanthanum, and radioactive Thorium, with the chemical formula as $(Ce,La,Th)\ PO_4$. Some researchers have found Rb, Sr, Cs, Ba, Sc, V, Cr, Co, Ni, Cu, Zn, Ga, Pb, Y, Zr, Nb, Ta and Th in the red dunes of Tamil Nadu though in very low concentration.

The coastal Teri sands of Tamil Nadu contain about 6 % to 13% of total heavy minerals with about 75% of ilmenite, leucoxene and rutile (S Chandrasekharan & C Murugan, 2001).

Based on the geological set-up it can be conjectured that the Red dunes of Gopalpur-Aryapalli coastal tract will not only have heavy minerals, but also expected to contain Rare Earth Elements, though in low concentration.

Dr. B. M. Faruque
Editor

Recommended reading:

R. Jayangonda Perumal (2014) Teri red sands, Tamil Nadu. In V. S. Kale (Ed) Landscapes and Landforms of India. World Geomorphological Landscapes. Springer Science.

S. Chandrasekaran & C. Murugan (2001) Heavy minerals in the beach and the coastal red sands (Teris) of Tamil Nadu. Exploration and Research for Atomic Minerals.

SGAT Bulletin
Vol. 27, No. 1, June 2026, pp. 1-17

PRECAMBRIAN GEOLOGICAL FRAMEWORK OF THE ODISHA STATE: IMPLICATIONS ON ITS MINERAL PROSPECTIVITY

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ABSTRACT

The state of Odisha exhibits a diverse physiography and a complex geological framework, encompassing rock formations ranging from the Archaean to Recent. Its geological architecture primarily constitutes parts of two Archaean Cratons, e.g., the southern part of the Singhbhum Craton and the eastern part of the Bastar Craton, along with the Proterozoic high-grade metamorphic terrain of the Eastern Ghats Mobile Belt (EGMB), Proterozoic platformal sequences of Chhattisgarh and Kolhan basins, metasediments of the Gangpur Schist Belt and the Mesozoic Gondwana sediments. The state is endowed with major ore deposits covering ferrous, non-ferrous and energy minerals, which are exploited since decades. With the increasing demand for new minerals keeping pace with the scientific and technological advancement and commitment for clean energy, search for critical and strategic minerals like Co, Ni, PGE, graphite, Nb-Ta, Sc, RM, REE, Li, Ti-V bearing minerals, has been prioritized. For the exploration of these minerals, a better understanding on the mineral systems with respect to the geological setting of a region is essential. The present write up attempts to highlight the Precambrian geological framework of the state and discusses about the mineral prospectivity of different geological segments for future exploration.

Keywords: *Singhbhum Craton, Bastar Craton, Eastern Ghats Mobile Belt, Geological Framework, Mineral System, Prospectivity, Mineral Exploration.*

INTRODUCTION

The state of Odisha, covering an area of over 1.55 million sq. km is situated along the eastern margin of the Indian Peninsular Shield. The state exhibits diverse physiography with about 575 km-long coastline along the Bay of Bengal. The state has a complex geological framework, comprising rock formations ranging in age from the Archaean to Recent. It is primarily constituted of two Archaean cratonic blocks - southern part of the Singhbhum Craton in the north and eastern part of the Bastar Craton in the west. The Proterozoic high-grade metamorphic terrane known as the Eastern Ghats Mobile Belt (EGMB) occupies the south-eastern part. These units are locally overlain by Proterozoic platformal sequences of the Chhattisgarh and Kolhan Basins, Mesozoic Gondwana sediments and Quaternary deposits. The intervening region between the EGMB and Singhbhum Craton is occupied by the late Archaean (~2.8 Ga) Rengali Province in Riamal-Pallaharha region (Nanda et al., 2022 and references therein). The Gangpur Schist Belt (GSB) is considered equivalent and westward extension of the North Singhbhum Mobile Belt (NSMB) and lies north of the Singhbhum Craton in Sundargarh-Jharsuguda-Raurkela region. GSB is separated from the craton by a shear zone (Chakraborty et al., 2018).

Tectonism, magmatism, metamorphism, and prolonged weathering have played a pivotal role in the genesis of Odisha's rich mineral resources. The Singhbhum Craton hosts significant deposits of iron ore, manganese ore, chromite, nickel, platinum group elements (PGE), gold, copper, limestone and china clay. In contrast, the EGMB is endowed with large resources of bauxite, graphite and manganese ore. Occurrences of rare earth element (REE) and/or rare metal-bearing granites and pegmatites and gemstones are also known. The coastal area is endowed with Beach Sand Mineral (BSM) deposits of ilmenite, rutile, garnet, sillimanite and monazite. The Gondwana basins located in Mahanadi and Ib river regions are notable for substantial reserves of power-grade coal and fireclay.

Major deposits of ferrous, non-ferrous, and energy minerals have been explored and exploited for decades. However, depletion of high-grade ores and increasing demand shifted attention toward exploration of concealed deposits, low-grade and secondary enrichment zones. The surge of demand for technological development and global call for reduction of CO_2 emission have placed heavy reliance on a set of critical minerals and elements which have insecure supply chain and whose occurrences are limited to specific geological environments. In recent years, conventional source-transport-trap concept-based ore deposit models have gradually evolved into the mineral systems approach (Muller et al., 2025). In order to place mineral deposits containing a specific association of critical metals together, these authors have grouped the numerous metallic mineral systems into five broad genetic types, viz., (1) magmatic, (2) magmatic-hydrothermal, (3) hydrothermal, (4) basinal hydrothermal and (5) sedimentary deposits. However, the broad classification can again be subdivided into specific subgroups, e.g., mafic-ultramafic Ni-Cu + PG systems and Komatiitic Ni-Cu or layered Cr-PGE systems. This concept considers ore formation as the outcome of large-scale tectonic and geochemical processes operating over broad spatial and temporal scales (Wyborn et al., 1994). The mineral system approach emphasises on regional prospectivity analysis by integrating geological, geochemical, geophysical and hydrogeological data, and extracting mineral system information from these by data-driven and knowledge-driven methods. It provides a predictive framework for identifying undiscovered mineral deposits, thereby improving exploration target in underexplored regions (Hagemann et al., 2016; McCuaig et al., 2010).

This article examines the mineral prospectivity of different crustal segments of Odisha based on available information on geological setting and mineralisation.

GEOLOGICAL FRAMEWORK OF PRECAMBRIANS OF ODISHA AND MINERAL PROSPECTIVITY

1. SINGHBHUM CRATONIC BLOCK

The southern segment of the Singhbhum Craton is exposed in the north Odisha. It is a well-preserved granite–greenstone terrane comprising granitoids and associated low- to medium-grade supracrustal sequences. The nucleus/core complex of the craton is exposed in the eastern part of the cratonic block in Odisha. It preserves lithological assemblage formed mainly between ~3.6 Ga and ~3.0 Ga (Nanda et al., 2022). In contrast, its western part, exposed in Sundargarh-Jharsuguda-Deogarh districts, comprises lithological assemblages formed mostly between ~3.0 and 2.8 Ga. The core complex of the Singhbhum Craton is marked by continuous granitoid evolution with early tonalite-trondhjemite-granodiorite (TTG) gneisses, followed by progressively potassic granites-granodiorites and terminal A-type granite–granophyre intrusions. The associated supracrustal succession also records a broadly comparable evolutionary history, beginning with the amphibolite grade Older Metamorphic Group (OMG; ~3.6-3.5 Ga), followed by the BIF-bearing Iron Ore Group (IOG), comprising low- to medium-grade metasupracrustal volcano-sedimentary sequences ranging in age from ~3.5 Ga to ~3.0 Ga or younger (Olierook et al., 2019; Nanda et al., 2022; Mukhopadhyay et al., 2025).The Singhbhum Craton also hosts mafic–ultramafic complexes and extensive dyke swarms, termed as the 'Newer Dolerite'. Undeformed platformal sedimentary sequences such as the Keonjhar Quartzite and the Kolhan Group unconformably overlie the granite–greenstone basement. While the granitoid core of the Singhbhum Craton is largely non-mineralized, the supracrustal belts, younger reworked granites and mafic–ultramafic intrusives host diverse world-class deposits of iron ore, manganese ore, chromite, and emerging prospects for Au, Ni, PGE, REE, and rare metals. These granitoids and supracrustal belts have potential for discovery of more such economically significant and critical mineral deposits.

I. Mineral Potential of Granitoids

The Singhbhum Craton preserves one of the oldest records of crustal evolution. The cratonic nucleus is dominated by TTG gneisses, known as Older Metamorphic Tonalite Gneiss (OMTG), Singhbhum Granite Complex (east), and Bonai Granite Complex (west). While the tonalite-trondhjemite suite of rocks was emplaced during 3.45–3.44 Ga, the granites were emplaced during 3.35–3.32 Ga (Upadhyay et al., 2014). Occurrence of xenocrystic zircons of ~4.2 Ga from Champua, provides evidence of an older felsic proto-crust of Hadean age (Chaudhuri et al., 2018). The early Ca-Na-rich TTG suites are metaluminous I-type granitoids and interpreted to have formed through partial melting of hydrated primordial mafic crust or amphibolitic protoliths. Subsequent crustal reworking led to emplacement of voluminous K-rich granitoids. These were followed by intrusion of A-type Mayurbhanj, Tamperkola and Pal Lahara Granites and S-type granite plutons. Overall, the granitoids of Singhbhum Craton are compositionally diverse and I-, S- and A-type characters are exhibited by different batholiths and plutons. Geochemical trends from TTG to potassic granitoids reflect progressive crustal maturation and reworking during the evolution of the craton.

Syngenetic ore deposits are very rare in granites due to high viscosity of granite magma and low concentration of ore metals. I-type metaluminous granitoid complexes and TTG suite of granitoids and the expansive Singhbhum-Kaptipada-Nilgiri Granite complexes of the Eastern Singhbhum Block in Odisha are largely barren with respect to major metallic mineralisation. However, high volatile (H_2O, B, F) contents of granitic magma lead to reduction of viscosity and enrichment of Sn, W and U, which may form syngenetic Sn-W, U deposits. Generally, reworked, evolved and volatile-rich S-type granites can be fertile for primary Li, Be, Sn, W deposits, and granites associated with alkaline magmatism may possess Nb-Ta and REE deposits. Many granitic bodies in the Western Singhbhum Block around Sundargarh-Jharsuguda-Deogarh area associated with Gangpur, Bonai and Darjing Groups of supracrustals (GSI, 2017) are more evolved, tourmaline-bearing, indicating their volatile-rich geochemical nature and form favourable areas for U-Th, Nb-Ta mineralization and REE-RM prospects (Nanda et al., 2022).

Be, Li, Nb-Ta, Sn, REE being incompatible in rock forming minerals, these are commonly concentrated in late fractions of pegmatite melts. Granitic magmas, with very high initial H_2O (up to 12 wt.%) content, lead to generation of pegmatite melts on fractional crystallisation. Collisional to post-collisional S-type granites, formed by melting of marine metasediments, contain anomalous amounts of Li, Cs, Ta Be, Rb, Ga, Sn, B and P. Such rocks can be identified by presence of boron (tourmaline) and phosphorus (apatite) enrichment. The pegmatites and granitic pegmatites associated with such granitic plutons are potential for Li-Cs-Ta (LCT-type) mineralization and semi-precious stones. The A-type (anorogenic) granites, from depleted mantle source or remelted due to ponding of basalts, contain anomalous amounts of Nb, V, F^+, Be, Sn, U and Th. Such rocks are commonly enriched in fluorine (fluorite, fluoro-apatite). A-type granites (e.g., ~2.8 Ga Tamparkola Granite) may be targets for such rare metal potential. The pegmatites associated with such granitic plutons are potential for

Nb-Y-F (NYF-type) mineralization and semi-precious stones. Zones rich in U, REE and rare metals occur in Jharsuguda–Bamra sector (Pandey et al., 2007). Notably, the pegmatites associated with the Jharsuguda Granite are classified as the 'Beryl type' rare-metal pegmatites belonging to N-Y-F family (Pandey et al., 2007), indicating potentiality of the region for Nb, Y, REE, and related critical mineral resources.

The occurrence of A-type and S-type granites, highly fractionated pegmatites and volatile-rich granitic melts further suggests strong potential for concealed pegmatite hosted rare-metal and critical mineral deposits. Continued integrated studies involving geochemistry and isotope geology may help delineate economically viable resources of rare-metal & rare-earth elements along with U and Th within the marginal parts of the Singhbhum Craton segment in Odisha.

II. Mineral Potential of Supracrustal Belts

(a) OMG Supracrustals:

The Older Metamorphic Group (OMG) is dominated by amphibolite-facies metasediments such as para-amphibolites, quartzite, schists (cummingtonite, kyanite), marble, minor BIF and ortho-amphibolites. The metavolcanic components are limited and sparsely distributed. As such, these rocks are not significant for mineralisation

(b) IOG Supracrustals:

The Iron Ore Group (IOG) supracrustals include Banded Iron Formations (BIF) bearing volcano-sedimentary sequences. These form discontinuous curvilinear belts around the eastern (~3.5 Ga Gorumohisani Belt; Jodder et al., 2021), southern (~3.37-3.50 Ga Tomka-Daitari Belt; Krayer et al., 2026) and western (~2.7 to 2.5 Ga Bonai-Kendujhar Belt; Mukhopadhyay et al., 2025) peripheries of the cratonic nucleus. These are composed of chemogenic sediments such as BHJ, BHQ, BMQ and banded chert, volcanic rocks (mafic-felsic compositions), tuffs and volcaniclastics along with clastic metasediments such as shale/phyllite and quartzite. The IOG supracrustals are of great economic significance due to association of huge iron and manganese ore resources in these belts. The chemogenic BIFs and Mn-bearing pelitic metasediments of the IOG have undergone hydrothermal and supergene enrichment, forming major iron and manganese ore deposits. The key mining belts include Horse-shoe shaped Jamda-Koira belt, Daitari, Gandhamardan and Badampahar-Gorumahisani, contributing significantly to India's high-grade iron ore production. Haematite is the main iron ore in the deposits of Odisha, while magnetite is insignificant. Total haematite reserves/resource of Odisha is about 9,409 million tonnes, which accounts for about 39% total haematite reserves/resources of India.

(i) The **Badampahar-Gorumahisani Belt** (BG Belt) occurring in the eastern part of the Singhbhum cratonic nucleus is dominated by meta-chert, banded magnetite quartzite (BMQ) and mafic volcanics (Ghosh and Baidya, 2017). This belt is characterized by higher grade metamorphism and association of ultramafic volcanic (komatiites) in contrast with the other belts. The acid volcanic yielded an age data of 3.51 Ga (Jodder et al., 2021) and komatiites an age of 3.34 Ga (Bachhar et al., 2021).

(ii) The **Tomka-Daitari Belt** (TD Belt) occurring in the southern part of the Singhbhum cratonic nucleus comprises mainly metachert and metabasalt. Minor but important BHJ horizons host the iron ore deposit. Associated dacite yielded an age of 3.51 Ga (Mukhopadhyay et al., 2008).

(iii) The horse shoe shaped **Jamda-Koira Belt** (or Bonai-Kendujhar Belt) occurring in the western part of the Singhbhum cratonic nucleus has voluminous BIF and shale/tuff, which are ferruginous and manganiferous at places. Chert, banded haematite jasper (BHJ), tuff, pyroclastics, stromatolitic dolomite and mafic volcanics ranging from andesitic basalt to picritic basalt are also present. Association of dolomite and manganiferous shale is unique to this IOG belt. The BIF in the Western IOG records sedimentation during the Neoarchean-Paleoproterozoic transition (ca. 2,734 Ma to 2,513 Ma) (Mukhopadhyay et al., 2025). Nanogold occurrences are gradually being identified in carbonate phases mainly in dolomite in many geological formations in parts of Precambrian terranes under specific environment. New studies can be directed towards these new avenues.

In addition to the major belts, isolated occurrences of supracrustal sequences of smaller extent occur (i) near Gandhamardan (Kendujhar), in Simlipal Complex and Hadgarh Belt in the eastern part of the craton, and (ii) low-grade pelitic to psammopelitic rocks around Darjing and Bonai areas occurring towards the western part of the craton. The metavolcanic rocks of the IOG supracrustal sequences frequently show anomalous gold (Au) concentrations. Some important locations include southern extension of Kundarkocha gold mine of Jharkhand state and at Gopur in Kendujhar district. Isolated occurrences of aluminous laterite and low-grade bauxite associated with the BIF-shale horizons have been reported from Kadalia plateau and Kusumdih, in Sundargarh district. Laterite developed over the vast stretch of metavolcanics in Malangtoli-Nuakot sector hold promise for the higher concentration of Scandium (Sc).

III. Mineral Potential of Mafic-Ultramafic Complexes

The mafic-ultramafic complexes occur as discontinuously disposed intrusives, roughly along the southern margin of the craton bordering the Rengali Province. Important complexes include the Sukinda ultramafic complex and the Baula–Nausahi ultramafic complex (BNUC) (~3.12 Ga; Augé et al., 2003). These complexes, emplaced into the IOG supracrustal rocks, host major deposits of high-grade metallurgical chromite, besides large quantum of low-grade Ni-ore and Pt-Pd prospects. The Sukinda Complex hosts the largest chromite deposit of the country. Odisha contributes more than 95% of total chromite production in the country for domestic use and export. In BNUC, the early magmatic fractionates (dunite-peridotite) contain chromite, while later phases (pyroxenite–gabbro–anorthosite) host Cu–Ni sulphides, Au, and PGE (Pt–Pd) associated with ferritchromit and magnetite. Some of the dunite-peridotite-orthopyroxenite with high MgO content (~35 % or more) are used as flux material in steel industries. The Simlipal Complex also has intrusive dunite-peridotite-gabbro in the form of thick sill (e.g. Amjori sill). Exploration for Ni & PGE was carried out earlier. However, further exploration is not feasible at present, as it falls within the Similipal National Park and Tiger Reserve. The volcano-sedimentary sequence in the Simlipal Complex occurs in a near circular basin. Some authors argue that the basin was formed by meteorite impact (Singh et al., 2021).

The Mayurbhanj Gabbro (~3.09 Ga; Manikyamba et al., 2020) occurs as discontinuous intrusive bodies of gabbro-anorthosite-granophyre in the eastern margin of the craton bordering the Simlipal Complex (Saha,1994). Some of these gabbro-anorthosite bodies host Ti-V mineralisation in magnetite bands formed during late-stage magmatic fractionation. These are potential future sources of critical commodities like titanium and vanadium (Nayak et al., 2020). Report of gold (Au up to 396.5 ppb), PGE (PGE up to 1,094 ppb), sulphides and nano gold in altered feldspar, associated with Mayurbhanj Gabbro-Anorthosite complex at Sarat-Ghat near Noto, warrants further appraisal (Rasheed & Sarma, 2022). Small talcose meta-ultramafic bodies in the western block (Gurundia, Chandiposh) lack major ore deposits, but show beryl occurrences at granite contacts, indicating localised mineralisation potential. Extensive network of mafic dyke swarms (dolerite/quartz dolerite, minor peridotite-pyroxenite), belonging to the bracket term ‘Newer Dolerite’, intrude the older rocks at different times (~2.8, ~2.26 and 1.77 Ga; Srivastava et al., 2019). Some of these may have potential for Ni, PGE & Sc mineralisation. Moreover, these could provide pathways for movement of mineralising fluid.

IV. Mineral Potential of Siliciclastic Cover Sediments

Siliciclastic rocks, mostly conglomerate, gritty sandstone, quartz arenite occur discontinuously in large parts over the southern, central and northwestern part of the craton. These are grouped together as the Keonjhar Quartzite. This unit records development of stable siliciclastic shelf during the Mesoarchean (3.0-2.9 Ga) time. The basal conglomerate and grit of the Keonjhar Quartzite has been explored for Au and U at different locations (Mukhopadhyay et al., 2016). Though no major deposit has been located yet, the possibility cannot be ruled out. The Mankarchua Quartzite, considered equivalent to the Mahagiri and Keonjhar Quartzites unconformably overlie the Singhbhum/Bonai Granite and the Malangtoli Lava. The conglomerate unit contains variable proportions of detrital pyrite, arsenopyrite and uraninite representing a quartz-pebble conglomerate (QPC)-type U-Au deposit.

Archaean palaeosol horizons occur locally at the interface of Keonjhar Quartzite with Singhbhum Granite, indicating subaerial exposure and weathering/ hydrothermal alteration of the granites (Mukhopadhyay et al., 2014). These small discontinuous lensoidal to pocket type palaeosol outcrops are metamorphosed and contain pyrophyllite-an important industrial phyllosilicate mineral produced in Kendujhar and Mayurbhanj districts (Sahoo, 2020). Since kaolinite horizons developed over the granites are potential hosts for Nb, these pyrophyllite deposits may be explored for possible enrichment of Nb.

V. Mineral Potential of Platformal Sediments

Younger, undeformed platformal sediments comprising of sandstone, shale and limestone, known as the Kolhan Group, occur in the north-eastern part of the Singhbhum Craton. These sediments represent a stable shelf depositional environment. Although, no major known economic ore deposits are reported, limestone of the Kolhan basin is explored for cement industry.

2. BASTAR CRATONIC BLOCK

The eastern marginal part of the Archaean Bastar Craton is exposed in the western and southern parts of Odisha, covering parts of Sambalpur, Bolangir, Bargarh, Nuapada, Kalahandi, Nabarangpur, Koraput and Malkangiri districts. The granite-greenstone terrane of the craton is overlain by Proterozoic intra-cratonic sedimentary basins (known as the Purana basins), comprising thick sequences of sandstone, shale and limestone.

I. Mineral Potential of Granite-Greenstone Terrain:

The Archean Ca-Na rich TTG gneisses and granitoids are poor in metallic mineralisation. However, a small BIF hosted iron ore deposit occurs in a part of the Bengpal-Bailadila Supracrustals at Hirapur in Nabarangpur district. The greenstone rocks of the Bastar Craton are possible sources for the placer gold recovered through panning (e.g., Salimi in the Kolab River). Though economically viable primary gold deposits are yet to be established, scope for further exploration cannot be ruled out. Tin bearing S-type granites and associated Sn-Nb-Ta-Be-Li bearing albitised and greisenised pegmatites occur from Salimi in Malkangiri District of Odisha extending up to Dantewada in the Bastar for about 80 km stretch in NW-SE direction. These rocks host cassiterite, columbite-tantalite, beryl, lepidolite and amblygonite (Li-rich fluorophosphate) mineralisation (Faruque and Sarangi, 2020). These granitoid-pegmatite systems show promising potential for pegmatite hosted REE, rare metals (RM) and lithium. A small occurrence of chromite in ultramafic intrusive is known in Ramagiri area of Koraput district.

The contact zone between the Bastar Craton and the EGMB is marked by multiphase alkaline magmatism and defines a key mineralization corridor. These alkaline magmatic associations possibly represent a repository of REE as well as occurrences of lamprophyres and diamondiferous lamproites (e.g. at Kalmidadar, Nuapada district) along this zone suggesting a potential for diamond occurrence. In addition, outcrops of alkaline granites and rhyolites (Bhela-Rajna), fluorite-bearing granites (Nuapada) and granophyre-analcime syenite dykes (Paikmal) also hold enormous prospects for fluorite, REE and other rare metals.

II. Mineral Potential of Intra-cratonic Sedimentary Basins:

The Granite-Greenstone terrain of the Bastar Craton is overlain by thick sedimentary sequences in the multiple Proterozoic intra-cratonic basins in western Odisha, such as Khariar, Ampani, Indravati and Sabari. These basins are marked by thick sediments of orthoquartzite-carbonate-pelite, deposited in multiple sedimentary cycles interrupted by unconformities. Each cycle starts with arenaceous facies and ends up with shale-limestone facies. Presence of minor ~1,000 Ma felsic volcanics and pyroclastics are also reported in these basins. The limestone of these basins is of cement-grade and, therefore, currently exploited for cement industries. Presence of palaeosol has been reported at the unconformity base of the western and southern margins of Khariar basin. These are favorable locations for unconformity type uranium mineralization (Patra et al., 2013). These areas may be potential target areas for REE exploration also. Besides, glauconitic sandstone units have been identified in the Chhattisgarh basin, suggesting potential targets for potash mineralisation.

3. EASTERN GHATS MOBILE BELT

The Eastern Ghats Mobile Belt (EGMB) is an approximately 1,000 km long Proterozoic granulite belt developed along the eastern margin of the Indian Peninsular Shield, extending from Angul in Odisha to Ongole in Andhra Pradesh.

The belt comprises a diverse assemblage of high-grade metamorphic rocks, including the:

(i) orthopyroxene-bearing orthogneisses of mafic to felsic composition, collectively referred to as the Charnockite Suite;

(ii) granulite-facies metapelites, psammopelites, calc-silicate gneisses and marbles forming metamorphosed supracrustal sequences collectively referred to as the Khondalite Group;

(iii) associated metatexite and diatexite gneisses, garnetiferous granitoids, commonly mapped as leptynites;

(iv) diapiric intrusives of ~950-1,000 Ma massif-type anorthosite plutons;

(v) ~1,400-1,300 Ma deformed alkaline rocks (miaskitic nepheline syenite) along the craton-mobile belt contact zone disposed discontinuously in Koraput-Khariar-Sambalpur-Redhakhol-Riamal-Kamakhyanagar girdle (Ranjan et al., 2018; Sheikh et al., 2020);

(vi) ~980 Ma clinopyroxene-bearing syenite-clinopyroxenite bodies in Nayagarh area (Bhattacharjee et al., 2024).

The belt has undergone polyphase ductile deformation accompanied by long duration ultra-high temperature metamorphism (>900 °C). The dominant structural grain trends NE-SW, but gradually swings to WNW-ESE in its northern extremity. The EGMB has been divided into four lithozones: (i) Eastern Khondalite Zone (EKZ), (ii) Central Migmatite-Charnockite Zone (CMZ), (iii) Western Khondalite Zone (WKZ) and (iv) Western Charnockite Zone (WCZ) (Ramakrishnan et al., 1998). Based on isotopic signature of source of the granulites and tectono-thermal evolution of different segments, the EGMB is subdivided into Provinces and Domains, which are separated by major shear zones (GSI, 2020). Among these, the Eastern Ghats Province (EGP) extensively occupies the central and southern Odisha.

Tectonically, the EGP (north-western segment of the EGMB) has been thrusted westward over the passive eastern margin of the Bastar Craton, which is marked by prominent terrane-boundary shear zone. West-verging thrust systems have resulted in formation of nappes over the passive margin of the Bastar Craton, particularly in the Nuapada-Paikmal sector (Biswal et al., 2007). This contact zone is also locale of emplacement of lenses of miaskitic nepheline syenite during Mesoproterozoic age (ca. 1,300-1,400 Ma), for example, the Khariar Alkaline Complex in Nuapada district. A major tectonic feature cutting across the belt is the WNW-ESE trending Mahanadi Graben, which is often correlated with the Lambert Rift of East Antarctica. This graben hosts Gondwana sediments, including coal-bearing Lower Gondwana sequences in the Ib and Talchir regions.

The EGMB is an important repository of several economic minerals such as bauxite, graphite, manganese ore, crystalline limestone (marble), gemstones, pegmatite hosted rare metals (Be, Nb, Ta), dimension stone and several minor mineral resources. The lithological assemblages of the WCZ are largely barren. However, shear zones traversing these, which were the pathways for movement of mineralised hydrothermal fluid, are important exploration targets.

I. Mineral Potential of Metasedimentary Granulites

The granulite-facies pelitic-psammopelitic-calcareous metasediments of the Khondalite Zones (EKZ & WKZ) were associated with carbonaceous and manganiferous sedimentary protoliths. These horizons on metamorphism have been converted to crystalline graphite and primary manganese minerals respectively, mainly hosted in the pelitic metasediments. Manganese ores of the EGMB, the products of supergene enrichment of the primary Mn-minerals, are generally higher in phosphorus content compared to those of the Iron Ore Group. Discontinuous belts of potential graphite and manganese mineralisation have been identified and demarcated based on lithologies and structures in the belt (Behera and Mohakul, 2024). Subsequent deformation and supergene enrichment have played a role in their present disposition. Since the graphite is associated with anomalous V & Mo and Mn-ore with anomalous Co, as reported in many world occurrences, such occurrences are the ideal targets for these critical element concentrations. In the southern extension of the EKZ belt in Rajhamundry area of Andhra Pradesh, graphite is associated with wolframite and molybdenite (Umathay and Pophare, 2014).

The East Coast Bauxite deposits are spread over an area of ~25,000 Km^2, along a stretch of 300 km in the states of Andhra Pradesh and Odisha. Bauxite and aluminous laterite cappings occur extensively in the WKZ of the EGMB. These cappings are confined to gentle to moderately sloping areas with elevations of about 900 m to1,400 m above MSL. They are formed by in situ residual weathering of the parent rocks such as khondalite and peraluminous granite/charnockite units under tropical conditions during the Tertiary-Quaternary period. About 12 large cappings were explored in Odisha during mid-seventies and a total resource of about 1,572 million tonnes bauxite of average Al_2O_3 content of 45% was established. Odisha alone accounts for 41% of country's resources of bauxite (2,057 million tonnes out of 4,958 million tonnes; IBM year Book: 2024). The lithomarge associated with the bauxite deposits contain anomalous amounts of Ga and other critical elements, which needs further integrated holistic approach for re-evaluation.

II. Mineral Potential of Peraluminous Granites & Pegmatites

The anatectic melting of Al-rich metapelites of the EGMB generated diatexitic peraluminous granites and Al-Be-B-F bearing pegmatites in favourable zones. These pegmatites have produced precious-semiprecious gem minerals like aquamarine, heliodor, goshenites, V rich emeralds of beryl group; cat's eye/ cymophane and rare alexandrite of chrysoberyl group; schorl, verdelite of tourmaline group; topaz group (colourless and yellow); almandine, spessartine and hessonite garnets of garnet group; amazonite of feldspars group; sillimanite cat's eye; iolite of cordierite species; rock crystal, amethyst and citrine of quartz group and others. High temperature-pressure conditions of metamorphism along the northern and western margin of the EGMB bordering the Bastar and Singhbhum cratons led to formation of pockets of high Mg-Al granulites with assemblages of corundum (locally ruby), sillimanite, orthopyroxene, cordierite, sapphirine and spinel. Ruby is noticed locally at the contact of mafic-ultramafic granulites and peraluminous granite-pegmatite. The desilication of high Mg-Al melts at the contact of ultramafic bodies converted corundum into ruby (chromophore of chromium from the ultramafics entering corundum lattices). Such ruby occurrences are found in Jilingdar and Hinjlibahal in Kalahandi district. The miaskitic nepheline syenite and related alkaline rocks occurring at the contact zone between the EGMB and Bastar craton/Rengali Province are associated with low-silica peraluminous pegmatites, which occasionally host blue corundum (including sapphire). Both ruby and sapphire occurring sporadically along the craton-EGMB boundary are indicative of their localisation along high P-T zones marking subduction and continent-continent collision (Stern et al., 2013).

III. Mineral Potential of Shear Zones in the Contact Regions

The meta-igneous granulite assemblages of the WCZ are largely barren of mineralisation. However, shear zones traversing these, which were the pathways for movement of mineralised hydrothermal fluid are important exploration target locations. One such important location is the Adash Cu-Au deposit hosted in the northern extension of the WCZ in the Rengali Province. Sporadic Pb-mineralisation occurs within shear zone related vein quartz traversing charnockites near Saintala in Balangir district. It probably extends northward up to Karmeli in Baragarh district. The ferrodiorite and ferromonzonite representing late magmatic fractionates of ~950 Ma Anorthosite-Mangerite-Charnockite-Granite (AMCG) Complexes at Chilika, Balangir and Turkel massifs are reported to be rich in HFSE, P, Zr and REE (Raith et al., 1997). These late fractionates of high-Al source basaltic melts may have potential for HREE and may be targeted for exploration.

4. RENGALI PROVINCE

The Rengali Province comprises three distinct litho-tectonic domains: (i) southern granulite terrain (Adash-Rengali-Bhuban region), (ii) central segment of amphibolite-grade metasediments and migmatites and (iii) northern low-grade supracrustals (Deogarh region). Prior to 2000, the southern granulite terrain of the Rengali Province was traditionally included in the EGMB as part of the Western Charnockite Zone. The central and northern zones were considered as southern marginal part of the Singhbhum Craton. The Debagarh and Malyagiri supracrustals were regarded as equivalents of the Iron Ore Group (IOG), despite the absence of major banded iron formations (BIF). Studies post-2001 revealed that the granulites extending from the Badrama Complex in the west to Bhuban in the east, including Duburi-Jajpur Road up to the Brahmani Lineament (or Sukinda Thrust) represent a Neoarchaean province (2.7–2.9 Ga).

I. Mineral Potential of Southern Rengali Granulite Province

The high-grade metamorphosed volcanics and graphitic sediments of the Southern Rengali Province locally host promising Cu-Ni mineralisation and cryptic gold occurrences, as documented near Adash. Several pods and lenses of chromiferous ultramafics occur interdigitated with the granulites of the Bhuban-Jenapur segment in Sukinda-Tangarpada-Asurbandh belt in the southern Rengali Province. Chromite and Ti-V magnetite are the principal economic minerals in this segment, which also shows potential for platinum group elements (PGE). A notable occurrence of fuchsite quartzite containing detrital chromite is present in the area. The rock exhibits well-preserved sedimentary structures such as current bedding and graded bedding.

II. Mineral Potential of Central Rengali Province

The central zone of the Rengali Province is not known to host major ore deposits. However, the excellent development of porphyroblastic garnets (up to 20 cm in diameter) in psammopelitic amphibolite-grade kyanite-staurolite-muscovite schists in the Jhilli (Kamakhyanagar) area provides a source of semi-precious garnets, which are also suitable for use as abrasives. These staurolite-bearing schists may hold potential for lithium mineralization, as established in similar lithologies elsewhere (Xiao et al., 2026).

III. Mineral Potential of Northern Rengali Province

The northern zone of Rengali Province is akin to the southern marginal part of the Singhbhum Craton. The zone is known for emplacement of 2.8 Ga A-type granite plutons at Pal Lahara and Tamperkola. Though, this segment lacks any known major ore deposits, local occurrences of carbonaceous or graphitic schists have been reported. However, these granites and associated pegmatites may hold potential for REE and RM mineralisation.

5. GANGPUR SCHIST BELT AND UPPER BONAI/ DARJING GROUP

The ENE-WSW trending Gangpur Schist Belt (GSB) is a Proterozoic metasedimentary sequence comprising greenschist-amphibolite facies of arenaceous, argillaceous, calcareous and carbonaceous metasediments. The sedimentation in the GSB is estimated to have taken place between c. 1.65 Ga and c. 1.45 Ga. The GSB forms a regionally folded synclinorium in North Odisha. Towards south, this is underlain by an older Upper Bonai/ Darjing Group separated by a horizon of deformed conglomerate of Raghunathpalli Formation. The Upper Bonai/Darjing and the GSB are interpreted to be the westward extensions of the southern and northern domains of the North Singhbhum Mobile Belt respectively. Two-mica S-type granite bodies of Itma, Ekma and Timma localities, intrusive into the sequence, and recently dated at 1,777 ± 14 Ma (Chakraborty et al., 2018), are potential hosts to Sn-W-Li mineralisation.

I. Mineral Potential of metasedimentary rocks

Major limestone and dolomite horizons, used as raw material for cement and steel making, occur in the Biramitrapur Formation which extends for over 50 km and 96 km in the northern and southern limbs of the synclinorium respectively with average thickness of about 700 m. The syngenetic gondite-type manganese ore deposits occur interstratified with metapelites and metapsammites of the Goriajhor Formation in Sundargarh district. Four major ore assemblages have been recognized: Mn-oxide, Mn-silicate (Gondite), Mn-silicate-oxide and Mn-silicate-carbonate in this formation (GSI, 2017). Association of Co and Li in these litho-assemblages may be assessed.

Sedimentary exhalative (SEDEX) type Pb-mineralization associated with garnetiferous quartz-muscovite schist in the Sargipalli prospect extends over 1,200 m strike length with a width of 20 – 40 m in contact with a calc-magnesian rock (GSI, 2017). The principal ore mineral is galena, with subordinate amount of pyrite, pyrrhotite, arsenopyrite, cubanite, bornite and tetrahedrite.

II. Mineral Potential due to granite & pegmatite emplacement

The impure carbonate lithologies are locally converted to calc-silicate hornfels and skarn rocks as a result of contact metamorphism and metasomatism due to emplacement of peraluminous granitoids. Tungsten mineralization is reported in the skarns of this region at the contact of massive granites (Chowdhury and Lentz, 2011). This occurs at the contact between calcite-bearing dolomitic marbles and in close spatial association with the Pb-Cu-Ag sulfide deposits. Overall, the lithology, tectonics, magmatism, and metamorphism in the Gangpur Group indicate potentiality of this belt for Sn-W-Mo, Cu-Pb-Zn, Cs-Li-Ta and REE mineralisation.

III. Mineral Potential of Quartz-pebble conglomerates

Significant uranium and anomalous concentration of gold are present in basal as well as interlayered quartz-pebble conglomerate (QPC) bands of Baratangra-Bagiyabahal-Daldali tract (Jana et al., 2016). The occurrence of Au-Ag-PGE has been reported from the uraniferous QPC horizons at Mankarchua area. The detrital uraninite, magnetite and chromite grains are mostly embedded in chlorite masses in the matrix. The basal QPC in Odisha sector needs reassessment.

6. DHANJORI GROUP & ITS MINERAL POTENTIAL

The Dhanjori Group of rocks occurs in the NE corner of the Singhbhum Craton in part of Mayurbhanj District extending into Jharkhand. This Group comprises (i) the Upper Dhanjori Formation constituted of tholeiitic basalt (locally pillowed), ultramafic intrusives and tuffaceous sediments, and (ii) the Lower Dhanjori Formation constituted of quartzite (arkosic, gritty and conglomeratic), phyllite, gritty and pebbly shale with minor quartzites, ultramafics and mafics (Gupta et al., 1985). Based on new U-Pb detrital zircon ages from the Dhanjori and Chaibasa Formations, it is inferred that the lower part of the Dhanjori succession was deposited during the Mesoarchean (<2,990 Ma) and Chaibasa sedimentation took place during the Paleoproterozoic (<1,870-1,830 Ma) (De et al., 2026). The southern part of the Singhbhum Shear Zone passes through this volcano-sedimentary sequence and has hosted Cu-mineralisation in Kesharpur-Madanasahi area. Tectonically interleaved mafic-ultramafic schists within the Romapahari granite are sites of copper mineralization with enhanced nickel concentration (Tripathi et al., 2024). The ongoing exploration has established significant reserve of Cu and associated U (Mahanta et al., 2021).

Minor veins of anatectic peraluminous Be-bearing granite and pegmatite intersecting mafic-ultramafic schists/phyllonites (talc-chlorite schists) in the Singhbhum Shear Zone have produced sporadic occurrence of emerald and locally phenakite in Saraskana area, north of Bangiriposhi which extend northwards into Jharkhand (Sahu et al., 2018; Minz & Sing, 2025). Chromium from ultramafic schists acted as the chromophore.

PROSPECTIVITY AND TARGETS FOR FUTURE EXPLORATION

The supracrustals especially their intrusives, quartz reefs and residual/lateritic profiles are the possible targets for the future exploration for cryptic rare elements and noble metals.

The pegmatites in the western Singhbhum and the eastern Bastar cratonic blocks are fertile and need reinvestigation for REE, RM, Li and Sn-W-Mo. The EGMB, which is constituted of residual products of a high grade, longlasting metamorphism, migmatisation and polyphase deformation, is generally depleted in basemetals and lighter elements. However, peraluminous pegmatites and quartz veins containing Be-B-F-Al minerals, some of which are locally gem minerals, occur in the reactivated shear zones and zones of extensive anatectic melting of supracrustals (Khondalite Group of metasediments). Besides, such zones also have at places galena and allanite-fluorite mineralisation in Bolangir region. These pegmatites and quartz veins need a relook for REE, RM and Li.

The graphitic horizons and skarn zones at the contact of calc-granulites/gneisses with granitoids may be examined for V and W-Mo. The small and dispersed inland riverine placers in khondalite dominant zones may be as rich as the Puri-Ganjam beach placers in Th, Ti, Zr and REE. A review of this aspect may be rewarding. The reworked staurolite bearing metasediments in the Rengali, Darjing, Bonai and Gangpur Groups may be explored for Li. Much of the global supply of light REEs (LREE; La-Sm), including Nd and Pr, is mined from carbonatites. However, carbonatites typically lack heavy

REEs (HREE; Eu-Lu and Y) such as Tb and Dy, which enhance the high-temperature properties of permanent magnets. Instead, these highly sought after heavy REEs are predominantly extracted from clay-hosted (or regolith-hosted) REE deposits (Knorscha et al., 2025). The regolith, palaeosols and clays in Precambrian and Phanerozoic formations may be investigated for adsorbed REE, Nb, Sc and Rare Metals.

A summarized account of the mineral potential of mainly Proterozoic litho-sequences of Odisha is tabulated (Table-1) and reflected on the geological map of Odisha demarcating the mineral prospectivity (Figure-1).

Conclusion

Mineral resources are the products of complex geological processes developed under a myriad of tectonic regimes leading to their uneven distribution. Although traditional exploration techniques practiced through generations achieved significant success in identifying and utilising major mineral resources, industrial and technological progress coupled with commitment towards net-zero emission enhanced the demand for critical minerals especially in greenfield areas. Thus, it is imperative that superior conceptual models based on better understanding of the metallic mineral systems are employed to prognosticate the mineral prospectivity of a terrain.

The state of Odisha is endowed with major mineral deposits (Iron and Mn ore, Bauxite and Chromite), the exploitation of which have been the major driving factor for its economic development. Odisha is emerging as a significant player in the critical minerals sector owing to its favourable geological setting and structural framework. The extensive beach placer deposits of monazite, derived from rocks of the Eastern Ghats Mobile Belt (EGMB), together with the discovery of REE mineralization in syenite and syenite pegmatites by GSI in Nayagarh area, have opened a new geological province for rare earth elements (REE) within the Eastern Ghats Mobile Belt (EGMB). Rare-metal pegmatites enriched in beryllium (Be), niobium (Nb), tantalum (Ta) and other critical elements, occurring along prominent shear zones associated with the Tel and Mahanadi river systems, represent promising future exploration targets. The fractionated zones of the Bolangir Anorthosite Complex may also host high-field-strength elements (HFSE) such as zirconium (Zr), hafnium (Hf), niobium (Nb), tantalum (Ta) and titanium (Ti). A preliminary assessment of Odisha's geology further suggests potential for scandium (Sc) enrichment in supergene zones developed over mafic rocks as well as Nb-REE mineralization within clay-rich weathering profiles over granitic terrains. These geological environments warrant systematic exploration for critical mineral resources.

The present paper while dealing with the geological complexities of the State, attempted to highlight the possible areas having potential for critical mineral occurrences. The data based modern exploration strategies supported by AI & ML and with a thorough understanding of the mineral systems can certainly achieve the target of identifying greenfield critical mineral occurrences.

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Table-1: Mineral prospectivity of Archaean-Proterozoicterranes of Odisha

Geological Province	Sl. No.	Geological Formation		Known economic mineral occurrences or deposits	Prospect of other mineral & elements
1. Singhbhum Craton:	**1a.**	IOG supracrustals (Meso-Neoarchaean)	BIF: BHJ, BMQ, BHQ	Iron ore deposits (hematite and magnetite)	Au
			Mafic-UMF volcanics / metavolcanics	Au prospects	Cu, Ni, Sc
			Mn-shales, wad	Mn-oxide ores	Li, Co
			Black chert, carbonaceous phyllite		Au
			Stromatolitic dolomite (in Horse-shoe basin)		Au
	1b.	Mafic-UMF Intrusives (Mesoarchaean)	Dunite-peridotite-chromitite-enstatitite	Orthomagmatic Chromite, Supergene Ni-laterite	Sc
			Clinopyroxenite-gabbro-ferrogabbro-anorthosite (Baula-Nausahi)	Xenolithic chromite, magnetite, ferritchromit Pt-Pd	Cu, Ni, Au
			gabbro-ferrogabbro -anorthosite	Ti-V magnetite	Pt-Pd, Cu, Ni, Au
	1c*.	Neoarchaean Paleosol between the Singhbhum Granite and cover sediments	low grade metamorphism of residual weathering product of granite	Pyrophyllite	REE, Li, Nb
2. Bastar Craton Granite-Greenstone Terrain	**2a.**	Metavolcano-sedimentary supracrustals	BIF hosted iron ore in Nabarangpur area	Iron Ore	
	2b.	Stanniferous granite	Cassiterite in pegmatite	Sn, Nb, Ta	Li, REE, RM
	2c.	Alkali granite/rhyolite (pantellarite)	Intrusive in to Bastar gneisses at Bhela-Rajna		REE, Li
	2d.	Granophyre, analcime syenite	Intrusive in to Bastar gneisses & granite		REE, Li
	2e.	Lamproite	Intrusive in to Bastar gneisses & granite	Diamond	
Proterozoic Sedimentary Basins on the Bastar Craton	**2f.**	Sabari basin	Limestone		
	2g.	Khariar basin	Rhyodacite flow in metasedimentary sequence		REE

3. EGMB	**3a.**	High-grade pelitic metasediments interlayered with carbonaceous, manganiferous and calcareous bands of the Khondalite Group	Remobilasation & concentration of graphite	Graphite	V, W, Mo
	3b.		Supergene enrichment of Mn from Mn-metapelite	Mn-oxide ore (Mn)	Li, Co
	3c.		Supergene enrichment of bauxite from metapelite	Bauxite (Al)	Ga, Ge, REE, Ti, Th
	3d.	Anorthosite plutons	Late fractionate: ferrodiorite		REE
	3e.	Syenite-pyroxenite	Cpx bearing syenite of Nayagarh-Khandapara	REE in allanite-apatite-titanite	
	3f.**	Alkaline Complexes	Gneissic nepheline syenite	Nepheline, sapphire	REE
4. Rengali Province	**4a.**	Granulite facies metavolcanics and graphitic schists	Associated with charnockite	Cu, Ni, Au	
	4b.	Kyanite-staurolite-garnet-muscovite schist	Meta-psammopelite		Li, REE
	4c*.	Mafic-ultramafic bodies	Intrusives	Chromite	PGE
	4d*.	Rhyolite and microgranite in Sukinda-Kalinganagar-Jajpur road	Intrusives		Li, REE
5. Gangpur & Bonai /Dhanjori Metasediments	**5a.**	Metasediments in Gangpur Schist Belt	Manganiferous metapelites & Limestone	Mn Ore, Limestone	
		Contact between Garnet-mica schist & dolomite	SEDEX type	Pb-Zn prospect at Sargipalli	
	5b.	Tourmaline bearing Granite/Pegmatite	Peraluminous volatile-rich granites		Pb, Nb-Ta, REE, B, Be
	5c.	Quartz-pebble conglomerate (QPC) in Mankarchua area	Baratangra-Bagiyabahal-Daldali tract	Au-Ag-PGE-U	
6. Dhanjori Group	**6a.**	Sheared mafic volcanic	Singhbhum Shear Zone	Cu, U	
	6b.	Granite-UMF contact	Singhbhum Shear Zone	Emerald	REE

* - is not reflected on the map. 3f**- see the legend & map.

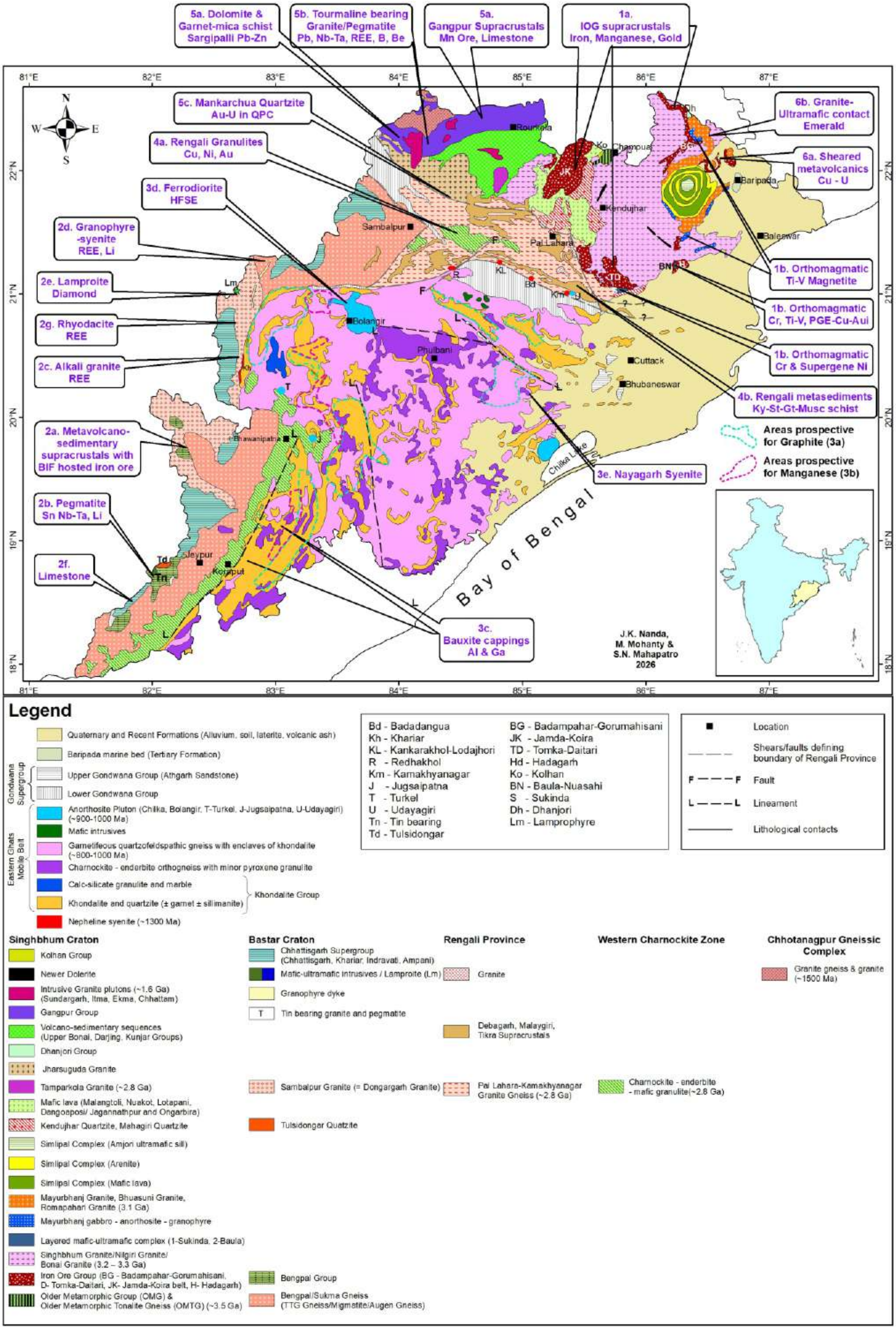

Figure-1: A generalised geological map of Odisha showing major geological formations/groups/suites and important economic mineral deposits. Map modified after Nanda, Mohanty and Mahapatro (2022). For explanation of serial numbers in the stickers refer the Table-1.
The pointer from the sticker of the map shows an approximate location on the map about one of the prospects/occurrences/deposits.

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SGAT Bulletin
Vol. 27, No. 1, June 2026, pp. 18-30

NEXT-GENERATION MINERAL PROCESSING: INTEGRATION OF ENERGY-EFFICIENT COMMINUTION, COARSE PARTICLE FLOTATION AND AI-DRIVEN SMART OPTIMISATION FOR SUSTAINABLE BENEFICIATION

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ABSTRACT

The mineral processing industry is undergoing a major technological transformation due to declining ore grades, increasing mineralogical complexity, rising energy consumption and stringent environmental regulations. Conventional beneficiation systems based on energy-intensive comminution and empirical flotation control are increasingly inadequate for the sustainable processing of low-grade and complex ores. This review critically examines recent advancements in next-generation mineral processing technologies, focusing on the integration of energy-efficient comminution, coarse particle flotation (CPF) and intelligent digital optimisation systems. Advanced comminution technologies such as high-pressure grinding rolls (HPGR) and stirred mills are discussed in terms of their ability to improve mineral liberation while significantly reducing specific energy consumption and overgrinding. The review further evaluates CPF technologies as transformative approaches for reducing grinding requirements and improving recovery of coarse liberated particles. Particular emphasis is placed on the emerging role of artificial intelligence, machine learning, digital twins and real-time monitoring systems in enabling adaptive and autonomous beneficiation circuits. Industrial case studies from Odisha, India, including the Daitari and Keonjhar iron ore regions and Sukinda chromite belt, demonstrate the practical applicability of integrated beneficiation technologies for low-grade ores, slimes and tailings. The study highlights future opportunities involving sustainable processing, critical mineral recovery, tailings valorisation and intelligent mineral beneficiation frameworks.

Keywords: *Energy-efficient comminution; Coarse particle flotation; Artificial intelligence; Smart mineral processing; Odisha iron ores*

INTRODUCTION

The mineral processing industry is undergoing a major transformation driven by declining ore grades, increasing mineralogical complexity, rising energy costs and growing environmental concerns. As high-grade deposits become progressively depleted, beneficiation plants are increasingly required to process low-grade and complex ores using more efficient and sustainable technologies (Wills and Finch, 2016). These challenges are particularly significant for iron ore, base metal and critical mineral resources where conventional beneficiation approaches often fail to achieve optimum recovery and resource utilisation.

Comminution remains the most energy-intensive stage of mineral processing, accounting for nearly 50-60% of total plant energy consumption (Napier-Munn et al., 1996; Tromans, 2008). Conventional grinding systems such as ball mills and semi-autogenous grinding (SAG) mills are characterized by low energy efficiency and excessive slime generation, which adversely affect downstream flotation performance (Fuerstenau and Han, 2003). Consequently, advanced comminution technologies such as high-pressure grinding rolls (HPGR) and stirred mills have gained increasing attention because of their ability to improve mineral liberation while reducing energy consumption (Daniel and Morrell, 2004; Jankovic, 2003).

Recent advances in flotation technology have further challenged the traditional concept that finer grinding necessarily results in improved recovery. Coarse particle flotation (CPF) enables recovery of valuable minerals at relatively coarser particle sizes, thereby reducing grinding requirements and associated energy costs (Jameson, 2010; Kohmuench et al., 2010; Mesa and Brito-Parada, 2019). Simultaneously, rapid developments in artificial intelligence (AI), machine learning, real-time monitoring and digital process control are transforming mineral processing into a data-driven and intelligent industry capable of adaptive process optimisation (Aldrich and Liu, 2021; Quintanilla et al., 2024).

The future of sustainable mineral beneficiation lies in the integration of energy-efficient comminution, coarse particle flotation and intelligent digital optimisation systems. Such integrated approaches offer significant opportunities to improve recovery efficiency, reduce energy consumption and minimize environmental impacts, particularly for low-grade and complex ores. The conceptual interaction between these technologies is illustrated in Fig. 1. This review critically examines recent developments in these areas and their implications for next-generation sustainable mineral processing.

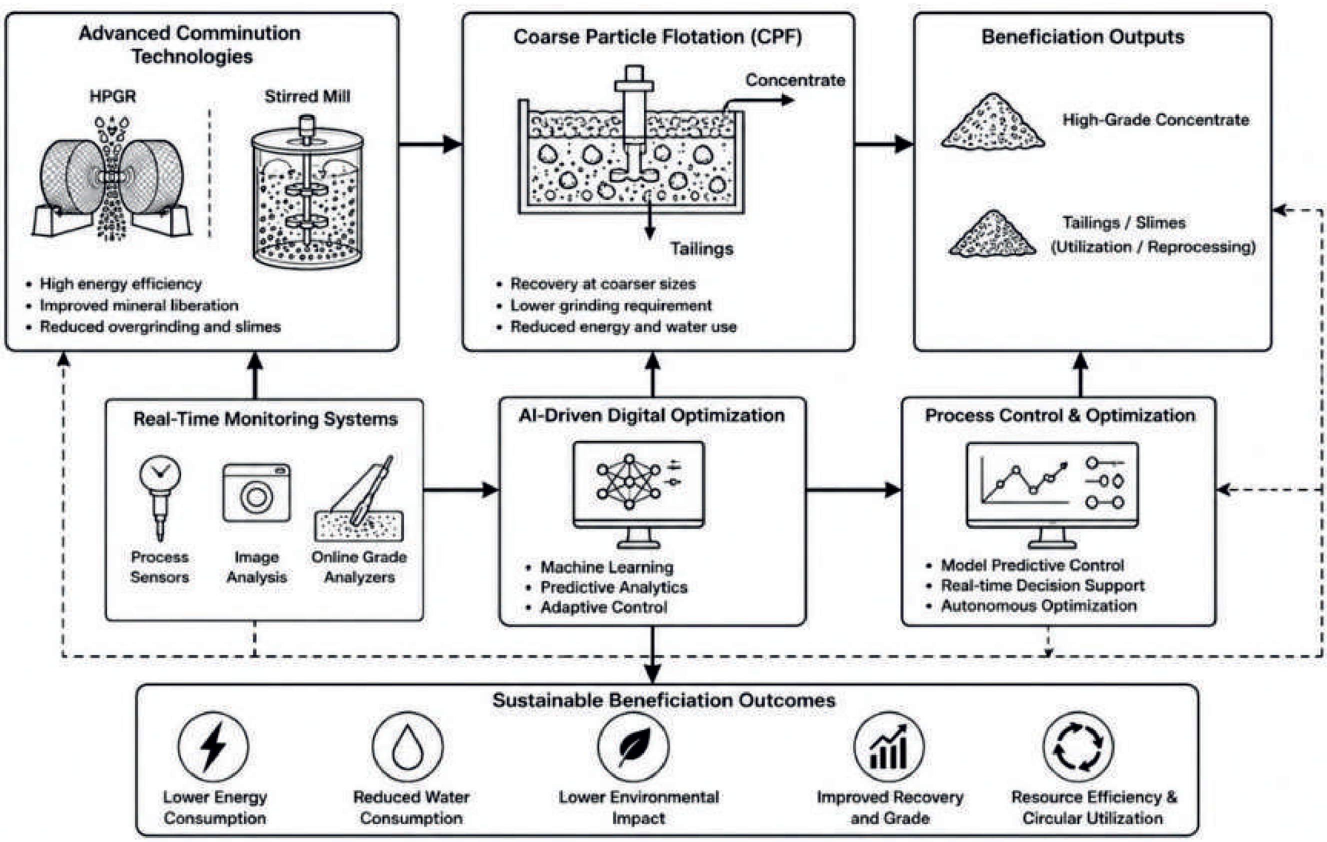

Fig. 1: Integrated conceptual framework of next-generation mineral processing showing the interaction between advanced comminution technologies (HPGR and stirred mills), coarse particle flotation (CPF), AI-driven digital optimisation, real-time monitoring systems and sustainable beneficiation pathways for low-grade and complex ores (Modified and compiled by the author based on Daniel and Morrell, 2004; Jameson, 2010; Aldrich and Liu, 2021; Quintanilla et al., 2024)

2. Challenges in Conventional Mineral Processing

Conventional mineral processing faces increasing challenges due to declining ore grades, complex mineralogy, rising energy costs and stringent environmental regulations. Modern beneficiation plants are increasingly required to process low-grade ores characterized by fine-grained mineral intergrowths, variable mineral compositions and complex liberation behaviour, making efficient separation difficult using traditional processing technologies (Wills and Finch, 2016; Fuerstenau and Han, 2003).

One of the major limitations of conventional beneficiation is the high energy requirement of comminution. Crushing and grinding account for nearly 50-60% of total energy consumption in a mineral processing plant (Napier-Munn et al., 1996; Tromans, 2008). Conventional ball mills and semi-autogenous grinding (SAG) mills operate through impact and abrasion mechanisms that are inherently inefficient, resulting in significant energy losses as heat and mechanical dissipation (Ballantyne and Powell, 2014). Excessive grinding also generates large quantities of ultra-fine particles and slimes, which adversely affect downstream flotation efficiency and increase operational costs (Fuerstenau and Han, 2003).

Conventional flotation systems similarly exhibit limitations when processing both ultra-fine and coarse particles. Fine particles suffer from poor particle-bubble collision efficiency, whereas coarse particles are prone to detachment due to gravitational and inertial forces, leading to reduced recovery (Jameson, 2010). Flotation performance is further influenced by variations in particle size distribution, pulp density, reagent dosage and hydrodynamic conditions, making stable process control difficult under variable ore characteristics (Gupta and Yan, 2016; Mesa and Brito-Parada, 2019).

Environmental sustainability represents another major challenge. Conventional beneficiation circuits consume large quantities of energy and water while generating substantial volumes of tailings and slimes. These factors contribute to increased greenhouse gas emissions, higher operating costs and long-term environmental management concerns (Ballantyne et al., 2012). In addition, significant quantities of valuable minerals often remain unrecovered in tailings because of inefficient liberation and separation processes.

These limitations highlight the need for next-generation mineral processing technologies that integrate energy-efficient comminution, improved flotation systems and intelligent process optimisation. Such approaches offer opportunities to enhance recovery, reduce energy consumption, minimize environmental impacts and improve the sustainable utilisation of low-grade and complex mineral resources.

3. Advanced Energy-Efficient Comminution Technologies

The increasing demand for sustainable mineral beneficiation has accelerated the development of advanced comminution technologies aimed at improving mineral liberation while reducing energy consumption. Conventional grinding systems such as ball mills and semi-autogenous grinding (SAG) mills are often characterized by low breakage efficiency, excessive overgrinding and high operating costs. Consequently, technologies such as high-pressure grinding rolls (HPGR) and stirred mills have emerged as important alternatives for next-generation mineral processing (Wills and Finch, 2016).

3.1. High-Pressure Grinding Rolls (HPGR)

High-pressure grinding rolls (HPGR) represent one of the most significant advances in modern comminution technology. HPGR operates through inter-particle compression, in which ore particles are compressed between two counter-rotating rolls under high pressure (Daniel and Morrell, 2004). Unlike conventional impact-based grinding systems, this mechanism promotes efficient crack propagation and particle breakage while minimizing energy losses.

A major advantage of HPGR is the generation of micro-fractures within mineral particles, which improve downstream grinding efficiency and mineral liberation (Tromans, 2008). Enhanced liberation increases exposure of valuable mineral surfaces and improves flotation performance. Industrial studies have demonstrated that HPGR-based circuits can reduce specific energy consumption by approximately 20-40% compared with conventional SAG-ball mill circuits (Ballantyne and Powell, 2014; Wei et al., 2025). Additional benefits include reduced steel consumption, lower wear rates and improved throughput capacity (Gupta and Yan, 2016). HPGR promotes inter-particle compression, generates micro-fractures, improves mineral liberation and reduces energy consumption compared with conventional ball milling circuits (Daniel and Morrell, 2004; Ballantyne and Powell, 2014; Wei et al., 2025). The fundamental differences between conventional ball mills, HPGR and stirred mills in terms of breakage mechanisms and product characteristics are illustrated in Fig. 2.

3.2. Stirred Milling Technology

Stirred mills, including IsaMill, Vertimill and tower mills, have become increasingly important for fine and ultra-fine grinding applications because of their superior energy efficiency and improved grinding performance (Jankovic, 2003; Rule, 2011). These mills operate predominantly through attrition and shear mechanisms, resulting in efficient particle breakage at relatively low energy input (Yue and Klein, 2005).

Compared with conventional tumbling mills, stirred mills can reduce energy consumption by approximately 30-40% while producing narrower particle size distributions and improved mineral liberation (Jankovic, 2003; Fuerstenau and Han, 2003). Their ability to achieve efficient ultra-fine grinding makes them particularly suitable for processing complex

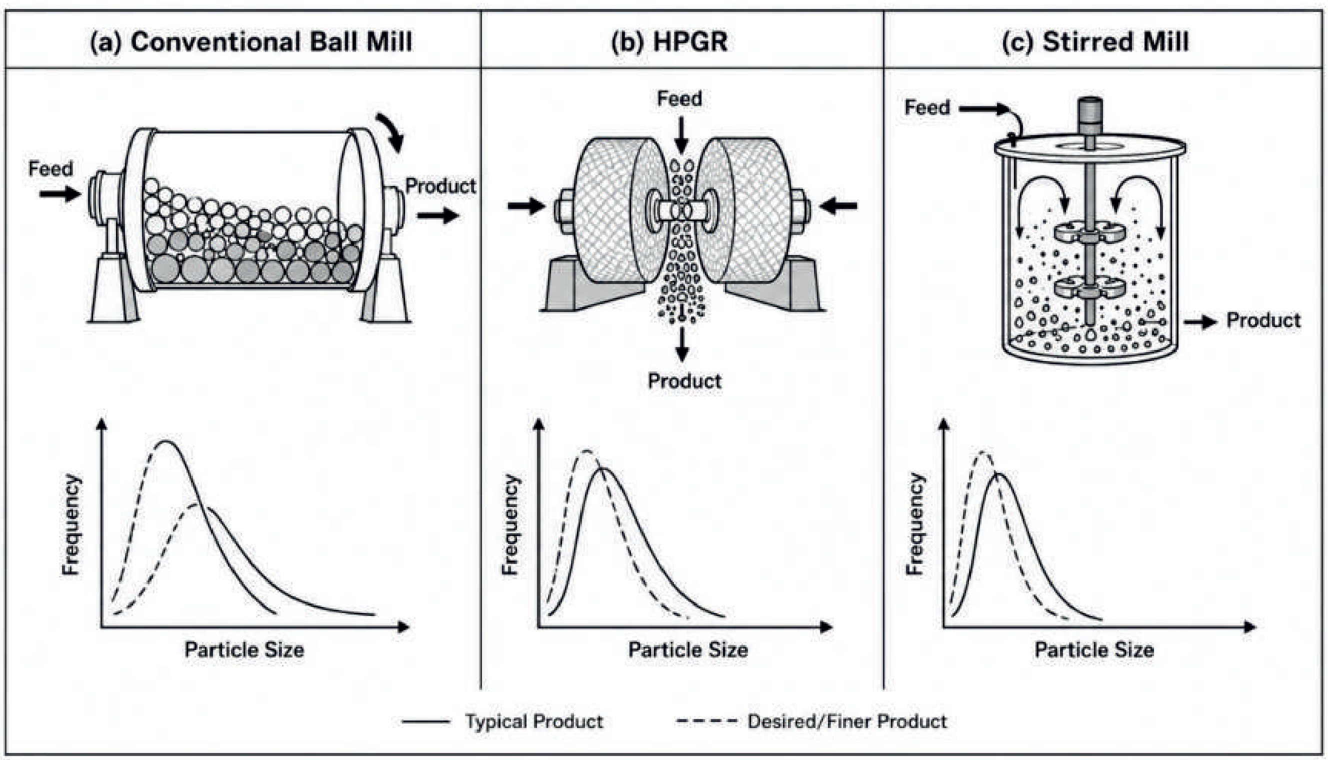

Fig. 2: Schematic comparison of conventional ball mill, high-pressure grinding roll (HPGR) and stirred mill technologies showing their principal breakage mechanisms and typical product size characteristics in modern mineral comminution circuits (Modified and compiled by the author based on Daniel and Morrell, 2004; Jankovic, 2003; Tromans, 2008; Ballantyne and Powell, 2014; Wei et al., 2025)

ores characterized by fine-grained mineral intergrowths. Furthermore, reduced overgrinding and lower slime generation contribute to improved flotation performance and process control (Gupta and Yan, 2016).

3.3. Integrated HPGR-Stirred Mill Circuits

The integration of HPGR and stirred milling technologies represents a major advancement in comminution circuit design. In such circuits, HPGR is generally used for primary size reduction and micro-fracture generation, whereas stirred mills provide efficient fine grinding of the pre-weakened material (Daniel and Morrell, 2004). This combination improves overall grinding efficiency, reduces energy consumption and enhances mineral liberation.

Integrated circuits also minimize excessive slime generation and overgrinding, thereby improving downstream flotation selectivity and recovery (Jankovic, 2003). Improved liberation characteristics contribute to reduced reagent consumption and higher concentrate quality. Furthermore, lower power consumption directly reduces greenhouse gas emissions and operating costs, making integrated HPGR-stirred mill circuits an important component of sustainable mineral beneficiation (Wei et al., 2025). The comparative characteristics of conventional and next-generation comminution technologies used in modern mineral processing systems are summarized in Table-1.

3.4. Significance for Sustainable Mineral Processing

Advanced comminution technologies play a critical role in improving the sustainability of mineral processing operations. Reduced energy consumption lowers operational costs and carbon emissions, while improved liberation efficiency enhances resource recovery and reduces mineral losses in tailings (Ballantyne et al., 2012). In addition, better particle size control and reduced overgrinding improve downstream flotation performance and water utilisation efficiency.

Consequently, HPGR, stirred mills and integrated comminution circuits provide the technological foundation for next-generation mineral processing systems aimed at achieving improved recovery, lower environmental impact and sustainable utilisation of increasingly complex and low-grade mineral resources.

4. Coarse Particle Flotation (CPF)

Coarse particle flotation (CPF) has emerged as an important advancement in mineral beneficiation by enabling the recovery of valuable minerals at relatively coarse particle sizes, thereby reducing grinding requirements, energy consumption and slime generation. Conventional flotation systems typically exhibit poor recovery of coarse particles because gravitational and inertial forces promote particle-bubble detachment, while fine particles suffer from low collision efficiency (Jameson, 2010; Mesa and Brito-Parada, 2019). CPF addresses these limitations through improved hydrodynamic control, particle suspension and bubble-particle stabilization, allowing efficient flotation of particles commonly within the 150-500 μm size range (Kohmuench et al., 2010). Technological developments such as fluidized-bed flotation and HydroFloat systems have significantly improved coarse particle recovery by minimizing turbulence-induced detachment and enhancing particle-bubble interactions (Kohmuench et al., 2010; Galvin et al., 2014). The effectiveness of CPF is further enhanced when integrated with advanced comminution technologies such as high-pressure grinding rolls (HPGR), which generate micro-fractures and improve mineral liberation at relatively coarse particle sizes (Daniel and Morrell, 2004). Such integration reduces excessive grinding while maintaining high metallurgical recovery, thereby improving overall process efficiency and sustainability. CPF offers several advantages, including lower energy and water consumption, reduced tailings generation, improved process throughput and enhanced resource utilisation, making it particularly attractive for low-grade ores, tailings reprocessing and complex mineral systems (Napier-Munn et al., 1996; Wills and Finch, 2016).

Table-1: Comparative evaluation of conventional SAG-ball mill circuits and advanced comminution technologies highlighting differences in breakage mechanisms, energy efficiency, liberation behaviour, slime generation and suitability for next-generation integrated mineral processing systems (Compiled and modified by the author based on Napier-Munn et al., 1996; Daniel and Morrell, 2004; Ballantyne and Powell, 2014; Wei et al., 2025)

Parameter	**Conventional SAG-Ball Mill Circuit**	**HPGR Circuit**	**Stirred Mill Circuit**	**Integrated HPGR-Stirred Mill Circuit**
Dominant breakage mechanism	Impact and abrasion	Inter-particle compression	Attrition and shear	Compression + attrition
Specific energy consumption	High	Moderate to low	Low	Lowest
Liberation efficiency	Moderate	High due to micro-fracturing	High for fine particles	Very high
Slime generation	Excessive	Reduced	Moderate	Significantly reduced
Product size control	Moderate	Good	Excellent	Excellent
Overgrinding tendency	High	Low	Low	Very low
Throughput capacity	Moderate	High	Moderate	High
Steel/media consumption	High	Low	Moderate	Reduced
Suitability for low-grade ores	Limited	Good	Very good	Excellent
Suitability for CPF integration	Poor	Excellent	Good	Excellent
Environmental sustainability	Moderate	Good	Good	Excellent
Industrial significance	Conventional technology	Energy-efficient pre-grinding	Fine and ultra-fine grinding	Next-generation integrated circuit

However, challenges related to hydrodynamic optimisation, scale-up and ore-specific performance still require further investigation (Mesa and Brito-Parada, 2019). The major advantages, sustainability benefits and operational limitations associated with CPF technologies are summarized in Table-2.

Table-2: Major advantages, sustainability benefits and operational challenges associated with coarse particle flotation (CPF) technologies in next-generation mineral beneficiation systems (Compiled and modified by the author based on Jameson, 2010; Kohmuench et al., 2010; Wills and Finch, 2016; Mesa and Brito-Parada, 2019)

Aspect	Advantages of CPF	Existing Limitations/Challenges
Energy consumption	Reduces grinding energy requirement	Requires optimized hydrodynamic control
Mineral recovery	Recovers coarse liberated particles	Coarse particle detachment remains challenging
Slime generation	Minimizes excessive fine generation	Limited effectiveness for poorly liberated ores
Water consumption	Lower due to reduced fine grinding	Water balance optimisation required
Flotation selectivity	Improved coarse particle selectivity	Sensitive to turbulence variation
Tailings generation	Reduced tailings volume	Scale-up to industrial operation remains challenging
Process throughput	Higher plant throughput possible	Requires modified flotation circuits
Sustainability	Reduced CO_2 emissions and waste generation	Capital cost may be higher initially
Integration with HPGR	Highly compatible due to coarse liberation	Ore-specific optimisation necessary
Industrial application	Iron ore, sulfides, chromite, tailings	Limited commercial implementation globally

5. Smart and Digital Mineral Processing Systems

The rapid advancement of digital technologies, automation and artificial intelligence (AI) is transforming mineral processing from conventional operator-dependent systems to intelligent, data-driven beneficiation frameworks. Conventional process control systems often struggle to respond effectively to ore variability, resulting in unstable grinding and flotation performance, delayed corrective actions and inefficient utilisation of energy and reagents (Wills and Finch, 2016; Gupta and Yan, 2016; Jameson, 2010). The integration of real-time monitoring technologies, including froth imaging, machine vision, online grade analysers and process sensors, enables continuous assessment of critical process variables and provides the foundation for advanced process optimisation (Moolman et al., 1994; Aldrich et al., 2010; Anvari and Benndorf, 2025). Model predictive control (MPC) systems further enhance operational efficiency by utilizing dynamic process models to optimize grinding and flotation performance under changing feed conditions (Qin and Badgwell, 2003; Bergh et al., 1999; Quintanilla et al., 2024). Recent developments in machine learning (ML), artificial neural networks (ANN), predictive maintenance and AI-driven decision support systems have improved process stability, recovery efficiency, reagent utilisation and equipment reliability by identifying complex relationships between process variables and metallurgical performance (Aldrich and Liu, 2021; Biradar et al., 2025). In addition, digital twin technology enables real-time simulation, predictive analysis and virtual optimisation of beneficiation circuits, supporting the development of autonomous mineral processing plants capable of adaptive process control (Lotter et al., 2016). Collectively, these technologies contribute to reduced energy consumption, improved resource utilisation, lower environmental impact and enhanced operational sustainability, thereby representing a key component of next-generation intelligent mineral beneficiation systems. The major applications of artificial intelligence, machine learning, digital twins and smart sensor technologies in modern mineral processing are summarized in Table-3.

6. Integration of Comminution, Flotation and Digital Optimisation

The future of mineral beneficiation increasingly depends on the integration of advanced comminution technologies, coarse particle flotation (CPF) and intelligent digital optimisation within a unified processing framework. Conventional mineral processing circuits often optimize grinding and flotation independently, despite the strong interdependence between particle breakage, mineral liberation, particle

Table-3: Major applications of artificial intelligence, machine learning, digital twins and smart sensor technologies in modern mineral processing and intelligent flotation optimisation systems (Compiled and modified by the author based on Qin and Badgwell, 2003; Aldrich et al., 2010; Aldrich and Liu, 2021; Biradar et al., 2025; Anvari and Benndorf, 2025)

Technology	Major Application	Process Parameter Optimized	Industrial Benefit
Froth image analysis	Flotation monitoring	Bubble size, froth stability	Improved recovery and grade
Machine learning (ML)	Predictive modeling	Recovery, reagent dosage	Dynamic optimisation
Artificial neural networks (ANN)	Process prediction	Flotation kinetics	Improved process stability
Model predictive control (MPC)	Advanced process control	Air flow, pulp level, reagent addition	Reduced operational variability
Digital twins	Virtual plant simulation	Entire processing circuit	Predictive optimisation
Online sensors	Real-time monitoring	pH, density, particle size	Faster corrective action
Hyperspectral sensing	Ore characterization	Mineralogical variability	Improved ore sorting
Predictive maintenance	Equipment health monitoring	Vibration, wear, temperature	Reduced downtime
Industrial IoT (IIoT)	Data integration	Plant-wide operational data	Centralized optimisation
AI-based decision systems	Autonomous beneficiation	Multi-variable optimisation	Intelligent process control

size distribution, surface properties and flotation kinetics (Napier-Munn et al., 1996; Fuerstenau and Han, 2003). Advanced comminution technologies such as high-pressure grinding rolls (HPGR) and stirred mills improve downstream flotation performance by enhancing mineral liberation, generating micro-fractures and reducing excessive slime formation (Daniel and Morrell, 2004; Tromans, 2008; Jankovic, 2003). These benefits are particularly important for CPF systems, where recovery of coarse liberated particles significantly reduces grinding energy requirements while maintaining high metallurgical recovery (Jameson, 2010). Simultaneously, real-time monitoring systems, machine learning, artificial intelligence and model predictive control enable dynamic adjustment of grinding and flotation parameters according to changing ore characteristics and process conditions, thereby improving process stability, recovery efficiency, reagent utilisation and energy performance (Qin and Badgwell, 2003; Aldrich and Liu, 2021; Quintanilla et al., 2024). Such integrated approaches are especially relevant for processing low-grade and complex ores characterized by variable mineralogy and liberation behaviour (Lotter et al., 2016). Consequently, the combined application of energy-efficient comminution, CPF and intelligent digital optimisation represents a key pathway toward sustainable mineral beneficiation through improved resource recovery, reduced environmental impact and enhanced operational efficiency.

7. Industrial Case Studies with Special Reference to Odisha

Odisha hosts some of India's most important iron ore, chromite, manganese and associated mineral resources, including extensive reserves of low-grade hematite-goethite ores, beneficiation fines, slimes and tailings. However, increasing depletion of high-grade ores and the complex mineralogical association of hematite and goethite with gangue minerals such as kaolinite, gibbsite and quartz present significant beneficiation challenges (IBM, 2023; Chokshi and Dutta, 2014; Patra et al., 2018; Patra et al., 2019). Studies on iron ore deposits from Daitari, Barsua and Noamundi indicate that effective liberation often requires fine grinding, which increases energy consumption and slime generation (Patra et al., 2018; Patra et al., 2019). Consequently, advanced beneficiation technologies such as high-pressure grinding rolls (HPGR), stirred mills, coarse particle flotation (CPF) and intelligent process optimisation have gained increasing relevance for improving recovery and sustainability. Recent investigations have demonstrated that HPGR-induced micro-fracturing can enhance liberation of hematite and goethite at relatively coarser particle sizes, thereby reducing excessive grinding requirements (Wei et al., 2025). Similar opportunities exist for beneficiation of low-grade chromite ores and tailings from the Sukinda belt, where improved liberation and flotation technologies can enhance resource utilisation (Jena et al., 2016). The growing adoption of digital monitoring systems, AI-assisted process optimisation and geometallurgical approaches is also expected to improve beneficiation efficiency under variable ore conditions (Aldrich and Liu, 2021; Biradar et al., 2025). Furthermore, beneficiation and reprocessing of fines, slimes and tailings are increasingly important for sustainable mineral resource management in Odisha, particularly in view of future resource security and circular economy objectives (MECON, 2024; Panda et al., 2024; Sahoo et al., 2025a; Sahoo et al., 2025b). The major mineral resources of Odisha, associated beneficiation challenges and suitable next-generation mineral processing technologies are summarized in Table-4.

8. Challenges and Future Scope

8.1. Challenges

Despite significant advances in energy-efficient comminution, coarse particle flotation (CPF) and intelligent digital optimisation, several challenges continue to limit the widespread industrial adoption of

Table-4: Major mineral resources of Odisha, associated beneficiation challenges and suitable next-generation mineral processing technologies for sustainable utilisation of low-grade ores, fines, slimes and tailings (Compiled and modified by the author based on Tripathy and Yanamandra, 2012 Patra et al., 2018; Patra et al., 2019; Panda et al., 2024; Sahoo et al., 2025a; Sahoo et al., 2025b)

Mineral Resource/Region	Major Mineralogical Characteristics	Beneficiation Challenges	Recommended Next-Generation Technologies
Daitari iron ores	Hematite-goethite ores with high alumina	Slime generation, poor liberation	HPGR + CPF + AI optimisation
Keonjhar BIF ores	Fine-grained BIF-associated ores	Locked particles, silica intergrowth	Stirred milling + CPF
Barsua iron ore fines	Low-grade hematite fines	Excessive fines and tailings	Selective grinding + flotation
Sukinda chromite ores	Fine disseminated chromite	Ultra-fine liberation requirement	HPGR-stirred mill circuit
Iron ore slimes	Ultra-fine iron-bearing particles	Low recovery efficiency	Advanced flotation + desliming
Tailings deposits	Partially liberated minerals	Resource loss and environmental risk	Tailings reprocessing + AI control
Blue dust (Daitari)	Fine friable hematite-rich material	Handling and utilisation issues	Pelletization + selective beneficiation
Ochre deposits	Iron-rich weathered material	Low grade and high impurities	Agglomeration and beneficiation

next-generation mineral processing technologies. Advanced comminution systems such as high-pressure grinding rolls (HPGR) and stirred mills require optimisation under highly variable ore characteristics, including changes in hardness, mineralogy, moisture content and competency (Daniel and Morrell, 2004; Tromans, 2008; Wills and Finch, 2016). Similarly, CPF performance remains sensitive to hydrodynamic conditions, particle liberation and turbulence control, making large-scale industrial implementation challenging (Jameson, 2010; Mesa and Brito-Parada, 2019). The increasing reliance on artificial intelligence, machine learning, digital twins and real-time monitoring systems also introduces challenges related to data quality, cybersecurity, model interpretability and implementation costs (Aldrich and Liu, 2021; Lotter et al., 2016). In addition, declining ore grades, increasing tailings generation, high water consumption and the need to reduce greenhouse gas emissions continue to pose significant environmental and sustainability concerns (Ballantyne et al., 2012; Lotter et al., 2016).

8.2. Future Scope

Future mineral processing will increasingly focus on the integration of advanced comminution technologies, intelligent flotation systems, artificial intelligence, geometallurgical modeling and sustainable resource utilisation frameworks. The development of autonomous beneficiation plants incorporating real-time monitoring, machine learning, predictive control and digital twins is expected to improve recovery efficiency, operational stability and energy performance (Qin and Badgwell, 2003; Aldrich and Liu, 2021; Quintanilla et al., 2024). Future research will also emphasize sensor-based ore sorting, hyperspectral mineral characterization and geometallurgical approaches linking ore characteristics with beneficiation performance (Lotter et al., 2016; Anvari and Benndorf, 2025). Increasing attention will be given to environmentally benign flotation reagents, tailings reprocessing, critical mineral recovery and circular economy strategies aimed at maximizing resource utilisation while minimizing environmental impacts (Mesa and Brito-Parada, 2019). Furthermore, integration of renewable energy systems, low-carbon process design and energy-efficient beneficiation technologies will be essential for achieving sustainable and climate-resilient mineral processing operations in the future (Ballantyne et al., 2012).

9. Concluding Remarks

The mineral processing industry is increasingly required to address the challenges of declining ore grades, complex mineralogy, rising energy consumption and stringent environmental requirements. This review highlights that advanced comminution technologies such as high-pressure grinding rolls (HPGR) and stirred mills offer substantial improvements in energy efficiency and mineral liberation compared with conventional grinding systems. Coarse particle flotation (CPF) further enhances process sustainability by enabling recovery at coarser particle sizes, thereby reducing grinding requirements, water consumption and slime generation. In parallel, artificial intelligence, machine learning, digital twins and real-time process monitoring are transforming mineral beneficiation into an intelligent and adaptive system capable of optimizing recovery and operational efficiency. The integration of these technologies represents a key pathway toward sustainable mineral processing through improved resource utilisation, reduced environmental impacts and enhanced economic performance. Their application is particularly relevant for the beneficiation of low-grade ores, fines, slimes and tailings in mineral-rich regions such as Odisha. Continued advances in energy-efficient processing, digitalization and circular economy approaches will play a critical role in shaping the future of next-generation sustainable mineral beneficiation.

Acknowledgements

The author acknowledges the support of Indian Bureau of Mines, Nagpur for access to academic resources used in this study.

Conflict of Interest

The author declares no conflict of interest.

Data Availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Funding

No fund was provided for this study.

Declaration

The author used AI-assisted language tools only for improving language clarity, grammar and manuscript organization. All scientific interpretations, analysis, figures, tables and conclusions were independently developed and verified by the author, who takes full responsibility for the content of the manuscript.

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SGAT Bulletin
Vol. 27, No. 1, June 2026, pp. 31-39

A BRIEF NOTE ON THE GONDWANA SEQUENCE OF EXTREME NORTHERN PRANHITA-GODAVARI BASIN, SOUTH INDIA

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ABSTRACT

The present work is focused on NNW-SSE Phanerozoic Gondwana sequence in Kagaznagar-Sirpur area of extreme northern Pranhita-Godavari (PG) basin, south India based on existing geological map, literature and additional data. Litho-stratigraphically, the Gondwana sequence is differentiated as coal bearing Barakar with feldspathic sandstone, ferruginous massive-cross bedded sandstone-thin silt stone intercalation as Kamthi, predominant argillaceous with thin discontinuous sandstone intercalation as Maleri and the coarse pebbly massive sandstone-clay clast conglomerate-thickly cross bedded sandstone with mega bedforms association as the Kota formations in the ascending order. The deformed Meso-Neoproterozoic Penganga-Sullavai Group sediments and the granitoids of Eastern Dharwar Craton (EDC) in the west and east occur as the basement rocks with NNW-SSE fault-bound contacts of syn-sedimentation and post-depositional character. The long continuous NE-SW Vattivagu and Garlapeta-Naweagaon transverse faults have dissected the Gondwana sequence with resultant dextral shifts of coal bearing southwestern Yempalli-Isgaon Barakar blocks towards Garlapeta-Cheepalli and Mikhri-Naweagaon in the northeast. Based on these observations, a revised Geological-structural map for Kagaznagar-Sirpur area is prepared in the present work.

Keywords: *PG basin, Gondwana sequence, Litho-stratigraphic classification, Barakar-Kamthi-Maleri-Kota formations, Basin Boundary-Transverse faults*

INTRODUCTION

The Phanerozoic terrestrial Gondwana deposits of Peninsular India is differentiated in Narmada-Satpura, Koel-Damodar, Rajmahal, Son-Mahanadi and the Pranhita-Godavari (PG) basins (Fig.1, inset map). The major global events like late Meso-Proterozoic Grenville, early Paleozoic Pan-African and upper Paleozoic Hercynian orogenies are widely recognized in the stratigraphic record (Rino et al., 2008). The upper Paleozoic Hercynian orogeny is witnessed by Permo-Carboniferous deglaciation with boulder bed-diamictite occurrences under cold climate condition in different sag-type basins, marking the period of initial Gondwana sedimentation. The later Permian rift-type basins development due to subduction of Panthalassan plate beneath the Gondwana land around 278 ± 2 Ma (Visser Prae Kelt,1996) is widely regarded as the major coal forming epoch over the entire Gondwana land in relatively warmer conditions. The Triassic (~233Ma) arid climate with quartzose units and red-bed deposition in the braided river system indicates a break in sedimentation in many Gondwana basins of Peninsular India (op. cit.). The Gondwana period ends with post-depositional late Mesozoic faulting (King, 1881) in response to the anti-clockwise oroclinal rotation of Indian land mass due to crustal sliding and ocean floor spreading along the Carlsberg ridge in the Arabian sea (Ahamad and Ahamad,1977). The faults in Gondwana sequence are widely regarded as the post-depositional with Precambrian ancestry. Thus, the overall linearity of Gondwana basins is corroborated with such late Mesozoic tectonic events (Mitra,1987).

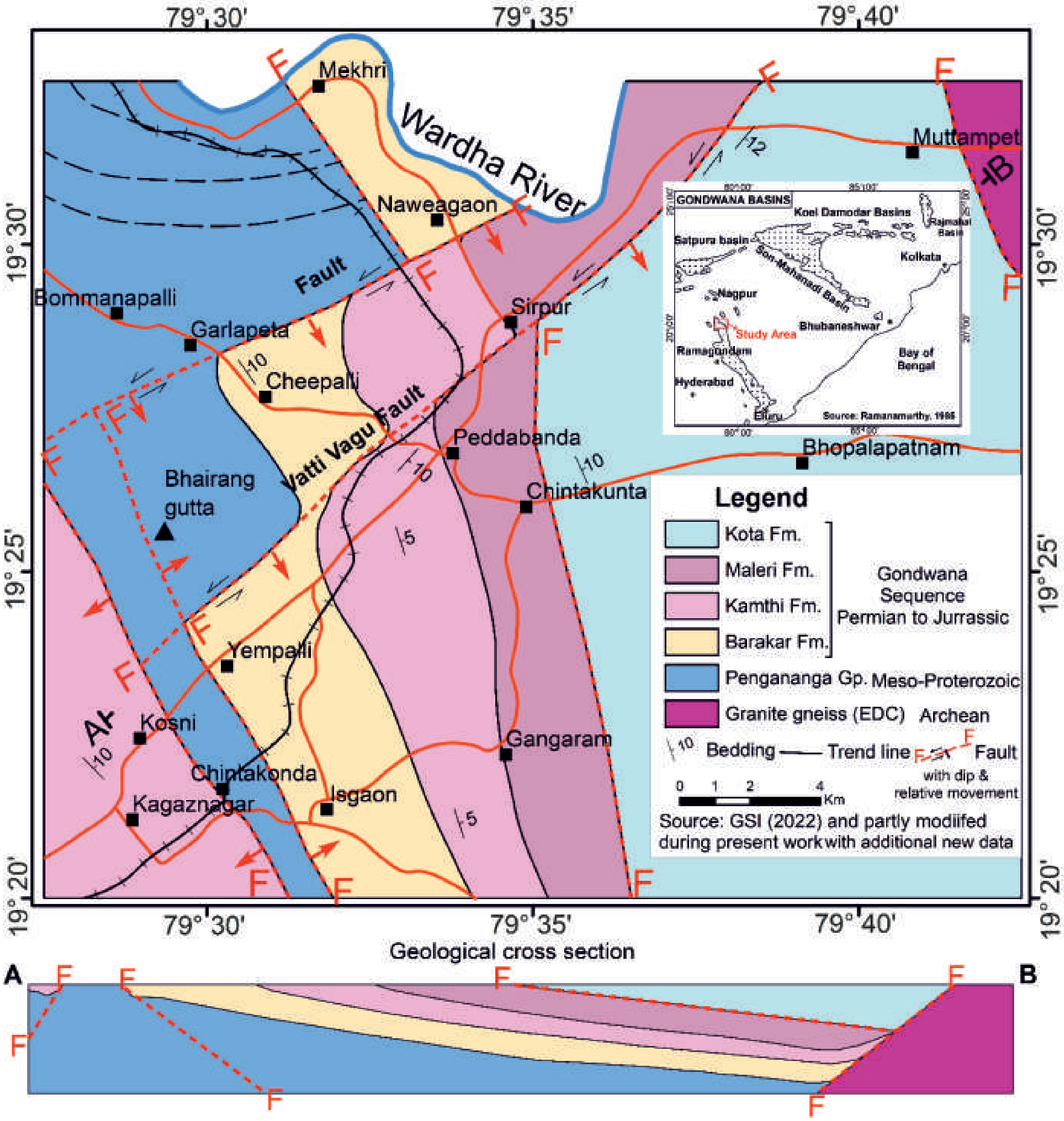

Fig. 1. Geological-structural map Gondwana sequence in of Kagaznagar-Siripur area, northern PG basin

In NNW-SSE PG basin, a complete lithostratigraphic succession of Permo-Carboniferous to late Mesozoic age (GSI,1997; Mukhopadhyay et al., 2010) is differentiated. After a long gap of King's (1881) pioneering work; GSI (1997) has adopted a two-fold classification of Gondwana sequence as lower and upper Gondwana based on the presence of Glossopteris-Gangamopteris and Ptilophyllum flora (Table-1). A step-like faulting in the underlying basement rocks for the accumulation of thick (3000+ m) Gondwana sequence in the deeper parts of entire PG basin (Sharma and Krishnarao, 2005; Quereshy et al.,1968) is reported. The existing views for the faults are of Precambrian ancestry in the PG basin (Ramanamurthy,1985; Ramanamurthy and Parthasarathi,1988); the recent works, however, has established the NE-SW and NNW-SSE structural elements reactivation mechanism of late Mesoproterozoic Grenville Easternghat and Paleozoic Pan-African orogenies (Burhanuddin, 2017; Ghosh and Saha, 2003; Burhanuddin and Sreenivasarao, 2024) in the entire PG basin. A 400 km long continuous Ahri (Maharashtra)-Cherla (AP) fault along eastern boundary of entire Gondwana sequence is differentiated as the syn-sedimentational structural feature (Ramanamurthy, 1985). The NNW-SSE terrestrial Gondwana sequence of PG basin abuts against Central Indian Tectonic Zone (Biswas, 2003) and the ENE-WSW coastal Krishna-Godavari (KG) paralic sediments (Kaila et al., 1990) in the north and south respectively. In recent works, the contact of terrestrial Gondwana with coastal KG sediments is delineated as a basin marginal boundary fault of late Mesoproterozoic Grenville ancestry (Burhanuddin, 2022) in similarity with the northern reactivated Paleozoic Ahiri-Cherla fault (Burhanuddin, 2022) of syn-depositional character (Ramanamurthy, 1985).

Table-1: A comparative statement of litho-stratigraphic classification of Gondwana sequence in PG basin

GSI (1997)		**Mukhopadhyay et al (2010)**			**Burhanuddin (2022) Southern PG basin**		**Kagaznagar-Sirpur area, present work**
Formation	Group	Formation		Group	Formation	Group	Formation
Chikyala/ Gangpur	Upper Gondwana	Chikyala/ Gangpur ----?----?----			Gangpur	Dammapeta Group	
Kota		Kota			Kota		**Kota** (Clay clast conglomerate-massive & thickly cross bedded sandstone of mega-bed forms & pebble bed intercalation-thin clays)
		----?----?----			-- Disconformity --		-- Disconformity --
Maleri		Dharmaram Maleri Bheemaram Yerrapalli	Biozones (Kutty & Sengupta, 1989)	Maleri Group	Maleri	Godavari Group	**Maleri** (Predominant clays of varied colours-fine silt stone-shale assemblage with thin discontinuous sandstone)
Kamthi: Upper Middle Lower (Coal bearing)	Lower Gondwana	Upper		Kamthi Group	Kamthi		**Kamthi** (Ferruginous massive-cross bedded sandstone with thin discontinuous ferruginous silt stone & pebble bed intercalations)
		----?----?---- Middle Lower (Coal bearing)			-- Disconformity --		--Disconformity--
Barren Measure		Barren Measure Barakar		Barakar	Barakar	Damuda Group	**Barakar** (Coarse pebbly massive-cross bedded sandstone-carb shale-coal-shale assemblage)
Barakar							
Talchir		Talchir			Talchir		

The Gondwana sequence of extreme northern part, south of Wardha river in Kagaznagar-Sirpur area is re-analyzed (Fig. 1 & Table-1) in present work based on new data input on the existing map (GSI, 2022) in corroboration with the latest works (Burhanuddin, 2022) of southern PG basin. The coal bearing Barakar, Kamthi, Maleri and Kota formations in ascending order over the deformed Meso-Proterozoic Penganga Group (Burhanuddin and Sreenivasarao, 2024) in west and granitoids of Eastern Dharwar Craton (EDC) in the east as basement rocks with fault-bound contacts are differentiated. In southwestern part, a linear patch of NNW-SSE Penganga Group occurs amidst the Gondwana sequence as an upthrown block with fault-bound contact (Fig. 1). The occurrence of Kamthi Formation directly over the Penganga basement near Kagaznagar (western part) reiterates the concept of underlying Barakar erosion before the onset of Kamthi sedimentation (Burhanuddin, 2022). Two NE-SW southerly dipping Garlapeta-Naweagaon and Vattivagu transverse faults across the entire Gondwana sequence are differentiated. Based on these observations, the coal bearing southern Yempalli-Isgaon Barakar block and the similar dextrally shifted northern Garlpeta-Cheepalli and Mikhri-Naweagaon Barakar blocks (Fig. 1), due to transverse faults, need further attention for economic coal potentialities.

Geological background and Structural aspects
Regional:

The NNW-SSE Phanerozoic Gondwana sequence of PG basin is displayed in between western and eastern belts of Meso and Neoproterozoic Pakhal-Penganga-Sullavai groups in the northern part (Sreenivasarao, 2001). In southern part, the Granite-greenstone terrain of EDC and Eastern Ghats Mobile Belt (EGMB) along PG basin's western and eastern margins occur as basement for the Phanerozoic Gondwana sediments (Burhanuddin and Sreenivasarao, 2024). The deformation of Meso-Proterozoic sediments due to Grenville Easternghat orogeny in southern PG basin (Burhanuddin, 2017; Ghosh and Saha, 2003) along with superposed Paleozoic Pan-African effects (Burhanuddin and Sreenivasarao, 2024) in the overall PG basin has been recorded. The isolated patches of Meso-Proterozoic Penganga and Neo-Proterozoic Sullavai groups amidst the Gondwana sequence in northern part is also reported. A 400 km long southerly discontinuous Ahiri-Cherla syn-depositional fault of Precambrian ancestry (Ramanamurthy, 1985; Ramanamurthy and Parthasarathi, 1988) is differentiated as the eastern Gondwana boundary. In recent works, these eastern and western boundary faults of PG basin are found as the reactivated structural elements of Paleozoic Pan-African ancestry (Burhanuddin and Sreenivasarao, 2024). In southern half of PG basin, the eastern margin is differentiated as an erosional unconformity along the contact of EDC granitoids in north and the EGMB in the south (op. cit.). In addition to this, the southern boundary against the coastal Gondwana sequence of the KG basin (Kaila et al.,1990) is also differentiated as the re-activated fault of late Meso-Proterozoic Grenville ancestry (Burhanuddin, 2022). Based on northern PG basin's eastern syn-depositional southerly discontinuous boundary including western continuous post-depositional fault-boundary and a southeastern erosional contact; northern graben and southern half graben configurations is interpreted (op. cit.) in the PG basin. In Gondwana sequence of PG basin, several transverse and median ridges are reported based on geophysical works (Venkatapatiraju, et al., 2023). Thus, the overall PG basin is differentiated as northern Godavari, central Kothagudem and southern Chintalapudi sub-basins with ENE-WSW Kothagudem-Bhadrachalam and NE-SW Pamuleru fault-bound contacts (Rajarao, 1982). In recent works, another Gundala-Bodu-Sampthanagaram sub-basin along with narrow "Paloncha neck"; is identified in between NW-SE intra-basinal Kinnerasani and ENE-WSW Kothagudem-Bhadrachalam transverse faults (Burhanuddin and Prasad, 1994; Burhanuddin, 2022). The NW-SE fault-bound Proterozoic basement occurrence, named as Rajulugutta amidst the younger

Gondwana sequence (North of Godavari River), is delineated with youngest and older litho-stratigraphic units on either side of it. The younger and older litho-stratigraphic units of Gondwana are displayed with fault bound and normal-unconformable contacts (Rajarao, 1982). The occurrence of discontinuous coal bearing Barakar patches as upthrown blocks (op. cit.) amidst vast tracts of younger Kamthi in southern PG basin too is delineated with fault bound contacts of rotational movement (Burhanuddin, 2022).

The Gondwana sequence is differentiated as lower and upper Gondwana based on Glossopteris-Gangamapteris flora. Litho-stratigraphically, the Gondwana is classified as Talchir, Barakar, Barren Measures, Kamthi, Maleri, Kota and Gangpur/Chikiala formations (Table-1) in the ascending order (GSI, 1997; Mukhopadhyay et al., 2010). In southern PG basin, the litho-stratigraphic units like Barren Measures, coal bearing lower Kamthi units (Ramanamurthy, 1985; GSI, 1997) are found as un-tenable based on the facts of lateral discontinuity and a close similarity of both with the underlying Barakar (Burhanuddin and Prasad, 1994; Laxminarayana and Burhanuddin, 1989; Laxminarayana et al., 1995; Burhanuddin, 2024). Thus, the Barren Measures and coal bearing lower Kamthi units are considered as part of Barakar Formation (Burhanuddin, 2022). In Southern PG basin, based on identification of two erosional surfaces in between Barakar-Kamthi and at the base of Kota Formation; a three-fold litho-stratigraphic classification of Gondwana sequence as Damuda (Talchir-Barakar), Godavari (Kamthi-Maleri) and Dammapeta (Kota-Gangpur/ Chikiyala) groups is attempted in the recent works (op. cit.). A break-in sedimentation after Barakar and before the onset of Kamthi development is further corroborated with the views of Visser Prae Kelt (1996). A meandering channel deposit of Maleri with the replacement of rudaceous-mega bed forms association of Kota in a braided river system is further viewed as a period of erosion before the onset of Kota sedimentation (Burhanuddin, 1991 and 2022).

Study area: In Kagaznagar-Sirpur area, a detailed litho-stratigraphic succession of Gondwana sequence along with a comparative statement of GSI (1997), Mukhopadhyay et. al (2010) in corroboration with the latest works (Burhanuddin, 2022) is tabulated as Table-1. The continuous deformed NW-SE Meso-Proterozoic Penganga and Neo-Proterozoic Sullavai groups (Deb, 2003) with superposed Pan-African effects in Asifabad sector occur as basement for the Gondwana Supergroup along the western margin. The E-W trends of hinge part abut against NNW-SSE faulted Gondwana contact near Mikhri in north (Fig. 1); defining as a Palaeozoic limb parallel slip. The transformation of same structural feature as a reactivated NW-SE post Gondwana fault of Palaeozoic Pan-African ancestry (Burhanuddin and Sreenivasarao, 2024) is envisaged. Along the eastern margin, the basement granite gneiss of EDC is displayed with a similar NNW-SSE fault-bound contact against the youngest Kota Formation near Muttampet. This fault is the southern continuation of 400 km long Ahiri (Maharastra)-Cherla (AP) eastern boundary syn-depositional fault (Ramanamurthy, 1985) and the same is considered as a reactivated structural feature of Paleozoic Pan-African ancestry up to Cherla (AP) in the south (Burhanuddin and Sreenivasarao, 2024). This overall syn-depositional structural feature is traced in the northeastern part of PG basin along the contact of younger stratigraphic unit of Gondwana against the basement rocks (GSI, 1997). Thus, the overall northern PG basin is witnessed by older and youngest stratigraphic units in the western-eastern parts with the post-syndepositional fault bound contact respectively.

The basal Talchir facies of cold climate is absent in this part in similarity with other parts of PG basin. These observations suggest a discontinuous lensoidal nature of Talchir stratigraphic unit in the individual sectors of PG basin. The subsequent gradational pebbly greyish feldspathic sandstone-pebble bed-shale-carbonaceous shale-coal facies of Barakar indicates a change in climate from cold to humid/ warm. Further, the presence of fresh feldspar in Barakar sandstone points to an incomplete weathering with less transport before its deposition from nearby source as proximal to mid-alluvial fan deposit (Mitra, 1987). The Barakar litho-package is differentiated as channel (sandstone), flood plain (shale) and back-swamp (coal) deposits of a braided system (Burhanuddin, 1991 and 2022). In vertical sections, the repeated cycles of massive-cross bedded sandstone facies for considerable thickness can be interpretated as the process of frequent channel encroachment for non-development of flood plain-back swamp deposits in the overall PG basin. Thus, the limited coal forming events were prevailed in contrast to the northern Damodar valley basin (op. cit.). The southern Yempalli-Isgaon coal bearing (Premchand, SCCL, Personal communication), central Garlapeta-Cheepalli and the northern Mikhri-Naweagoan blocks are differentiated as the Barakar Formation from south to north in close contact with the younger Kamthi Formation. In general, the discontinuous greenish facies of Tachir are gradationally overlained by the greyish facies of Barakar in the entire PG basin. Thus, the Talchir and Barakar are classified as the Damuda Group (Burhanuddin, 2022).

A thick ferruginous-coarse arenaceous assemblage of massive-cross bedded sandstone as multistoried units with very thin intercalations of ferruginous siltstone-discontinuous pebble beds intercalation is defined as the Kamthi Formation. Regionally, the Kamthi occurrence indicates a change in climate from humid to semi-arid conditions (Visser Prae Kelt, 1996) with no carbonaceous matter accumulation. In southern part of PG basin, the basal arenaceous Kamthi with an erosional surface with restricted argillaceous lenses at Ramagundam (Ramanamurthy, 1985) and in Manuguru (Burhanuddin, 2022) coalfields unconformably overlie the Barakar. The basal arenaceous-argillaceous Kamthi is differentiated as a meandering channel deposit (Burhanuddin, 1991 and 2022). The upper Kamthi too is ferruginous with multi-storied cross bedded unit in number of hill sections within ferruginous siltstone and discontinuous pebble bed intercalation. These siltstone-pebble bed intercalation are interpreted as the flood-plain and channel lag deposits in an overall braided channel system for the upper Kamthi (op. cit.). The predominant argillaceous Maleri Formation gradationally overlies the arenaceous-rudaceous Kamthi. Accordingly, the Kamthi-Maleri formations are classified as the Godavari Group (Burhanuddin, 2022) in accordance with the principles of litho-stratigraphic classification (Table-1). The Kamthi Formation extends from Chintakunta in south to Sirpur in the middle and further towards northeast up to Wardha River (Fig. 1). As such, the Maleri Formation is differentiated as Yerrapalli-Bheemaram-Maleri-Dharmaram biozones (Kutty and Sengupta, 1989) in the ascending order. In present work, this linear argillaceous band; however, is classified as Maleri Formation as per the code of litho-stratigraphic nomenclature (GSI, 1997) in contrary to the earlier works (GSI, 2022) as Yerrapalli Formation.

A narrow-linear zone with massive clay-clast conglomerate occurrence in between Maleri-Kota Formation is identified as an erosional plane (disconformity) near Chintakunta (Fig. 1) in similarity with the southern part of PG basin (Burhanuddin, 2022). Thus, the upper Kota unit unconformably overlies the Maleri Formation in extreme eastern part. A thick arenaceous facies with repeated cycles of clay clast conglomerate-massive sandstone-thickly cross bedded coarse sandstone of mega-bed form association (Burhanuddin, 2022) is defined as the upper Kota Formation. The younger Chikyala/Gangpur Formation in this part is absent in similarity with other parts of PG basin. Thus, the Kota Formation with the erosional base in Sirpur-Kagaznagar area is classified as the part of Dammapeta Group in similarity with the southern PG basin (Burhanuddin, 2022). Accordingly, the overall lithostratigraphic succession in Kagaznagar-Sirpur area is differentiated as Damuda (Barakar), Godavari

(Kamthi-Maleri) and Dammapeta (Kota) groups as per the code of litho-stratigraphic nomenclature works in accordance with the latest works in southern PG basin (op. cit.).

The linear Chintakonda-Kosini Meso-Proterozoic Penganga outcrop occurrence amidst Gondwana in between two NNW-SSE post-depositional faults of opposite dips is interpreted as an upthrown block. These two faults are found in contact with eastern coal bearing Barakar and western ferruginous Kamthi formations. Further, the occurrence of Kamthi Formation directly over the Penganga Group without any underlying Barakar near Kagaznagar (Fig. 1) attest to the views of part/total removal of the Barakar before the onset of Kamthi sedimentation in similarity with the southern PG basin (Burhanuddin, 2022). Thus, a disconformity (erosional plane) is proposed at the base of Kamthi Formation in Kagaznagar-Sirpur area too (Table-1). As such, in overall PG basin, the NNW-SSE, N-S and NE-SW to ENE-WSW faults occur as basin marginal boundary, intra-basinal and transverse faults (op. cit.). The overall NNW-SSE lithological contacts of entire Gondawana sequence are aligned parallel to the both western and eastern margin NNW-SSE faults except in northeastern part along the contact of Maleri-Kota Formation as NE-SW due to Vatti Vagu transverse fault (Fig. 1). The entire NNW-SSE Gondwana sequence is dissected by the NE-SW Vattivagu and Garlapeta-Naweagoan transverse faults in similarity with the ENE-WSW faults in the southern Chintalapudi sub-basin (op. cit.). In between these two NE-SW faults, the Yempalli-Isgaon coal bearing Barakar is marked by the dextral shifts from southwest to northeast as Garlapeta-Cheepalli and Mikhri-Naweagoan blocks (Fig. 1). These NNW-SSE and NE-SW post depositional faults are found as the reactivated structural features of Paleozoic Pan-African and Meso-Proterozoic Grenville orogenic ancestry (Burhanuddin and Srinivasarao, 2024; Burhanuddin, 2017) in the entire Gondwana sequence of PG basin. The linear Kosini-Chintakonda Meso-Proterozoic Penganga occurrence amidst Gondwana as Rajulgutta (Rajarao, 1982) is resulted due to an intra-basinal NW-SE fault along the Mancherial-Eturnagaram section (north of Godavari River). In southern PG basin, the older basement Mailaram Metamorphic High and youngest Kota Formation have been resulted on either side of ENE-WSW traverse (Wrench) fault due to the rotational movement with differential throws all along the fault zone from one end to other. Further, the occurrence of discontinuous Barakar patches amdist vast Kamthi are found as upthrown blocks due to post-depositional NW-SE and NE-SW faults of similar rotational movements (Burhanuddin, 2022).

Conclusions

- In Kagaznagar-Sirpur area, the entire Gondwana sequence is differentiated as the basal Damuda (Barakar), middle Godavari (Kamthi-Maleri) and upper Dammapeta (Kota) groups with two dis-conformity planes similar to the southern PG basin.
- A linear Penganga Group occurrence in southern part amidst the Barakar-Kamthi formations is interpreted as an upthrown block with two NNW-SSE faults of opposite dips.
- A NNW-SSE syn-depositional eastern boundary in southern continuation of regional Ahiri-Cherala syn-depositional fault in the extreme northeast along the contact of youngest Kota Formation-granitoids of EDC is differentiated.
- In between two NE-SW transverse faults, the dextral shifts of individual units from southwest to northeasterly is differentiated.
- The NNW-SSE and NE-SW faults are found as the re-activated structural features of Paleozoic Pan-African and late Meso-Proterozoic Grenville ancestry in accordance with latest works in the entire PG basin.

Acknowledgements

The help of Shri Muzimuddin and B Lingaiah, Geological Survey of India, Hyderabad, during the preparation of this manuscript is highly acknowledged.

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SGAT Bulletin
Vol. 27, No. 1, June 2026, pp. 40-60

ANALYZING CHEMISTRY OF GROUNDWATER AT DIFFERENT DEPTHS USING HYDROCHEMICAL AND STATISTICAL METHODS: A CASE STUDY FROM KANIHA BLOCK, ODISHA

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ABSTRACT

The objective of the present study is to observe the variation of groundwater chemistry in different aquifer zones and evaluate the geochemical processes (both geogenic and anthropogenic) that are controlling it. For this study, 46 water samples were taken from both borewells and dug wells during the pre-monsoon period in the Kaniha Block, Angul District, Odisha. For this analysis, a borewell is considered a deep aquifer and a dug well a shallow aquifer. From analysis result, the chemical dominance in the groundwater of the study area is $Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$ and $HCO_3^{-} > Cl^{-} > SO_4^{2-} > NO_3^{-}$ for cations and anions respectively. The water from deeper aquifers is mostly alkaline as compared to that of the shallow aquifers, with the dominance of Ca^{2+}-HCO_3^{-} ions. From the Piper plot, it was found that Ca^{2+}-Mg^{2+}-HCO_3^{-} is the dominant hydrogeochemical facies of both aquifers whereas in shallow aquifer, it tends to move towards Ca^{2+}-Mg^{2+}-SO_4^{2-}/Cl^{-} facies due to the influence of anthropogenic factors such as agricultural runoff, leaching from fertilizers and domestic wastewater infiltration. From the study it is found that the concentration of EC, TDS, TH, Ca^{2+}, Mg^{2+}, Cl^{-}, SO_4^{2}, NO_3^{-} decreases from shallow aquifer to deeper aquifer and the concentration of total alkalinity, Na^{+}, K^{+}, and HCO_3^{-} increases as it moves from shallow to deeper aquifer. The geochemical behaviour of the water chemistry from one aquifer to the other aquifer is interpreted by using graphical methods such as Piper and Gibbs diagrams, bivariate plots of different chemical parameters as well as statistical techniques such as correlation coefficient, principal component analysis, and linear discriminant analysis.

Key words: *Vertical variation of groundwater quality, Piper Trilinear Diagram, Chloralkaline Index, Pearson Correlation Coefficient, Kaniha Block*

INTRODUCTION

Groundwater quality is critical to preserving human health and environmental sustainability, especially in locations where people rely on it for drinking and agriculture (Singh et al., 2021). The chemistry of groundwater is controlled by geogenic processes such as rock-water interactions, carbonate weathering, silicate weathering, mineral dissolution, ion exchange, and evaporation with precipitation of minerals (Gugulothu et al., 2022). Furthermore, anthropogenic factors such as overexploitation of aquifers, unregulated urban expansion, industrial pollutants and excessive fertilizer application have been reported to degrade groundwater quality. (Mahanta and Goswami, 2024; Subba Rao et al., 2024).

The geochemical processes influencing the groundwater quality is governed by topography, Lithological heterogeneity, aquifer recharge dynamics, changes in temperature and residential period (Das et al., 2023). Furthermore, vertical and horizontal changes in aquifer systems, including mineralogical composition and stratigraphic disposition, have a substantial impact on the chemical quality of groundwater. (Krishan et al., 2025; Bakshe et al., 2024).

Effective evaluation of groundwater chemistry requires a multidimensional approach that accounts for geographical, temporal, and vertical variation. The spatial and temporal variation of groundwater has been studied by many researchers (Das et al., 2023; Mishra et al. 2025). The vertical variation of water quality in a particular aquifer is very challenging and associated with collecting exclusive water samples from a particular depth within an aquifer. Typically, water samples obtained from a groundwater structure represent a fusion of water from various aquifers or fractures that the well accesses. However, for obtaining the representative data on vertical variations in groundwater chemistry under prevailing field conditions, it is only possible by selecting wells of varying depths that tap into different aquifers or fracture systems (Roy and Chintalacheruvu, 2024). The vertical variation is related to aquifer depth and stratigraphy that present different geochemical footprints due to differential flow routes and lithological interfaces. (Ahmed et al., 2019). Localized contamination, irrigation return flows, and precipitation can also change the chemistry of water below the surface. (Manikandan et al., 2020). Often obtaining precise information on the exact depth of wells is impracticable; therefore, reliable and measurable data on water level depths can be considered for depth-wise studies of water chemistry across different aquifer systems. Hence, the selection of borewells and dug wells has been done systematically by considering the depth of the well and water level data. On a broad spectrum, dug wells and borewells are frequently utilized as stand-ins for shallow and deep aquifer systems respectively for analysis of vertical hydrogeochemical profiling (Salem et al., 2022). The dug wells, being generally connected to the upper unconfined aquifer, offer insights into the recharge mechanisms that operate in the short term. Conversely, the borewells are in deeper confined/semi-confined aquifers and thus offer a view of older water and its chemical composition (Reddy et al., 2018). This methodology facilitated a comparative analysis of hydrochemical variations between shallow and deep groundwater systems, thereby enhancing the reliability of the overall assessment.

The hydrogeological study in and around the Kaniha Block is very limited, though it is a key area for coal mining and power generation within the Talcher coalfield, marked by significant industrial activity, swift urban growth and a reliance on groundwater for both domestic and agricultural purposes. Previous research in and around the area has predominantly concentrated on hydrochemical characterization, water quality assessment with spatial analysis, and health risk evaluation (Sahu et al., 2021; Naik et al. 2022; Dalai et al. 2023). The earlier investigations have identified spatial variability in groundwater quality and localized contamination; however, they are largely confined to surface-level or shallow aquifer analysis and do not sufficiently address vertical heterogeneity within aquifer systems. Understanding the vertical variation of groundwater quality is crucial, as contaminant distribution, geochemical processes according to lithological variation, environmental conditions and residence time can vary significantly with depth due to stratification, confined conditions and differing hydrogeological characteristics. However, no researcher has worked in Kaniha Block dedicatedly to address the groundwater geochemistry. Hence, the present study aims at evaluating the changes of water chemistry from one aquifer to other and the geochemical processes involved in different aquifer systems with detailed geochemical evaluation. This study used hydrogeochemical and statistical methods to distinguish the predominant procedures influencing the evolution of groundwater in the study area.

The findings of such a study will provide critical insights for policymakers and water resource managers, enabling depth-specific groundwater management, improved well-design practices, and long-term protection of water resources, thereby ensuring a safe and reliable water supply in this environmentally sensitive region.

Study Area

The study area, Kaniha Block, one of the revenue blocks of Angul District is located in the central part of Odisha, spanning an area of 723 km². Geographically, the block lies between latitudes 21°00’47.942” -21°15’ 10.896” N and longitudes 84°56’41.571”-85°12’ 35.663” E, which is shown in Fig. 1. The block is situated at an average height of 139 m above mean sea level (MSL) and about 179 km from Bhubaneswar, the state capital of Odisha, India. The region is economically very important, as many industries, like coal mines and thermal power stations, are situated in the region. The total population of Kaniha Block is 1,43,109 (as per the 2011 census) and most of the people depend upon agriculture. Northern hilly areas are covered with both dense and open forests, which is around 45% of the total area. The agricultural land with settlement occupied 34% of the study area. The southern part is a thickly populated area.

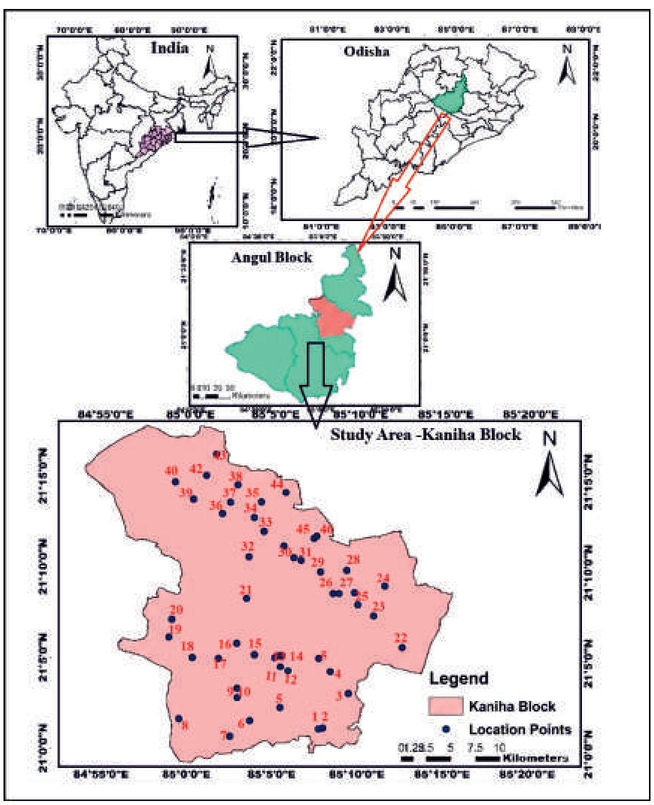

Fig. 1: Location of study area

Geological formation and hydrogeological setting

Geologically, the block is divided into two parts, which is shown in Fig. 2a. The northern part is characterized by Iron Ore Supergroup of rocks comprising of quartzite, quartz mica schist and Eastern Ghats Supergroup of rocks comprising of quartz-feldspar-garnet-sillimanite-graphite schist/gneiss (Khondalite), charnockite, pyroxene granulite, granite, and gneiss (CGWB, 2016; Keesari et al., 2016). These rocks exhibit limited primary porosity; however, secondary porosity developed through fracturing supports restricted groundwater movement. In contrast, the southern portion features undulating plains dominated by Gondwana Supergroup of rocks, comprising of sandstone, shale, conglomerate, and coal beds. The Barakar Formation, known for its coal seams also functions as a major aquifer system (CGWB, 2023). The Brahmani River with tributaries like Tikra Jhora, Singhada Jhora, and Bhalutungri Nallah, defines a rectangular drainage system controlled by regional structural trends.

Groundwater occurs both in sedimentary and crystalline formation under water table condition in weathered zone and semi-confined to confined condition in fractured zones of the underlying crystalline formation. On the basis of their confinement, aquifers can be classified into 2 types; Aquifer-I and Aquifer-II. The Aquifer I is unconfined and weathered, extending up to a maximum of 30 m bgl and Aquifer II lies in deeper fractured zones and is semi-confined to confined in nature extending up to 200 m bgl to 300 m bgl (CGWB, 2016). The thickness of the weathered zone spatially increases from north to south as the change of lithology from crystalline metamorphic to sedimentary formation (Fig. 2b). The disposition of aquifer is represented schematically in a 3-D model shown in Fig. 2c. Groundwater recharge is mainly through direct

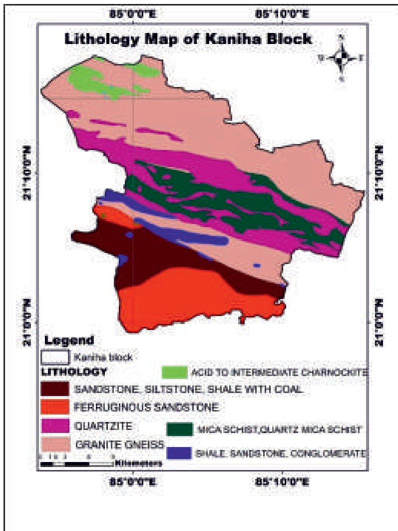

Fig. 2a: Lithology Map of Study Area

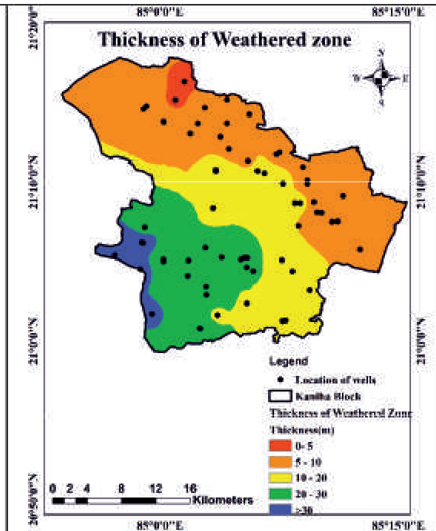

Fig. 2b: Spatial Map of Thickness of Weathered Zone

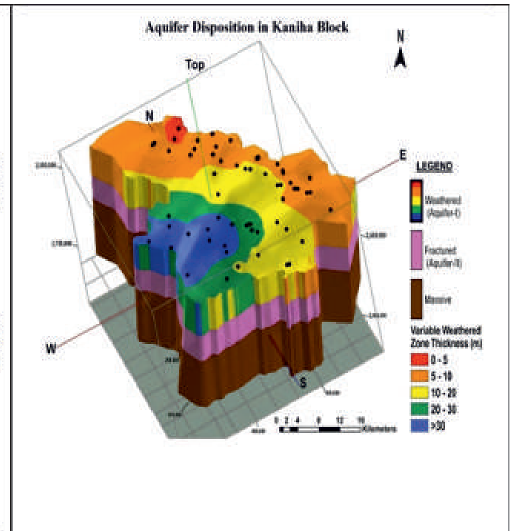

Fig. 2c: Schematic Diagram of 3D-Model Aquifer Disposition of Study Area.

rainfall infiltration. Study area experiences a tropical monsoon climate, which receives rainfall mainly from the south-west monsoon with an average annual rainfall of 1,203 mm. The mean annual wind speed is approximately 6.8 km/h. Groundwater within each geologic formation varies both vertically and spatially due to variations in lithology, depth to water level, and aquifer conditions.

MATERIALS & METHODOLOGY

A total of 46 groundwater samples were collected strategically from 23 bore-wells and 23 dug-wells in pre monsoon season, 2022 which are extensively used for drinking and domestic purposes (Fig. 1). The location points of every dug well and borewell were geotagged by handheld GPS for spatial analysis. Each sample was stored in a 500 ml polyethylene bottle that had been pretreated by soaking in 1:1 HCl for 24 hours and rinsed twice with distilled water. The collected samples were sealed and transported to the laboratory under controlled conditions. The collected groundwater samples were analysed for various physical and chemical parameters using standardised laboratory methods. The parameters such as pH and EC were measured in the field, and other parameters such as total alkalinity(TA), total hardness (TH) with major cations and anions like calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium(K^{+}), bicarbonate (HCO_3^{-}), chloride (Cl^{-}), sulphate (SO_4^{2-}), nitrate (NO_3^{-}) and fluoride (F^{-}) were analysed in laboratory by standard methods (APHA, 2012). All chemical concentrations were expressed in milligrams per litre (mg/L), while pH was unitless, and EC was measured in µS/cm. To ensure data reliability, the ionic balance error percentage (IBE%) was calculated between total cations and anions, expressed in milliequivalents per litre (meq/L). The calculation follows:

$$IBE\% = \frac{\Sigma TC - \Sigma TA}{\Sigma TC + \Sigma TA} \times 100 \qquad (1)$$

Where,

ΣTC = Total concentration of cations (meq/L).

ΣTA = Total concentration of anions (meq/L).

The acceptable limit for IBE% was maintained within ± 5%, ensuring analytical precision.

Graphical Interpretation

After obtaining the analytical results, various hydrogeochemical diagrams such as Piper plot, Gibbs plot, and bivariate plots were created for comprehensive interpretation of geochemical behaviour of groundwater.

The Piper trilinear diagram (Piper, 1944) is plotted using major cations (Na^+, Ca^{2+}, Mg^{2+}, and K^+) and anions (HCO_3^-, Cl^- , and SO_4^{2-}) for interpreting hydrochemical facies. The plot consists of two triangular plots (one for anions and one for cations) are integrated with a central diamond shaped field, categorizing water into different types (Subba Rao et al., 2017). The diamond plot, divided into six fields, represents hydrochemical facies such as Ca^{2+} -HCO_3^-, Na^+-Cl^-, Ca^{2+}-Mg^{2+}-Cl^-, Ca^{2+}-Na^+ -HCO_3^-, Ca^{2+}-Cl^-, and Na^+-HCO_3^- types. The geochemical processes affecting groundwater chemistry, such as precipitation, rock-water interaction and evaporation-crystallization, are identified using the Gibbs diagram (Gibbs, 1970). The anion ratio [Cl^- / (Cl^- + HCO_3^-] and cation ratio [(Na^+ / (Na^+ + Ca^{2+})] are plotted against TDS. This plot aid in differentiating between lithological, evaporative, and atmospheric controls (Krishan et al., 2025). Ionic ratios are commonly employed to assess the origin and evolution of groundwater from shallow aquifer to deep aquifer (Manikandan et al., 2020). The bivariate plots are used to study the geochemical processes,which occurred during water-rock interaction in multiple aquifer systems. These plots are Ca^{2+}/Na^+ vs. HCO_3^- /Na^+ , Ca^{2+} /Na^+ vs. Mg^{2+}/Na^+, Na^+ vs. Cl^-, (Ca^{2+} + Mg^{2+}) vs. HCO_3^-, (Ca^{2+} + Mg^{2+}) vs. (HCO_3^- + SO_4^{2-}), (Ca^{2+} + Mg^{2+}) vs. (Na^+ + K^+) , (Ca^{2+} + Mg^{2+}) vs Cl^-,(Ca^{2+} + Mg^{2+} - HCO_3^- - SO_4^{2-}) vs. (Na^+ - Cl^-), Na^+/Cl^- vs EC, Ca^{2+} vs Na^+, and Ca^{2+} vs Mg^{2+}. These ionic relationships are commonly used in hydrogeochemical research to interpret the sources and mechanisms such as ion exchange, silicate weathering, carbonate dissolution and anthropogenic or evaporation influence the groundwater chemistry. They aid in the differentiation of processes (Gugulothu et al., 2022).

Chloro-Alkaline Index (CAI)

The Chloro-Alkaline Index (CAI) was originally proposed by Schoeller (1977), which is used to evaluate ion exchange and adsorption processes between groundwater and the surrounding aquifer materials (Gugulothu et al., 2022).

The CAI is calculated using the following formula:

$$CAI\text{-}1 = \{Cl^- - (Na^+ + K^+)\}/Cl^- \quad (2)$$

$$CAI\text{-}2 = \{Cl^- - (Na^+ + K^+)\}/\{SO_4^{2-} + HCO_3^- + CO_3^{2-} + NO_3^-\} \quad (3)$$

All ion concentrations are expressed in milliequivalents per liter (meq/L).

Statistical Interpretation

The multivariate statistical methods were applied to understand the source of the ions and factors affecting the groundwater chemistry. The descriptive statistics are used to calculate minimum, maximum and mean values as well as standard deviation, which analyses the differential variables in different aquifers (Ahmed et al., 2025; Krishan et al., 2025). In addition to descriptive statistics, correlation coefficient analysis (CCA) and linear discriminant analysis (LDA) have been carried out to evaluate the differential geochemical characteristics in multiple aquifer system.

The relationship between chemical parameters was examined through bivariate analysis by applying Pearson's correlation coefficient which portrayed the hydrogeochemical process or any factor other than physicochemical variables affecting the system. The level of relationship among variables such as strong ($r > 0.7$), moderate ($0.5 < r \leq 0.7$) and weak ($r < 0.5$) has been depicted from the data of the coefficient of correlation (Ahmed et al., 2019). In addition to this, linear discriminant analysis (LDA) was carried out to differentiate groundwater based on unconfined to confined aquifer type to understand variations arising from differences in recharge, residence time and geochemical evolution (Mammeri et al., 2023). The linear discriminant function (LD Function) serves as a mathematical equation within linear discriminant analysis (LDA) to distinguish between multiple groups (classes) using predictor variables such as pH, EC, TDS and others (Amiri & Nakagawa, 2021). The derivation of linear discriminant (LD) functions depends on the count of groups and predictor variables in the model (Roy and Chintalacheruvu, 2024). The accuracy and statistical validation of the discriminant model verify using Wilks' Lambda, canonical correlation and leave-one-out cross-validation (Mammeri et al., 2023). Wilk's Lambda indicates the effectiveness of the discriminant function; lower values suggest better discrimination. Canonical correlation validates the strength of association between aquifer type and discriminant scores. All the statistical analyses were made using XL-stat Microsoft Excel and Jamovi software.

RESULTS AND DISCUSSION

Groundwater Chemistry

A detailed statistical analysis was conducted to assess the groundwater quality of both shallow and deep aquifers using 46 water samples and 14 physicochemical parameters. The descriptive statistical analysis of all parameters from the shallow aquifer and deep aquifer are given in Table-1. The distribution of chemical parameters according to their dominance in the study area is $Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$ and $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$ for cations and anions respectively. The pH ranged from 6.72 to 7.98, with a mean of 7.36, suggesting slightly acidic to alkaline conditions in shallow aquifer, whereas in deep aquifer water quality is an alkaline type, ranging from 7.38 to 8.70 (mean H ≈ 8.01). Deep aquifers tend to have more stable and slightly more alkaline water, possibly due to prolonged interaction with subsurface minerals and limited exposure to surface contaminants. Alkalinity in deep aquifers may reflect carbonate buffering capacity from prolonged geochemical processes (Marghade et al., 2021, Mahanta et al.,2020). EC varied from 686 to 2,456 µS/cm, with a mean of 1,585.52 µS/cm in the shallow aquifer whereas in the deep aquifer, it varies from 390 to 2,473 µS/cm (mean ≈1,228.96 µS/cm). EC is an indicator of dissolved ion content. Both aquifers show moderate mineralization, with slightly higher values in shallow aquifers, potentially due to evaporation and high anthropogenic loading with lack of hydraulic gradient. TDS values vary from 439.04 to 1,571.84 mg/L (mean

Table-1: Summary of descriptive statistics of different hydrochemical parameters in shallow and deep aquifers.

	Shallow Aquifer				Deep Aquifer			
Parameter	**Minimum**	**Maximum**	**Mean**	**Standard deviation (n-1)**	**Minimum**	**Maximum**	**Mean**	**Standard deviation (n-1)**
pH	6.72	7.98	7.36	0.31	7.38	8.70	8.01	0.30
EC	686.00	2456.00	1585.52	508.82	390.00	2473.00	1228.96	550.03
TDS	439.04	1571.84	1014.73	325.64	249.60	1582.72	786.53	352.02
TA	70.00	550.00	259.57	132.09	50.00	500.00	288.91	119.80
TH	145.00	393.00	255.43	68.49	90.00	280.00	165.09	51.85
Ca^{2+}	28.56	118.00	71.16	23.27	13.65	87.92	43.02	18.72
Mg^{2+}	6.49	30.49	18.14	6.71	5.71	25.89	14.71	4.42
Na^{+}	12.56	75.65	39.55	17.78	31.19	85.00	59.59	14.57
K^{+}	1.21	8.89	4.45	1.97	2.41	12.36	8.07	2.78
Cl^{-}	18.23	110.65	76.03	20.96	12.20	91.25	46.58	20.99
HCO_3^{-}	100.54	298.56	209.17	51.33	160.25	305.00	240.96	44.91
SO_4^{2-}	8.60	77.56	44.76	18.44	1.80	71.70	30.48	20.65
F^{-}	0.13	1.12	0.59	0.27	0.15	1.58	0.76	0.37
NO_3^{-}	9.87	29.50	16.84	4.36	3.07	29.65	10.33	6.13

Here, all the values are in mg/L except pH and EC. The EC is expressed in µS/cm.

≈1,014.73 mg/L) in shallow aquifers whereas in deep aquifer, they range from 249.60 to 1,582.72 mg/L (mean ≈786.53 mg/L). Both aquifers fall within acceptable limits for drinking water, but shallow aquifers show slightly higher mineral content. The hydrochemical difference between shallow aquifers and deep aquifers is due to surface recharge by precipitation and runoff conditions in hard terrain with the influence of the evaporation process. Total Hardness (TH) in deep aquifer is generally lower (hard type), with a narrow range, whereas in shallow aquifer higher median values and wider range, reflecting more contact with calcium and magnesium-bearing minerals (Sahu et al., 2021). Surface interactions and recharge influence hardness levels in shallow aquifers. Ca^{2+} and Mg^{2+} levels are consistently higher in shallow aquifers. Groundwater in shallow aquifers is more reactive with soil and rock layers, contributing to higher hardness levels. Na^{+} and K^{+} are more variable in groundwater of deep aquifers. The concentration of Na^{+} increases from shallow phreatic/unconfined aquifer to that of the deep confined aquifer. These variations depict differences in geological formations and the occurrence of ion exchange processes with longer resident times at depth. (Marghade et al., 2021; Bakhara and Mahanta, 2021). K^{+} is the least abundant cation in groundwater due to its association with clay minerals. The mobilization of potassium in deeper aquifer is more due to long residence periods. Bicarbonate dominates alkalinity and reflects the buffering capacity in deep aquifers. The enrichment of HCO_3^- in shallow aquifer to deep aquifers is due to more water-rock interaction during the recharge process (Ahmed et al., 2019). The concentration of chloride ions decreases from shallow aquifers to deep aquifers despite the elevation of Na^{+} towards deep aquifers due to non-geogenic processes such as landfills, waste dumps, septic tanks, industrial effluents and animal activities. Elevated nitrate and sulphate concentrations in shallow aquifers are strong indicator of anthropogenic pollution like fertilizers, wastewater infiltration or agricultural runoff (Keesari et al., 2016). The concentration of F^- increases from shallow aquifer (mean 0.59) to deep aquifer (mean 0.76) due to dissolution of F^- bearing minerals in alkaline conditions and high residence period in the aquifer system (Mahanta and Goswami, 2024).

Hydrochemical facies and mechanism governing hydrochemistry

The Piper diagram (Fig. 3) shows a dominant Ca-Mg-HCO_3 hydrogeochemical facies in groundwater of both shallow and deep aquifers, illustrating the significant influence of carbonate and silicate weathering as key geogenic processes (Kumar et al., 2024). In cation triangle, samples are clustered along Ca^{2+} and Na^{+}-K^{+} suggesting mineral dissolution from calcite, dolomite and silicate-rich rocks in the aquifer (Singh et al., 2021). The anion field demonstrates bicarbonate enrichment in deep aquifer, signifying primarily governed by natural silicate and carbonate rock weathering, with minimal influence from anthropogenic salinization. A few shallow aquifer samples show dispersion into the mixed water type zones (Ca-Mg-Cl) and (Ca-Cl) potentially due to dissolution or reverse osmosis influenced by clay minerals and contributing to elevated Cl^- concentration in surface-affected zones due to evaporation and anthropogenic sources (Mishra et al., 2025). In contrast,

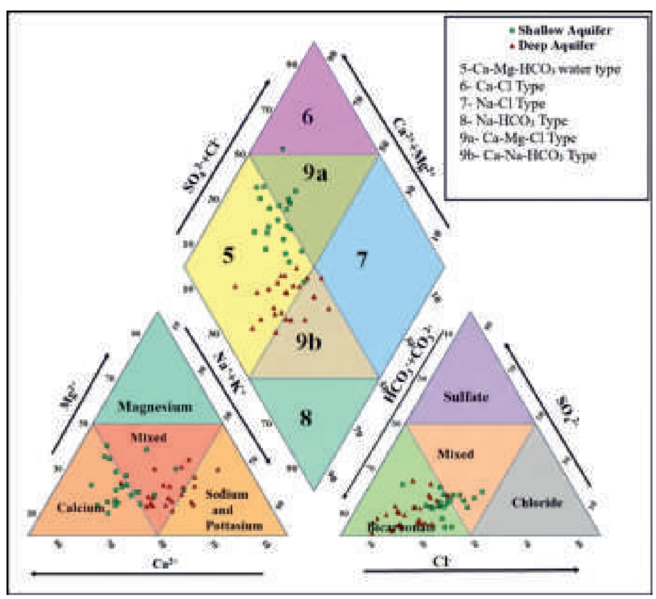

Fig. 3: Piper Diagram for water type determination for shallow and deep aquifers

the deep aquifer samples retain a tighter grouping in the Ca-Mg-HCO_3 field and few samples in Ca-Na-HCO_3 zones, hinting at varying degrees of water-rock interaction in intermediate zones and being indicative of longer residence time with ion exchange reactions, reduced anthropogenic impact, and better buffering capacity from deeper lithological formations. (Bakshe et al., 2024).

From Gibbs diagram (Fig. 4a & 4b), it shows that most of the samples from both shallow and deep aquifers fell within the rock dominance zone which signifies that rock-water interaction is the most important geogenic process affecting the groundwater chemistry. However, some shallow aquifer samples having high TDS values were inclined towards evaporation crystallisation zone which signified that evaporation processes affect the groundwater chemistry.

Depth-dependent geochemical evolution

The geochemical evolution in groundwater along different aquifer depths can be effectively understood by considering the ionic ratios, which identifies the major geochemical processes happening across depth. Understanding the significance of ionic ratios is essential for the geochemical assessment of groundwater with evaluation of hydraulic condition like hydraulic gradient, flow velocity, stages of saturation and mobility of ions (Yu et al., 2025). The major geochemical processes governing the water chemistry along the depth are carbonate or silicate weathering, dissolution of minerals, ion exchange reaction and geochemical equilibrium (Keesari et al., 2016). The dissolution and precipitation of mineral processes depend on the saturation of the minerals and equilibrium conditions. In this study, we examine ionic connections within both deep and shallow aquifer systems to decode their geochemical characteristics.

The Ca^{2+}/Mg^{2+} ratio provides the information about the extent of the role played by either carbonate or silicate weathering. Shallow aquifers typically have higher Ca^{2+}/Mg^{2+} ratios (>2) which justified that silicate weathering is the predominant process (Bakshe et al., 2024). From biplot Ca^{2+} vs Mg^{2+} (Fig. 5a) some of the shallow aquifer samples are marked between the 1:1 and 1:2 lines, which is governed by calcite weathering under fresh recharge conditions and most of the points are distributed in between the 1:2 and1:3 line, which signifies that calcite dissolution has taken place. Some of the points fell beyond the 1:3 line, suggesting silicate weathering. In contrast, deep aquifers have a lower ratio than shallow aquifers, which suggests a combined influence of carbonate dissolution or ion exchange where Na^{+} replaces Ca^{2+}. The points falling below the 1:1 line

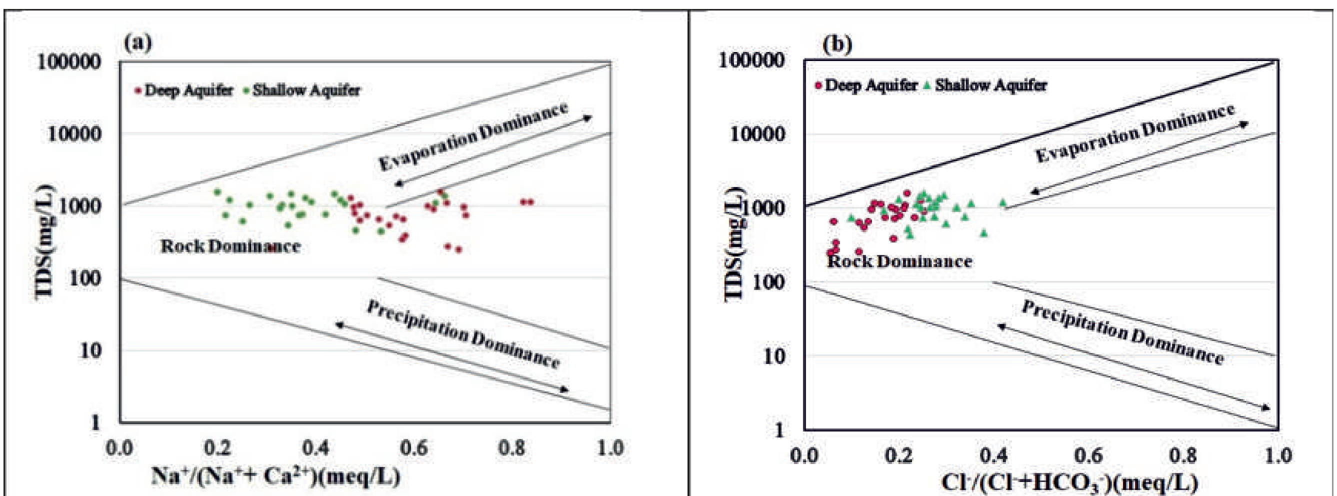

Fig.4 (a) and (b): Gibbs plot

indicate the dissolution of calcium-sodium plagioclases (i.e., from andesine to oligoclase), suggesting an excess of calcium, probably from calcic plagioclase dissolution and deep aquifer points lying above the 1:1 line, indicating a major contribution from sodium-rich plagioclases (Gao et al., 2023).

Na^+/Cl^- ratios are used to explain its contribution to the groundwater system through dissolution of evaporate deposits or ion exchange reaction (Fig. 5b). Na^+/Cl^- ratios of the groundwater of the study area varied from one aquifer to the other aquifer, and the trend line having low R^2 (0.3486) in deep aquifer sample suggests that not only dissolution process control water chemistry, but also other sources are involved in it. Na^+/Cl^- ratio often exceed One (1) in deep aquifers. which suggest cation exchange reaction with silicate weathering (Ribinu et al., 2023). The higher concentration of Na^+ over Cl^- could be a consequence of hydrolysis of plagioclase feldspars present in the country rocks. Ratios near 1 in shallow aquifers reflected that halite dissolution and the occurrence of points above the 1:1 line indicated that freshwater recharge followed by evaporation, which justified the dominance of evaporation-driven concentration or direct chloride contamination from anthropogenic sources occurred. Though dominance of Cl^- over Na^+ indicates reverse ion exchange, considering the climatic condition and land use pattern of the study area, genesis of Cl^- might be from a nongeogenic origin such as irrigation-return-flows (Zhang et al., 2020).

The influence of dissolution and evaporation processes in the study area could be better explained by utilising the ratio between Na^+/Cl^- and EC. The ratio of Na^+/Cl^- in shallow aquifer samples had an almost constant trend line with an increase in the electrical conductivity as shown in Fig. 5c, which signifies the effect of evaporation and evapotranspiration (Gaur et al., 2022). In the deep aquifer zone, the trend line shows the negative slope which indicated the water chemistry due to high evapotranspiration, long residence time and reverse ion exchange (Reddy et al., 2018). The bivariate plot between Ca^{2+} and Na^+ as shown in Fig. 5d, clearly indicated the dominance of Na^+ in deep aquifer due to silicate weathering with ion exchange process whereas carbonate weathering is the primary geochemical process responsible for elevation of Ca^{2+} concentration in shallow aquifer (Srivastav et al., 2026). However, some shallow aquifer points fall above 1:1 line indicating evaporation process. The higher $(Ca^{2+} + Mg^{2+}) / (Na^+ + K^+)$ ratio in shallow aquifers, indicate dominance of alkaline earth over alkali metals (Fig. 5e). This indicates that contribution of alkaline-earth metals in shallow groundwater is due to mostly carbonate and silicate weathering and limited ion exchange processes (Srivastav et al., 2026; Nasher & Ahmed, 2021). In deep aquifer, some points falling above the 1:1 line and some of the samples falling below the 1:1 line indicate that at the intermediate depth reverse ion exchange reaction elevated the concentration of Ca^{2+} and Mg^{2+} ions over Na^+ and K^+. After passage of the transition zone, the water types changed to $Na\text{-}HCO_3$. The high Na^++K^+ concentration supports the occurrence of silicate weathering and cation exchange between groundwater and clay minerals in the subsurface due to long residence time (Zhang et al., 2020).

The bivariate correlation between Ca^{2+} and SO_4^{2-} (Fig. 5f) is an essential tool for evaluating the geochemical mechanism that distinguishes geogenic mineral dissolution and secondary processes like ion exchange or anthropogenic contamination (Hota et al., 2023). In shallow aquifer there is a moderate correlation ($R^2 = 0.37$) between Ca^{2+} and SO_4^{2-} reflecting a link between recharge and surface processes. The trend line indicated that Ca^{2+} moderately increased with SO_4^{2-}, suggesting dominance of Ca^{2+} and SO_4^{2-} due to carbonate dissolution other than the gypsum or anhydrite dissolution (Gaur et al., 2022). The additional amount of SO_4^{2-} is contributed to the phreatic aquifer system from the anthropogenic source, such as agricultural runoff and infiltration of domestic sewage (Zhang et al., 2020). In deep aquifers, lack of correlation between

Na^+/Cl^-

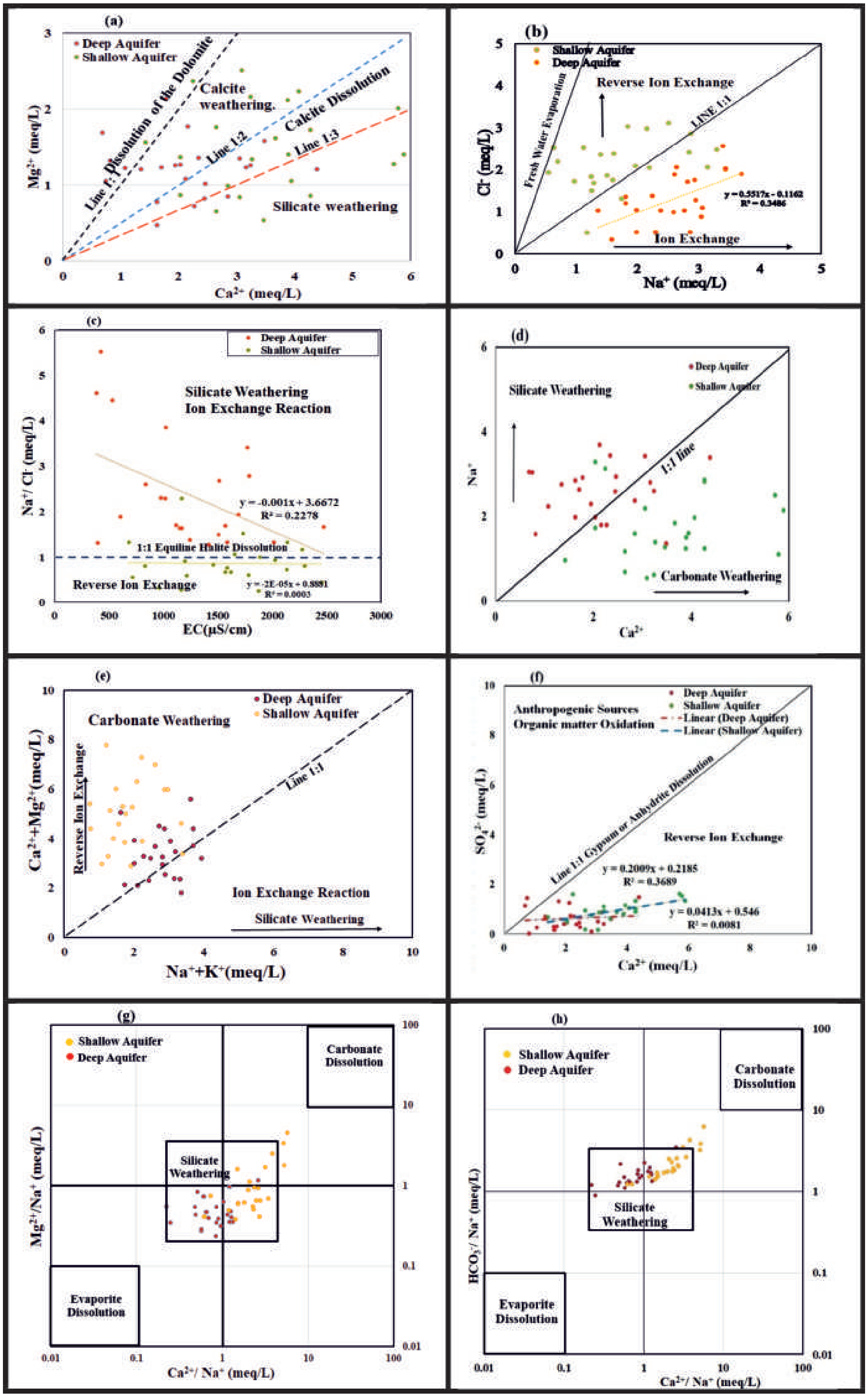

Fig. 5: Bivariate plots: (a) Ca^{2+} vs. Mg^{2} (b) Na^{+} vs. Cl^{-} (c) Na^{+}/Cl^{-} vs. EC (d) Ca^{2+} vs. Na^{+} (e) (Ca^{2+} + Mg^{2+}) vs. (Na^{+} + K^{+}) (f) Ca^{2+} vs. SO_4^{2-} (g) Mg^{2+} /Na^{+} vs. Ca^{2+} /Na^{+} (h) HCO_3^{-} /Na^{+} vs. Ca^{2+}/Na^{+}

Ca^{2+} and SO_4^{2-} ($R^2 = 0.01$) indicated that both ions were derived from independent sources other than gypsum dissolution (Nasher & Ahmed, 2021). The contribution of calcium in deep aquifer is by the process of reverse ion exchange reactions and weathering of plagioclase feldspar and pyroxenes within the metamorphic terrain (Yu et al., 2025). The low SO_4^{2-} concentrations at depth is contributed by the process of sulphate reduction and oxidation of organic matter in Gondwana coal-bearing strata.

The bivariate plot of Mg^{2+}/Na^+ vs. Ca^{2+}/Na^+ and HCO_3^-/Na^+ versus Ca^{2+}/Na^+ on a logarithmic scale is a diagnostic geochemical tool to evaluate the dominant mineral weathering processes influencing groundwater chemistry (Gao et al., 2023). This plot enables differentiation between three key weathering regimes: silicate weathering, carbonate dissolution and evaporite dissolution, based on the relative molar concentrations of major cations (Yu et al., 2025). In the plot Mg^{2+}/Na^+ vs. Ca^{2+}/Na^+ (Fig. 5g), most of the samples from both the deep aquifer and shallow aquifer fell within the central silicate weathering domain. This suggests that silicate mineral dissolution (e.g., feldspars, pyroxenes, amphiboles) is the predominant geochemical process controlling the ionic composition of groundwater (Gugulothu et al., 2022). A few sampling points, particularly from shallow aquifers, trend slightly towards the upper-right corner, indicative of carbonate dissolution, where Ca^{2+} and Mg^{2+} concentrations are elevated relative to Na^+. Samples from deep aquifers show tighter clustering within the silicate weathering field, suggesting homogeneity, minimal anthropogenic interference and longer residence times (Nasher and Ahmed, 2021). From the plot of HCO_3^-/Na^+ versus Ca^{2+}/Na^+ (Fig. 5h) deep aquifer is more tightly clustered, indicating homogeneous geochemistry and prolonged interaction with silicate minerals. The water from shallow aquifers is slightly more dispersed, with a minor shift toward the carbonate zone. This may be due to shorter residence time, surface infiltration and influence of anthropogenic activities such as fertilizer usage or domestic effluents (Gugulothu et al., 2022).

The plot ($Ca^{2+}+Mg^{2+}$) vs. HCO_3^- (Fig. 6a) indicated the source of Ca^{2+} and Mg^{2+} in groundwater. The samples from the shallow aquifer fell above the equiline (1:1), which indicated that carbonate dissolution is not the only factor that contributes to Ca^{2+} and Mg^{2+}, but the other geochemical processes also occurred in the system (Ibrahim et al., 2023). The excess alkaline earth metal is derived from additional geochemical processes such as ion exchange reactions and reverse ion exchange reaction. This dominance in the shallow aquifer system is due to intense water-rock interaction and hydrochemical conditions of the aquifer (Kumar et al., 2006). In contrast, the samples from the deep aquifer fell in between line 1:1 to 1:2 (0.5), which specified that the groundwater chemistry is mainly due to the dissolution of carbonates as well as ion exchange reaction. The concentration of Ca^{2+} and Mg^{2+} depleted along deeper aquifers, indicating that cation exchange processes occurred in confined aquifer zones due to longer residence times and equilibrium conditions (Kumar et al., 2006). Shallow aquifers show slightly elevated bicarbonate relative to Ca-Mg, possibly due to organic matter oxidation or higher atmospheric CO_2 dissolution in recharge zones (Ibrahim et al., 2023).

The plot ($Ca^{2+}+ Mg^{2+}$) vs. $HCO_3^-+SO_4^{2-}$ (Fig. 6b) distinguishes weathering sources. The points falling above the equiline suggest carbonate weathering, whereas the points falling along the equiline resulted from carbonate and silicate weathering (Nasher and Ahmed, 2021). Most of the deep aquifer samples fell below the line (1:1), indicating calcite weathering and gypsum dissolution, whereas some of the points are falling close to the equiline suggesting both carbonate and silicate weathering (Roy et al., 2020). The shallow aquifer points fell above 1:1 equiline, showing that a reverse ion exchange reactions took place enriching the concentration of Ca^{2+} and Mg^{2+} (Ibrahim et al., 2023).

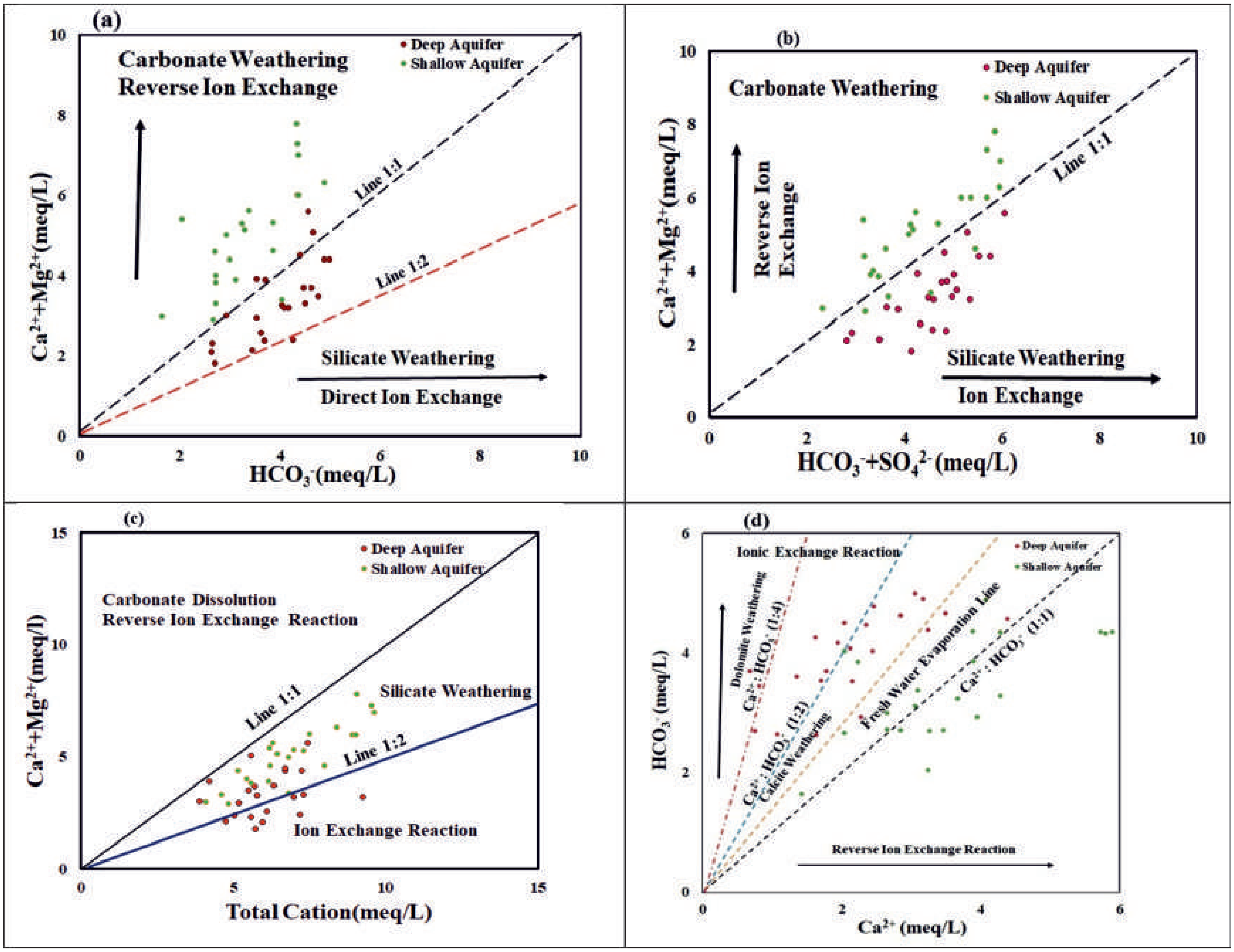

Fig. 6: Bivariate Plots: (a) (Ca^{2+} + Mg^{2+}) vs. HCO_3^- (b) (Ca^{2+}+ Mg^{2+}) vs. (HCO_3 +SO_4) (c) Ca^{2+}+Mg^{2+} vs. Total Cation (d) Ca^{2+} vs. HCO_3^-

The plot between total cation versus Ca^{2+}+Mg^{2+} (Fig. 6c) showed that all the samples from both the deep aquifer and shallow aquifer fell below the equiline 1:1, reflecting the weathering of calcium and magnesium-rich minerals (Sidhu and Chandel, 2023). Some points from deeper aquifer fell below the 1:2 line suggesting other geochemical processes, such as ionic exchange reaction, occurring along with silicate weathering (Nasher and Ahmed, 2021).

The plot of Ca^{2+} versus HCO_3^- (Fig. 6d) shows that the chemistry of groundwater from shallow to deep aquifers is influenced by carbonate and silicate weathering, evaporation processes, reverse ion exchange reactions and cation exchange processes (Nasher and Ahmed, 2021). The shallow aquifer samples distributed along the zone 1:1 line and freshwater evaporation line signify that the rapid carbonate dissolution occurred in the weathered phreatic aquifer. The points falling below the 1:1 line signify that concentration increases with respect to bicarbonate which is due to reverse ionic exchange reactions, silicate weathering and gypsum/anhydrite dissolution (Ibrahim et al., 2023). The "Fresh Water Evaporation Line" trend indicates that the precipitation of Ca^{2+} in shallow groundwater balances with HCO_3^- due to the evaporation process. The deep aquifer samples are predominantly clustered between 1:2 and 1:4 line which justifies the dominance of silicate weathering over carbonate dissolution. The points near

1:2 line is characterised by calcite weathering and shifted towards the 1:4 line, suggesting dolomite weathering or more incongruent dissolution of silicate minerals like plagioclase and alkali feldspar in Charnockitic gneiss (Sidhu and Chandel, 2023). The higher concentration of HCO_3^- ions relative to calcium is due to weathering of sodic plagioclase, and carbonate minerals and depletion of Ca^{2+} ion due to cation exchange reaction (Salem et al. 2022).

The plot between $Na^+ + K^+ - Cl^-$ versus $(Ca^{2+}+Mg^{2+}) - (HCO_3^- - SO_4^{2-})$ (Fig.7) explained the change of geochemical behaviour of the groundwater according to depth (Salem et al., 2022). In shallow aquifer system, the slope is -0.937, which suggested that reverse ion exchange occurred due to continuous recharge, high flow velocity with short duration for rock water interaction (Sidhu and Chandel, 2023).

The carbonate weathering remains dominant geochemical process in shallow aquifer zone with limited sodium enrichment. In contrast, in the deep aquifer zone, ion exchange takes place which shows negative slope equal to -1 (-1.0889). The advanced stage of ion exchange occurred in deep aquifer due to longer residence time and stronger interaction with clay-rich formations, promoting reverse ion exchange processes

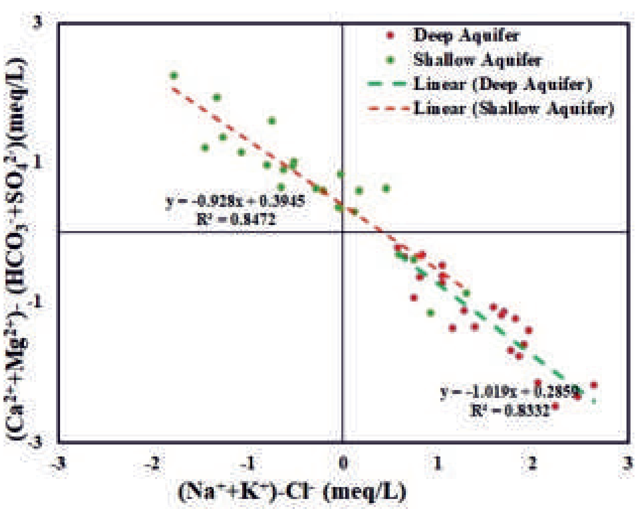

Fig.7: Ion ratio diagram of $Na^+ + K^+ - Cl^-$ vs. $(Ca^{2+} + Mg^{2+}) - (HCO_3^- + SO_4^{2-})$

(Yu et al., 2025). The coefficients of determination ($R^2 \approx 0.84$) are higher for both aquifers, indicating that exchange processes follow a consistent geochemical mechanism across the multi-aquifer system (Salem et al., 2022).

Ion Exchange

CAI-1 and CAI-2 exhibiting positive values in the shallow aquifer signifies the predominance of reverse ion exchange. Na^+ and K^+ replacing Ca^{2+} and Mg^{2+} from aquifer matrix into the groundwater formed positive indices (Gugulothu et al., 2022), whereas ion exchange occurs when Ca^{2+} and Mg^{2+} ions in groundwater mix with clay minerals, releasing Na^+ ions. This phenomenon is commonly intensified by agricultural activities, especially under conditions of excessive irrigation and return flow, which lead to sodium enrichment and further drive reverse exchange reactions (Kumar et al., 2024).

Despite this trend, the groundwater still exhibits a dominant Ca-Mg-HCO_3 facies, pointing to active carbonate weathering, though the gradual increase in Na^+ levels hints at an evolving facies toward mixed or Na-type water (Gugulothu et al., 2022). In contrast, the deep confined aquifer presents a more complex geochemical signature, with CAI values showing a near 50:50 distribution between ion exchange and reverse ion exchange. Negative CAI values here indicate direct ion exchange, where Ca^{2+} and Mg^{2+} in groundwater are exchanged with Na^+ and K^+ adsorbed on aquifer matrix surfaces (Sahu et al., 2021; Zhang et al., 2020). This typically reflects longer groundwater residence times and prolonged water-rock interaction, allowing cation exchange to proceed within feldspathic and clay-rich lithologies (Marghade et al., 2021). Nevertheless, many deep aquifer samples continue to exhibit the Ca-Mg-HCO_3 facies, indicating that carbonate and silicate weathering remain dominant processes, with ion exchange playing a progressively modifying role (Subba Rao et al., 2017). Fig. 8 (CAI-1 vs. CAI-2) represents the cation ion exchange and reverse ion exchange processes.

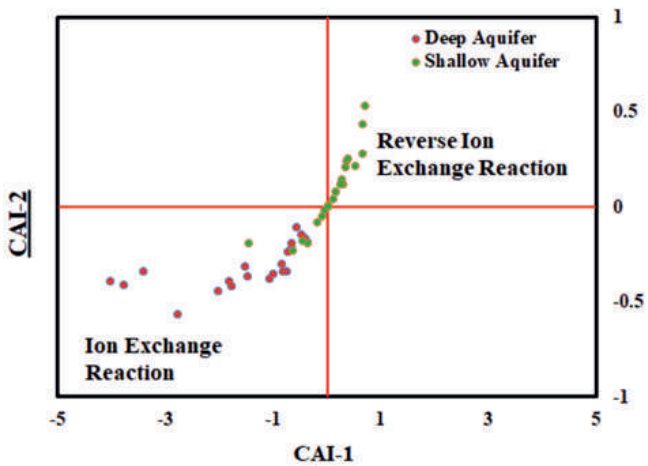

Fig.8: Schoeller's ion exchange reactions (CA1-1vs. CAI-2)

Correlation Matrix

The correlation matrix for shallow groundwater highlights significant relationship among major hydrochemical parameters, which described the dominant geochemical processes that alter the water chemistry (Table-2). A strong correlation between EC and TDS (r=1.000) indicated that salinity of the groundwater in shallow aquifer is influenced by surface soil hydrogeochemical processes such as weathering of organic matter and evaporation process as well as due to anthropogenic contamination. (Ribinu et al., 2023). Strong positive correlations of TDS with TH (0.660), Ca^{2+} (0.664), Cl^- (0.651), HCO_3^- (0.646) and SO_4^{2-} (0.566) suggest that mineralization in shallow aquifer is due to carbonate weathering, dissolution of calcium sulphate and evaporation process (Das et al., 2023). In addition to these processes, anthropogenic activity such as agricultural runoff and wastewater discharge in the study area also regulated the water quality in shallow to intermediate zone. The strong relationship between TH and Ca^{2+} (r = 0.893) and Mg^{2+} (0.514) suggests that hardness is mainly influenced by calcium and magnesium ion, revealing the effect of carbonate lithology. HCO_3^- also shows a strong relationship with TH (0.714) and Ca^{2+} (0.637), underscoring the role of carbonate weathering such as calcite/dolomite dissolution which also justified the strong association of total hardness with Cl^- (0.589) and SO_4^{2-} (0.659). The moderate correlation between alkalinity and pH (0.587) explained that alkalinity is controlled by bicarbonate buffering,

Table-2: Correlation matrix of the 14 physico-chemical variables of shallow aquifer groundwater

Variables	pH	EC	TDS	TA	TH	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	HCO_3^-	SO_4^{2-}	F^-	NO_3^-
pH	**1**													
EC	0.327	**1**												
TDS	0.327	**1.000**	**1**											
TA	**0.587**	**0.647**	**0.647**	**1**										
TH	**0.452**	**0.660**	**0.660**	**0.518**	**1**									
Ca^{2+}	0.349	**0.664**	**0.664**	**0.569**	**0.893**	**1**								
Mg^{2+}	0.316	0.235	0.235	0.095	**0.514**	0.087	**1**							
Na^+	0.099	**0.517**	**0.517**	0.343	0.060	0.102	-0.027	**1**						
K^+	0.028	-0.299	-0.299	-0.114	-0.066	-0.254	0.242	0.041	**1**					
Cl^-	0.255	**0.651**	**0.651**	0.493	**0.589**	**0.551**	0.319	0.388	-0.220	**1**				
HCO_3^-	0.338	**0.646**	**0.646**	0.440	**0.714**	**0.637**	0.378	**0.557**	0.000	0.395	**1**			
SO_4^{2-}	0.263	**0.566**	**0.566**	**0.501**	**0.659**	**0.607**	0.355	0.280	0.215	**0.420**	**0.448**	**1**		
F^-	-0.085	0.255	0.255	-0.073	0.214	0.201	0.210	0.066	-0.323	0.239	0.098	0.250	**1**	
NO_3^-	0.033	0.397	0.397	0.238	0.398	0.391	0.136	0.273	-0.122	0.277	**0.416**	0.249	0.043	**1**

consistent with carbonate dissolution. The silicate weathering, limited ion-exchange processes and minor anthropogenic inputs contributed to the water chemistry as signified by moderate relationship of Na^+ with EC (0.517) and HCO_3^- (0.557) (Hota et al., 2023). Cl^- shows correlation with EC and TH, suggesting genesis is from mixed sources such as mineral dissolution and possible human inputs. On the contrary, K^+ and F^- exhibit weak or negative correlations with most parameters, suggesting localized or independent sources with limited mobility in shallow aquifer (Hota et al., 2023). NO_3^- has moderate correlation with EC (0.397) and HCO_3^- (0.416), indicating the role of anthropogenic influences like agricultural activities and domestic runoff. The dataset displays a hydrochemical regime dominated by water-rock interaction, particularly carbonate weathering with minor contributions from silicate weathering, ion exchange reaction due to evaporation and surface derived anthropogenic activities.

The correlation matrix of deep aquifer is presented in Table-3. In deep aquifer, the strong relationship between EC and TDS (1.000) confirmed that electrical conductivity is entirely governed by total dissolved ionic concentration which is derived from water rock interaction having longer residence time. The dominant salinity source in deep aquifer is controlled by pyrite oxidation in coal seams and carbonaceous shale, which is revealed from the correlation between EC, TDS and SO_4^{2-} (0.769) (Srivastava et al., 2026). Though pyrite oxidation produces the acidity, carbonate buffering neutralises the acidity mostly. Hence, the sulphate concentration rises without declining of pH value which is justified by the relationship between SO_4^{2-} and pH (-0.171). The strong correlation between TH-Ca^{2+} (0.931), TH-HCO_3^- (0.709) and Ca^{2+}-HCO_3^- (0.703) reflects the continued influence of carbonate dissolution. The moderate to strong positive correlation between EC-Na^+ (0.544), EC-Cl^- (0.619), Na^+-Cl^- (0.590) indicates sodium chloride enrichment in deep aquifer due to ion exchange reaction. The sodium enrichment is not only

Table-3: Correlation matrix of the 14 physico-chemical variables of deep aquifer groundwater

Variables	pH	EC	TDS	TA	TH	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	HCO_3^-	SO_4^{2-}	F^-	NO_3^-
pH	**1**													
EC	-0.107	**1**												
TDS	-0.107	**1.000**	**1**											
TA	0.241	**0.587**	**0.587**	**1**										
TH	0.098	0.178	0.178	0.275	**1**									
Ca^{2+}	0.076	-0.001	-0.001	0.220	**0.931**	**1**								
Mg^{2+}	0.166	0.457	**0.457**	0.214	**0.303**	-0.023	**1**							
Na^+	0.255	**0.544**	**0.544**	**0.610**	0.163	0.121	0.044	**1**						
K^+	0.028	-0.016	-0.016	-0.033	-0.026	-0.039	-0.084	0.253	**1**					
Cl^-	0.117	**0.619**	**0.619**	**0.614**	**0.584**	**0.543**	0.235	**0.590**	-0.150	**1**				
HCO_3^-	**0.391**	-0.151	-0.151	0.142	**0.709**	**0.703**	0.164	0.310	0.200	0.250	**1**			
SO_4^{2-}	-0.171	**0.769**	**0.769**	0.409	0.259	0.090	**0.384**	**0.486**	0.143	**0.394**	-0.052	**1**		
F^-	0.143	**0.467**	**0.467**	0.332	-0.110	-0.241	**0.349**	0.299	-0.238	0.262	-0.269	**0.371**	**1**	
NO_3^-	-0.280	0.395	0.395	0.134	0.395	0.224	**0.388**	0.057	-0.260	0.177	0.148	**0.358**	-0.057	**1**

due to the silicate weathering, but also ion exchange process producing sodium enrichment. The correlation between total alkalinity with Na^{+} (0.610), Cl^{-} (0.614) and SO_4^{2-} (0.409) explained that alkalinity of groundwater in deep aquifer is not only controlled by bicarbonate buffering but also by mineralisation processes (Srivastava et al., 2026). The moderate correlation of Mg^{2+} with EC (0.457), SO_4^{2-} (0.384), NO_3^{-} (0.388) indicated that magnesium contributed to groundwater from dolomitic dissolution and weathering of ferromagnesian mineral in crystalline and sedimentary terrain. The positive correlation between F^{-} with EC (0.467) and SO_4^{2-} (0.371) and negative correlation with Ca^{2+} (-0.241), HCO_3^{-} (-0.269) indicated that fluoride enrichment occurred under alkaline, water-rock interaction conditions, with a mix of evaporation, mineral dissolution and ion exchange controlling groundwater chemistry (Roy et al. 2020). The weak correlation between NO_3^{-} with EC (0.395), SO_4^{2-} (0.358), Mg^{2+} (0.388) signifies limited anthropogenic contamination in the deep aquifer.

Linear Discriminant Analysis

Linear Discriminant Analysis (LDA) was applied to classify shallow and deep aquifer systems by evaluation of the hydrochemical distinction between using major ions and physicochemical parameters (Mameri et al. 2023). For identification of most crucial variable that contributed difference between deep aquifer and shallow aquifer, the stepwise DA was adopted (Jiang et al., 2021). From Table-4, the significant value of 11 parameters out of 14 parameters (pH, EC, TDS, TH, Ca^{2+} , K+, Na^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-} and NO_3^{-}) are less than 0.05, which were identified for analysis of the model. The other 3 parameters (TA, Mg^{2+} and F^{-}) were eliminated from the model as they have not significant value (<0.05). The robustness of the model was tested using Box's M statistic, which yielded a significance value of 0.851. This confirms that covariance matrices of the groups are homogenous and LDA is statistically valid for the data set.

Table-4: Tests of Equality of Group Means

Parameters	Wilks' Lambda	F	df1	df2	Sig.
pH	**0.657**	22.936	1	44	0.000
EC	0.896	5.102	1	44	0.029
TDS	0.896	5.096	1	44	0.029
TA	0.986	0.608	1	44	0.440
TH	**0.640**	24.729	1	44	0.000
Ca^{2+}	**0.689**	19.893	1	44	0.000
Mg^{2+}	0.916	4.036	1	44	0.051
Na^{+}	**0.719**	17.183	1	44	0.000
K^{+}	**0.637**	25.086	1	44	0.000
Cl^{-}	**0.663**	22.383	1	44	0.000
HCO_3^{-}	0.901	4.858	1	44	0.033
SO_4^{2-}	0.880	6.026	1	44	0.018
F^{-}	0.972	1.266	1	44	0.267
NO_3^{-}	**0.729**	16.374	1	44	0.000

The discriminant analysis generated a single canonical discriminant function having Wilks' Lambda value of 0.215 with a chi-square value of 57.672 ($p < 0.001$) which indicated that discriminant function significantly differentiates between shallow and deep aquifers (Table-5 and Table-6). The low value of Wilks' Lambda suggests strong separation between the groups (Jiang et al., 2021). The eigenvalue of the discriminant function was 3.655, and the corresponding canonical correlation was 0.886, indicating a strong relationship between the discriminant scores and the grouping variable. High discriminatory power is indicated by the squared canonical correlation (R^2-0.785), which suggests that the discriminant function accounts for about 78.5% of the dataset's variation.

Table-5: Eigen values for the discriminant analysis

Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
1	3.655	100.0	100.0	0.886

Table-6: Wilks' Lamda and Chi-square test for the discriminant analysis

Test of Function(s)	Wilks' Lambda	Chi-square	df	Sig.
1	0.215	57.672	13	0.000

The coefficients of the discriminant functions are used to ascertain the discriminating power of the variables (Table-7). According to the results of the canonical discriminant function coefficients, the most crucial hydrochemical parameter for differentiating between shallow and deep aquifer variation is HCO_3^- (1.357), which is followed by K^+ (0.344), pH (0.316) and SO_4^{2-} (0.202). On the other hand, the parameters TH (-0.824), Ca^{2+} (-0.624) and Na^+ (-0.463) show significant negative loadings. The linear discriminant analysis biplot is presented at Fig. 9. The discriminant accuracy of the model was tested by cross-validation which produces a classification accuracy of 87.0% (Table-8).

Table-7: Standardized canonical discriminant function coefficients

Standardized Canonical Discriminant Function Coefficients													
Variable	pH	EC	TA	TH	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	HCO_3^-	SO_4^{2-}	F^-	NO_3
Function 1	0.32	0.11	0.34	-0.82	-0.62	-0.40	-0.46	0.34	-0.15	1.36	0.20	0.46	0.01

Table-8: Classification results of discriminant analysis

AQUIFER			Predicted GroupTotal Membership		
			Deep	Shallow	
Original[a]	Count	Deep	23	0	23
		Shallow	0	23	23
	%	Deep	100.0	0.0	100.0
		Deep	0.0	100.0	100.0
Cross-validated[b]	Count	Deep	19	4	23
		Shallow	2	21	23
	%	Deep	82.6	17.4	100.0
		Shallow	8.7	91.3	100.0

a. 100.0% of original grouped cases correctly classified. b. Cross validation is done only for those cases in the analysis. In cross validation, each case is classified by the functions derived from all cases other than that case. c. 87.0% of cross-validated grouped cases correctly classified

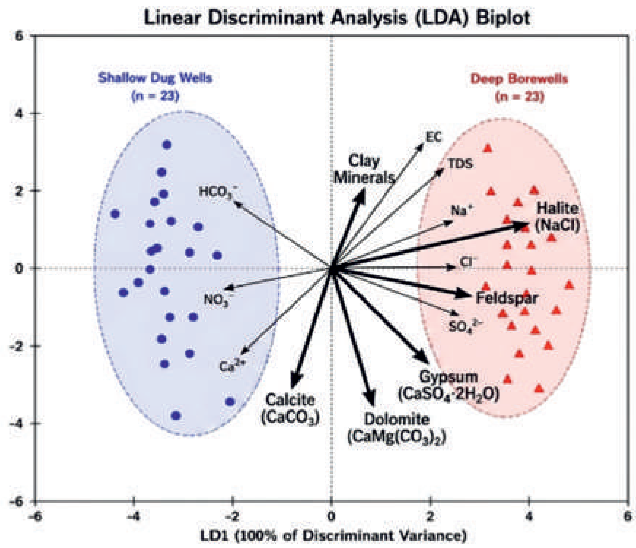

Fig. 9: Linear Discriminant Analysis (LDA) Biplot

According to this, deep aquifers with bicarbonate alkalinity and an alkaline pH are represented by the positive side of the discriminant function, whereas shallow aquifers with hardness and divalent cations are represented by the negative side (Mammeri et al., 2023). These geochemical characteristics show that carbonate dissolution affects the chemistry of shallow groundwater whereas silicate weathering and ion exchange control the evolution of deep groundwater (Gao et al., 2023). High concentrations of nitrate and chloride in shallow aquifers indicate an open system influenced by human activity, while increased bicarbonate in deep aquifers is indicative of closed system geochemical history (Mammeri et al., 2023). These results are consistent with currently proposed hydrogeochemical models for similar industrial and coal mining areas (Singh et al., 2021).

CONCLUSION

The comprehensive hydrogeochemical evaluation of groundwater in the Kaniha Block, Talcher Coalfield, using pre-monsoon data, reveals a clear understanding of the geochemical processes governing groundwater quality. The Piper diagram shows that both shallow (dug wells) and deep (tube wells) aquifers are predominantly of the Ca-Mg-HCO_3 type, indicating carbonate weathering as the dominant process. However, dug wells also exhibit slight shifts toward mixed and Ca-Mg-SO_4 facies, suggesting anthropogenic influences such as agricultural runoff and evaporation.

The Gibbs diagram indicates that the major controlling mechanisms of groundwater chemistry is the rock-water interaction and to some extent evaporation dominance, particularly in shallow aquifers, whereas that of the deep aquifers falling in the "rock dominance" field indicate minimal surface interaction and greater residence time. Ionic ratios, such as Ca^{2+}/Mg^{2+} and Na^+ /Cl^- and bivariate plots (e.g., SO_4^{2-} vs. NO_3^- , Ca^{2+} vs. SO_4^{2-}), suggest processes such as gypsum dissolution, ion exchange and leaching from coal-bearing strata. Chloro-alkaline indices (CAI-1 and CAI-2) further confirm ongoing ion exchange and reverse ion exchange processes, especially in areas with higher Na^+ concentrations. Correlation coefficient analysis reveals strong relationships between TDS and EC, and notable pairings like SO_4^{2-} with Ca^{2+} and NO_3^-, hinting at both geogenic inputs and anthropogenic sources (e.g., fertilizers, industrial effluents). Geochemical reactions such as silicate weathering, carbonate dissolution, and sulphate leaching are key contributors to groundwater chemistry. In deep aquifers, ion exchange is more pronounced due to longer water-rock interaction times, while shallow aquifers are more susceptible to anthropogenic contamination.

This integrated geochemical assessment indicates the importance of understanding hydrochemical facies, reaction pathways, and anthropogenic pressures to ensure sustainable groundwater management in industrially sensitive zones like the Talcher Coalfield.

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SGAT Bulletin
Vol. 27, No. 1, June 2026, pp. 61-63

SHORT COMMUNICATION: EARTH SCIENCE ON CROSS ROAD

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In October, 2024, the Earth Science Department of IIT, Bombay, held a brain-storming session on "Earth Science Education on Cross Road in India" attended by many learned Earth Scientists. The sole purpose was to refine the Earth Science Education and Techniques for the benefit of both students and employers. Obviously, the Earth Science Education is on cross road, not only in India but also in the world in general, as discussed below. Observation of degradation and deterioration of environment and ecosystem, consequent to the over use or abuse of the very earth resources the Earth Scientists search and supply to the Society, has arouse doubt on the integrity of their own profession. Some of the critical issues that put Earth Scientists on cross road are discussed below.

In early 1980s, a doyen of Indian Geology, while addressing the Geology students of the Institute, said "Earth is bejewelled - *Ratnagarva Vasundhra*". The duty of the Geologist is to bring out these *Ratnas* (Gold, Diamond, Coal & Oil etc.) for progress and sustenance of the family of Man. Subsequently, when a felicitation meeting at School of Mines, Dhanbad, awarded Life Time Achievement award to a stalwart in Mining Engineering, the awardee replied "I have made the largest number of pockmarks and holes on earth's surface and degraded the land, yet the geologists are honouring me!" It was like the story of the *professional dacoit Ratnakar becoming the Valmiki, the saint and author of Ramayana epic, in the later part of his life.* But the remark of the mining expert put the Geologists on a cross road.

Thou shall not tear apart the land, nor contaminate the water or pollute the air, but supply mineral matters to the Society. But the Bureau did not specify "How", putting their Geologists on cross road.

The famous Ecologist Aldo Leopold proposed a formula for Standard of Living as: L=A.E.T/P., where L is Standard of Living, A is Availability of Resources, E is Energy, T is Technology and P is for Population. Our observations show people living in mineral rich belt are invariably poor but those consuming maximum amounts of resources, the quality of life is not desirable. It appears, the value of Man in Society increases with the distance he maintains from the primary resources, for example, the Miner at the mine face and the Mineral Trader in the city market: clearly a societal aberration or Geologist in dilemma of a cross road.

A curious observation in the imagery of India showing Night Lights, is a conspicuous dark circular region at the centre where most coal fields lie and supply the very basic material to produce electricity to light India (Fig. 1).

The Technophyllitic Index of a mineral/material say Lead or Copper is decided by the amounts of its production or use in the Society. While on use, a minute fraction of the material leaks from the utility cycle into the air, water and soil of the region. This is known as Pollution Index of the concerned metal. The more we mine or use, the more is the leakage to the environment making pollution a fait accompli for a mineral hungry society. Geologist, the discoverer and supplier of minerals, cannot absolve from the responsibility and say "It is the musket that kills, not the Musketeer". Self-realisation puts Geologists on cross road.

Invariably, the parents and progeny (offspring) are identical in nature in every respect and irrespective of humans, animals or plants. If life has arisen from the rock, the siliceous earth ought to have given rise to a siliceous life indeed. But the biosphere is exclusively

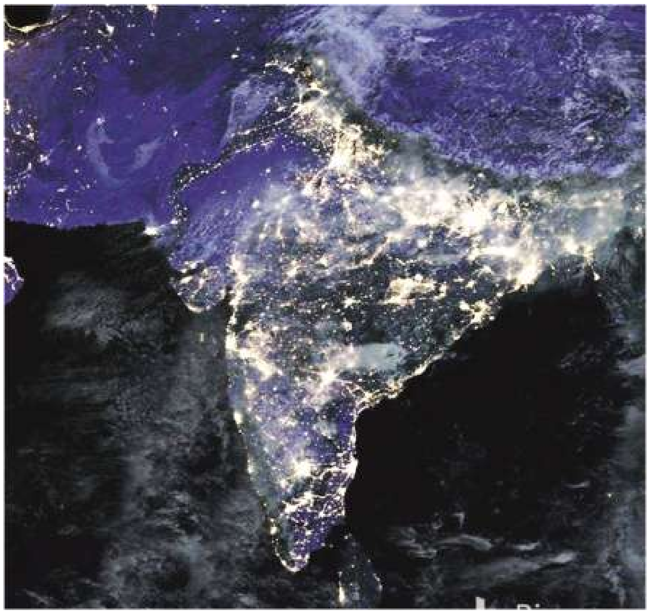

Fig. 1: Imagery of India in the night

carbonaceous. However, the Clay a silicate mineral shows primeval characters of life such as eating-excreting (Cation Exchange), high fidelity replication, symmetrical growth and species variation etc. and goes to show that life did start with Silicate. But immobility and “Complacency” (Stronger Covalency) of Silicon was a hindrance compared to the highly mobile Carbon which took over the grandeur of orchestration of life on the proto-earth. Silicon lost and Carbon gained. Geologists are aware of complete absence of native Silicon on the siliceous earth since last 4 billion years, but face today the free introduction of the element into the carbonaceous world to tap solar energy or for production of Si-wafer and Chips. Transplant of Chips in body has been attempted. The resurrection of the elemental Silicon into the regime of victorious Carbon in the organic world needs surveillance. As such, use of Silicon in body has been found to be carcinogenic and Si-Chips implanted are known to have been rejected. In this great experiment Silicon, the Geologists are in cross road too.

The first lesson a Geoscientist learns in Physical Geology is function of natural elements like Mountains and Rivers. Besides its universal role of collection and equitable distribution of precious rain water to every one along its path – plants, animals and Man, the river cleans our land and waste debris and supports a vibrant human culture. All world rivers have been doing so even before Man appeared in the scenario. In short, a river is an artery of the body. Geologists must ponder what it means by blocking of these arterial channels in the name of water resources harnessing. It is a clear discriminatory act to translocate common natural benefits to the mighty and deprive the Meeks and Weak - a clear case of robbing Peter to pay Paul. Should Geologists support such misadventure? The Engineering Geologists are on cross road.

Digging of earth for various developmental activities including mining is very common. The action leads to exposure of earth materials to oxygenated atmosphere. The crust of the earth has 8 % Ferrous Iron, which on digging and exposure tend to be oxidised to Ferric state. The Oxygen required comes from the atmosphere. Calculation shows that if only 300 Ft. of the earth meet this Ferrous-Ferric transformation (Lateritisation), it would strip out the entire Oxygen content of the atmosphere. Therefore, whenever we dig, it is for our grave.

In contrast, we have also observed that the great Pontiff Pope Paul, while on tour, whenever he comes out of the aircraft, his first action is to prostrate on the tarmac to kiss the earth. But the “Earth diggers” are known to rush to revere the “Earth kisser” at the earliest opportunity. We the digger of the earth are on cross road.

Epilogue: Window into future

Species transformation through Natural Selection and Species annihilation through Survival of the fittest to the extent of Extinction are accepted theory in biological evolution.

Environmental adversity is a driver of biological evolution, but its visibility is practically imperceptible during human history. However, cultural evolution with consequent behavioural changes apparently shows up during historical time span. Therefore, for us, humans, the ferocious lion has remained a lion and a toiling beetle has remained a beetle. But the Homo Sapiens, the Hunter & Gatherers from African plains have become the upright brainiac with computer, nukes and spaceship just in about 100,000 years. Similarly, in 16,000 years, persuasive domestication could transform the ferocious wild wolf to a passive pocket puppy, days are not far to put the “brainiacs” already in a “Progress trap” and with pressure of Artificial Intelligence, adopts into a new *Avtar* of machine man (Humanoid) or organic robot. Suggestion has been made in knowledgeable circle that the Homo Sapiens could put on an apparel of Cyborg – 90% Cyber and 10% Organic in not-so-distant future. For many Futurologists the future is already visible for a Sixth Extinction, this time not by Nature but by mankind themselves.

“In pursuit of supremacy and excellence, mankind is cruising in a Time Machine on a transformation Super Highway at speed approaching the velocity of light, at least mentally, when Red (Danger) appears Green (Safe) and now, have reached a cross road” and ready to face the disaster of the Sixth Extinction by turning Right (to Fight) or Left (Flight by leaving the battle).

Stephen Hawking once said “Let us pack up to migrate to another planet, we have made a trash of the Earth.” There is no planet B where humans can be settled since our metabolism is earth bound. We have only one home Earth A and Flight is not an existential solution.

To Fight the adverse situation, two alternatives are possible: (a) Take up the technological sword as the weapon of fighting. Our present dilemma of neck deep water is consequent to the technological reliance. Besides, the new panacea of AI, a by-product of Science and Technology, makes Man redundant, therefore not acceptable for self-integrity. (b) Adopt to the new environment and take up a new *Avtar*. Homo Sapiens become Cyborg, a new Species as stated earlier.

With all that said, Geologists may stand confused at the cross road of the anthropocentric transformation. It is wiser to leave the matter to Darwin’s biological evolution instead of meddling with the Natural selection and run after a technology hound for hunting of hare.

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SGAT Bulletin
Vol. 27, No. 1, June 2026, pp. 64-69

GEO-TOURISM IN ODISHA: PRESERVING 4.24 BILLION YEARS OF EARTH'S HISTORY

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ABSTRACT

Odisha possesses a unique geological panorama spanning from the Paleoarchean to the Holocene. Despite being a "geologist's paradise" for mineral exploration since the 19th century, the state's geoheritage remains under-utilized for public education and tourism. This paper summarizes the significance of key geosites-including the Nomira Pillow Lava, the Similipal Complex, and the Chilika Anorthosites-and proposes structured "Source-to-Sink" and "Craton-to-Coast" circuits. The study advocates for the formal protection of these sites through legislative action and the promotion of Scientif Tourism" to foster a scientific temper among the public.

Keywords: *Geoheritage, Geotourism, Singhbhum Craton, Nomira Pillow Lava, Eastern Ghats Mobile Belt, Similipal Complex, Mahanadi Graben, Hadean crust*

INTRODUCTION

Geotourism, a term coined by Thomas Hose in 1995, is knowledge-based tourism that focuses on the interpretation and conservation of abiotic natural attributes. Odisha's geological architecture (73% Precambrian) dictates its mineral wealth, river systems, and cultural history. Famous monuments like the Konark Sun Temple and Dhauli are carved from Khondalites, yet the "geology behind the scenery" remains invisible to the layperson.

Regional Geological Framework

The state is divided into two major cratonic domains: the Eastern Indian Craton and the Bastar Craton, bordered by the Eastern Ghats Mobile Belt (EGMB) and the Rengali Province, with the intermittent Mahanadi Graben, represented by the following major formations in the geological time scale.

- **Archean (3.6-3.1 Ga):** The Archean Eon (3.6-3.1 Ga) in Odisha is represented by the Older Metamorphic Group (OMG) and associated Tonalite-Trondhjemite-Granodiorite (TTG) gneisses exposed near Champua and other parts of the Singhbhum-Odisha Craton. These constitute the oldest recognizable supracrustal and plutonic rocks in the region. Recent detrital zircon studies have yielded grains as old as 4.24 Ga, offering a rare window into Hadean crustal relics within the Archean basement. The Archean terrain also hosts several important geosites of geological and heritage value, including: Nomira Pillow Lavas-classic submarine basaltic flows underlying the Banded Iron Formation; Gupteshwar Caves-developed in stromatolitic and dolomitic limestone occur in Jagdalpur Group of rocks in Gupteswar-Parasguda area of Malkangiri district and Sitabinji, a well-known tourist attraction in Kendujhar district, Odisha for its fresco paintings on a Rock Shelter called Ravan Chhaya. It is situated at a distance of 32 km from Kendujhar town.
- **The Proterozoic Eon** (2.5 Ga-541 Ma) is the longest in Earth's history and witnessed extensive geological, climatic, and atmospheric changes.

Beyond the EGMB, Odisha preserves several Proterozoic sedimentary basins and intrusions, including the Kolhan Group, Dhanjori and Chaibasa Formations, and the Iron Ore Group. The state also hosts emplaced anorthosite complexes of Chilika and Khariar Alkali Syenites, supporting significant Proterozoic magmatic activity. In Odisha, Proterozoic geology is dominated by the Eastern Ghats Mobile Belt, an expansive belt of high-grade metamorphic rocks in the central and southern parts of the state. Mahendragiri hills are located in the Gajapati district of Odisha, forming a part of Eastern Ghats Mobile Belt mountainous terrain.

- **Mesozoic(300-100Ma):** The Lower Gondwana sequence in Odisha's Mahanadi Graben comprises the Talchir, Karharbari, and Barakar Formations of Early Permian age. In both the Talcher and Ib River Valley coalfields, the Talchir Formation forms the basal glacial boulder bed with shales and sandstones, overlain by the Karharbari Formation carrying the lower coal seam. The overlying Barakar Formation hosts the main workable coal seams-multiple thick seams in Talcher and laterally continuous seams in Ib Valley-deposited in swampy fluvial settings, making it the primary coal-bearing horizon in the region.
- **Cenozoic:** Represented broadly by Baripada Miocene marine beds wherein the fossil assemblage includes shark teeth, fish bones, mollusc shells and microscopic marine organisms, Toba volcanic ash beds of Vamsadhara upstream valleys and the Mahanadi deltaic sediments. The evolution of Chilika lagoon and the shifting shorelines of the Last Glacial Cycle occurred in this period.

Significant Geo-sites of Odisha

The state of Odisha is blessed with grotesque features of mountains, plateaus, valleys, oceans, drainage systems, waterfalls, ponds, lakes, lagoon, swamps, creating varied habitats, hosting varied biodiversity, giving rise to six natural splendours (Patro,2026) like: The Similipal Biosphere Reserve in Mayurbhanj district in the north, the Eastern Ghats Mobile belt, the Mahendragiri in the south, the Satkosia gorge in the within Mahanadi Graben in central Odisha, the Bhitarkanika Wildlife Sanctuary and the Chilka Lagoon- the Ramsar Site, with unique marine fauna and flora, resident and migratory birds, the dolphins and Manikpatna ancient port. Weaving geological and archaeological features into these natural physiographic marvels, can be considered as elements of a few National Geoparks.

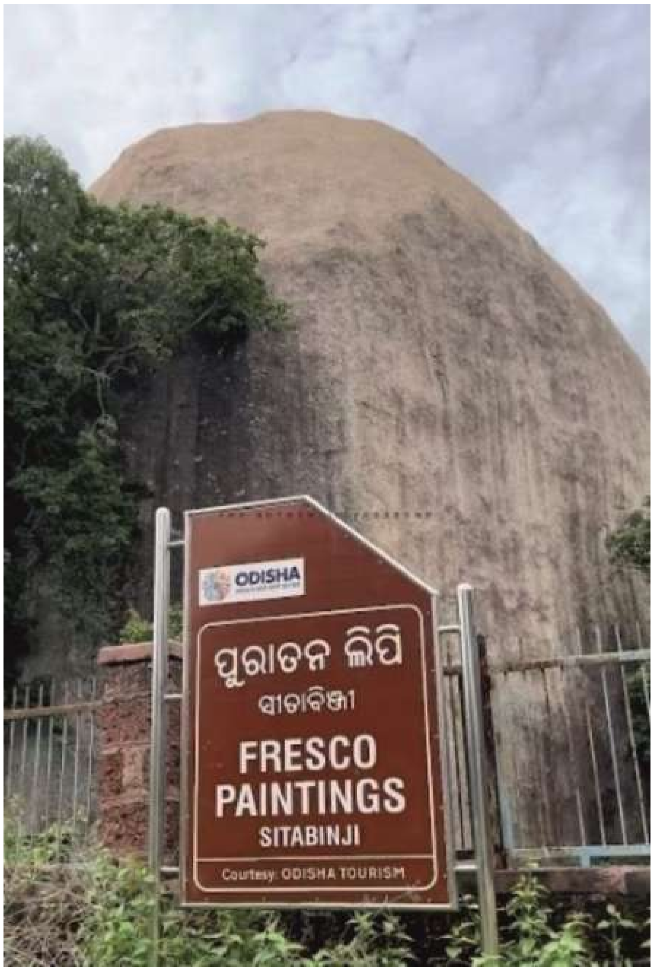
A brief description of the following geological, archaeological and habitats of biodiversity are included which may qualify to form a couple of clusters to be termed as national Geoparks.

The Nomira Pillow Lava (National Geological Monument), Kendujhar:

Located in Kendujhar district, these are rare evidence of Paleoarchean subaqueous volcanism. The ellipsoidal "pillows" feature radial cracks and chilled margins, providing a "way-up" criterion for stratigraphic orientation. Pillow lava is an indicator of marine environment within which the lava extrusion took place. These are associated with the base of the banded iron formation of Kendujhar-Sundergarh-Singhbhum Horse Shoe belt.

Sitabinji in Kendujhar district:

Sitabinji fresco painting on huge Tor shaped granite boulders, is at a distance of 32 km from Kendujhar. A granitic rock hill which catches visitors' attention is known as Rabanchhaya. A magnificent stone, that looks like a temple, adorns a courtyard with a height of about 45 m, which is the major attraction of the site. The gigantic tor granite boulders are embellished with the fresco paintings. Sita Mata is the presiding deity of the place. Ancient chronicles of Sita Maa having taken shelter sometime during their *banbas,* is believed to be the reason behind its sanctity. The attraction gets its name from a nearby stream, Sita.



Sitabinji: the granite tor natural architecture

Sana Ghagara, Kendujhar:

It is an ecotourist spot, located at only 5 km from Kendujhar town on the Kendujhar to Sambalpur National Highway (NH-49). The San Machakandana River meanders with rapids down the hills creating natural falls with sparkling spray of water. Thousands of tourists from different parts of Odisha and neighbouring states visit this often for picnics and excursions. The calm, serene, natural green forest environment with the beauty of water fall has been the best choice for nature loving tourist to visit Sana Ghagara waterfall. Sana Ghagara waterfall is good to visit anytime in the year due to its serene and fresh green ambience. The natural beauty of this forest canopy makes it a tourist hotspot. It is located at an average elevation of 600 m above M.S.L. and experiences a somewhat moderate summer and very cold winter. The area presents an undulating terrain with hills, pediments and "V" shaped narrow valleys. The hills and pediments are steep, meandering through which the Machhakandana Nala ultimately drains into the Aradei River, which is a tributary of the Baitarani River.

Sana Ghagara Waterfall, Kendujhar

The Similipal Complex:

The Similipal reserve is named after Simul tree, which grows abundantly in this forest. It is a spectacular circular volcano-sedimentary basin located in Mayurbhanj. Often mistaken for an astrobleme (impact structure), it is actually a Proterozoic basin featuring alternating bands of quartzites and spilitic lavas, with the differentiated Amjhori sill at its center. Asima Kar et al. (2022) propose an arc-subduction related setting for the Similipal complex which may be further confirmed through detailed major/trace elements and isotopic studies. Similipal National Park is one of India's well protected areas, located in the Mayurbhanj district of Odisha in the north-eastern part of the state. It also houses a tiger reserve under the Project Tiger, a biosphere reserve under the UNESCO, and a national park. Similipal is a rare ecological complex that encompasses dense *Sal* forests, numerous waterfalls, and a rich concentration of Asian elephants and Royal Bengal tigers. It also includes the only known population of pseudo-melanistic tigers.

Natural rock Arch:

The Geological Survey of India has discovered a magnificent Natural rock Arch, located in the Kanika range of Sundargarh forest division. This geological marvel is believed to have originated during the Jurassic period. GSI has also proposed Geo Heritage tag for Natural Arch. This oval-shaped arch has a length of 30 metres at the base and is 12 metres high. The alcove of the natural arch, has maximum height and width of 7 metres and 15 metres respectively. The Sundargarh natural arch, dates back to about 184 to 160 million years in the lower to middle Jurassic age. The lithology of the hill is coarse to gritty sized, red coloured, poorly sorted, immature, red ferruginous sandstone of Upper Kamthi Formation of Upper Gondwana Group (S. Mallick, 2023).

Chilika Lagoon & Anorthosite Massifs:

Chilika Lake is a 900 sq. km brackish water lagoon with estuarine characteristics along the east coast of India. Its area swells upto 11,165 sq. km during monsoon. It is spread over the Puri, Khordha and Ganjam districts of Odisha state and is at the mouth of the Daya River. It maintains its salinity because it is connected with Bay of Bengal near Arakhakud. It is the first wetland in India to be designated as a Ramsar site. It is rich in biodiversity. There are two small exposures of Anorthosite intrusive plutons dated at 983 Ma (Chatterji et al., 2008) near Balugaon and Ghantasila hills at Rambha. These calcium-rich rocks are rarely exposed on the Earth, and similar in composition to those Anorthosite found on the Moon, offering a high-value narrative for space-science tourism.

Konark Sun Temple:

The construction of the Sun Temple at Konark on the coastline of Odisha is attributed to king Narasingha Deva I of the Eastern Ganga Dynasty at about 1250 CE. Dedicated to the Sun God (Surya), much of the temple is now in ruins, as on date. Since the Deulo has dilapidated from the vagaries of nature, the remainder Jagamohan of the temple complex, has the semblance of a 30 m high chariot with exquisite wheels and horses, all carved from khondalite stone. The structures and elements that have survived are famous for their intricate artwork, iconography, and themes, including erotic *kama* and *mithuna* postures. It is a classic example of the Kalinga Architecture. The temple that exists today was partially restored by the conservation efforts of British India-era archaeological team. It was declared a UNESCO world heritage site in 1984. The Chandrabhaga Lake, South East of Konark, remains a major pilgrimage site for Hindus, who gather here every year for the Chandrabhaga Mela in the month of February.

The Sand Volcanoes of Angul:

Exposed along the Nandira Jhor, these circular features are “fossilized” fingerprints of ancient seismicity. Formed by liquefaction during Paleozoic earthquakes, they offer rare insight into the tectonic instability of the Gondwana basins.

Gupteswar Caves & Speleothems:

In Koraput district, due to the action of percolating water in the Eastern Ghats Mobile Belt, the calcareous component of calc-granulite has formed extensive cave systems. The hills in its vicinity are rich in mineral like bauxite and limestone, and are homes of multiple native tribes, whose lifestyle has remained largely unchanged over the course of centuries. The Gupteswar Lingam is a massive stalagmite, illustrating the intersection of geological precipitation and cultural mythology. The cave Shrine of Gupteswar nestles on a hill, 80 km from Koraput town, amidst lush green deep forest. The cave is a multi-chambered wonder work of nature. Sabari a rapid stream through stubborn Eastern Ghat rocks, provides an aesthetic meander near the Gupteswar Caves. The heavily wooded valley all around is a bonanza for the adventure lovers.

Talchir Glaciation:

Widespread facies architecture within the Talchir sedimentary succession are attributed to glacial, glaciofluvial, glaciolacustrine and glaciomarine depositional environments. Late Palaeozoic glaciomarine Talchir Formation of the Gondwana Supergroup, exposed in the Nandira Jhor river section of the Talcher Basin, records three distinct sedimentary cycles, viz., (a) Tens of metre thick sediments, characterized by conglomerate sandstone-shale, led by glacier advancements-retreats, are commonly interpreted as deglaciation cycles, (b) Sediments within cm-m scale interlaminated sandstone-siltstone-mudstone, produced by fluctuating storm surges and (c) Sediments represented by mm-cm scale sand and mud laminae, formed by day-to-day tidal fluctuations. Four major deglaciation cycles have been identified from the Nandir Jhor river section of Talchir Formation (Bhattacharya, 2013).

Baripada Marine Bed:

The Baripada beds, representing significant marine Tertiary exposures on the east coast, are distributed in Mayurbhanj and Balasore districts. Well-developed in the river cuttings of the Budhabalanga at Mahulia and Mukurmatia, these fossiliferous limestone beds contain remains of sharks, rays, crocodiles, and crabs. They provide evidence of marine transgression and regression during the Mio-Pliocene, proving that the present-day district headquarters-Baripada and Balasore were once, ten to fifteen million years ago, submerged under the sea.

Conclusion & Recommendations

Odisha's geoheritage is gradually becoming vulnerable to threat from rapid urbanization, infrastructure development and mining. To preserve these "outdoor classrooms" from any destruction the following steps are considered vital.

- **National Geopark Circuits**: Development of Circuits connecting these places of geoscientific, archaeological and anthropological significance along with establishment of museums and cultural hubs
- **Categorization:** Classifying sites into educational, scientific or recreational categories for targeted management
- **Community Enrichment:** Integrating these sites into the Puri-Konark-Chilika or Sitabinji-Nomira Pillow Lava-Sana Ghagara tourism circuits to diversify the local economy and promote knowledge-based travel

Proposed Geotourism Circuits

Circuit	Route	Theme
Circuit 1: Source-to-Sink	Khandagiri, Golbai, Rambha, Manikpatna, Konark	Transition from deep-crustal rocks (0.98 Ga) to vast still waters of lagoon and islands to Holocene spits with beach placers.
Circuit 2: Craton-to-Coast	Kendujhar, Sukinda, Talcher, Coast at Puri	Evolution from the ancient Singhbhum Granite to the Gondwana Coal basins to the golden beach and surf on the coastal tract.
Circuit-3:Caves-Waterfalls-Peak	Gupteswar-Koraput-Deomali	Majestic and cool panoramic mountain peaks, wide green valleys, guzzling rapids, caves in limestone with stalactite and stalagmite and a blend of *Shivling* mythology.

- **Conservation:** To inculcate sense of conservation of rare evidences of geoscience, saving archaeological marvels from destruction due to urbanization, mining and developments
- **Legal Promulgation:** State and Central authorities must enact laws for the protection of identified geosites with rare geological evidences for outdoor classrooms.

Acknowledgement:

We extend our heartfelt thanks to Prof Dr. B. Mishra, Editor: Geochronicle and Dr. B. M. Faruque for their insightful suggestions, critical review, and valuable inputs that significantly enhanced the overall quality of this manuscript.

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SGAT Bulletin
Vol. 27, No. 1, June 2026, pp. 70-78

OCCURRENCE OF MINERAL MATTER IN COAL FROM TALCHER, ODISHA, INDIA

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ABSTRACT

The mineral matter in coal refers to the inorganic non-combustible substances which are associated with coal through different stages of coal formation. It may constitute the crystalline mineral grains, dissolved ions in pore and surface water of coal or inorganic elements associated with macerals. The knowledge on the nature and abundance of mineral matter in coal has a paramount significance as they greatly influence the coal utilisation prospect and generation of environmentally hazardous chemical elements.

This paper discusses on the distribution of mineral matter in coal from the Talcher coal field, Odisha. Four different mineral associations were established through Scanning Electron Microscopic studies. The mineral groups are silicates (quartz, feldspar, kaolinite, zircon, garnet and Mn-silicate), oxides (magnetite, hematite, ilmenite and hollandite), carbonates (calcite, siderite, aragonite and ankerite) and other sulphates, phosphates and chlorides (gypsum, melanterite, fluoropatite and sylvite). An attempt has been made to derive the possible mode of formation of these minerals from their micro-morphology and texture.

Keywords: *Mineral matter, Talcher coal, Micromorphology*

INTRODUCTION

Mineral matter in coal refers to both crystalline and non-mineral inorganic elements which may have been formed through detrital, biogenic or authigenic processes during different stages of coal formation (Ward, 2016). They mostly occur as nodules, layers, fissure filling, rock fragments and small particles distributed throughout. Shreekant et al. (2004) have given a comprehensive classification based on the mode of occurrence of mineral matter into inherent, detrital, syngenetic and epigenetic minerals. A wide range of analytical techniques are adopted to analyse and decipher the presence and relative abundance of mineral matter in coal. Since the size of the mineral matter grains are often very fine, optical microscopic study does not help at times, instead the SEM analysis equipped with EDAX can provide substantive information on the distribution of mineral matter.

The presence of mineral matter in coal has a direct bearing on the trace elements concentration and controls to a great extent the possible environmental impact on coal utilisation. So, the objective of the present study was to decipher the presence of mineral matter in Talcher coal, their relative abundance and derive possible environmental impacts that might be caused during their utilisation.

Materials and Methods

Representative coal samples were collected from the different benches of mine faces from Bhubaneswari and Lingaraj colliery and pulverised to below 200 mesh size following conventional comminution technique.

The powdered sample was heated in a muffle furnace at 950°C for about 2 hours. The coal ash was then subjected to heavy media separation using bromoform as the media (sp. Gravity: 2.86). The sink fraction was properly cleaned and grain slides were prepared for microscopic and SEM-EDS study. The slides were coated with ultrathin gold to make it conducting before the slides were studied under Scanning Electron Microscope (Zeiss, Gemini 300) operating at 15 kV accelerating voltage. Different phases were identified on the basis of their morphology and spectral analysis.

Geology of the area

The study area belongs to Gondwana Group of Permian age in Talcher sub basin which forms a part of Son-Mahanadi Basin. Raja Rao (1982) and Maejima et al. (1999) earlier classified the area into Talchir Formation in south and Damuda Group in the north. Later, Damuda group was classified into Karharbari, Barakar, Barren measures and Kamthi Formations (Manjrekar et al., 2006; Goswami & Singh, 2013). The Gondwana group is differentiated from Precambrian basement by an unconformity. Structurally, the sedimentary beds of Gondwana are low angle north dipping homoclinal in structure truncated by E-W, NE-SW and WNW-ESW trending intra-basinal faults (Manjrekar et al., 2006; Raja Rao, 1982).

Coal seams belonging to the Karharbari (seam-I) and Barakar (seam-II-XIII) are exposed in the Talcher sub-basin, Angul district, as conformable beds alternating with carbonaceous shale and sandstone representing a classic example of cyclic sedimentation. Active mining operations are underway with highly mechanised mining equipment and produces 100-125 MT of coal per year. The produced coal mostly belongs to the sub-bituminous variety and are used in thermal power plants or exported.

Results and Discussion

Mineral matter in coal is contributed from three main sources: (a) the influx of detritus and volcanic fragments (Bailey and Kosters, 1983; Triplehorn, 1990; Ruppert et al., 1991), (b) the precipitation of dissolved minerals (Shotyk, 1988) and (c) the accumulation of skeletal or biological debris (Andrejko et al., 1983a and b). These are highly concentrated in lower-rank coals like brown coal, lignite, and sub-bituminous varieties (Given and Spackman, 1978; Miller and Given, 1978, 1986; Ward, 1991, 1992, 2002) and may constitute up to two-third of the ash, while the one third constitutes the organic sulphur binding the naturally occurring calcium and sodium or magnesium (Kiss, 1982).

The coal ash study of the low-rank sub-bituminous coal from Talcher revealed different types of minerals such as silicates, oxides, carbonates, sulphates, phosphates and chlorides. The detailed characteristics of these minerals are discussed below with a view to establishing their modes of formation.

Silicates:

Six different silicate mineral species were observed in the studied coal and are presented in Fig. 1 (a-f).

Quartz

Quartz is the most common occurring mineral phase. It's mode of occurrence can be grouped into (a) detrital grains denoted by the presence of angular or rounded grains, 2) reprecipitation of aqueous silica generated by the alteration of silicate minerals and 3) remnants of plant derived silica, such as phytoclasts and diatoms (Renton, 1982; Ward, 1984, 2002). Although, most of the quartz contributing to the Talcher coal are detrital in origin derived from the granitic basement (Fig. 1a).

Feldspar

Feldspar is also most commonly occurring mineral phase although in small concentrations (Renton,1982). Plagioclase feldspar exhibits a higher natural abundance than orthoclase (Renton, 1982). However, in Talcher coal, microscopic analysis indicates presence of unaltered orthoclase (Fig. 1b) that suggests a detrital or pyroclastic origin (Kemezys and Taylor, 1964).

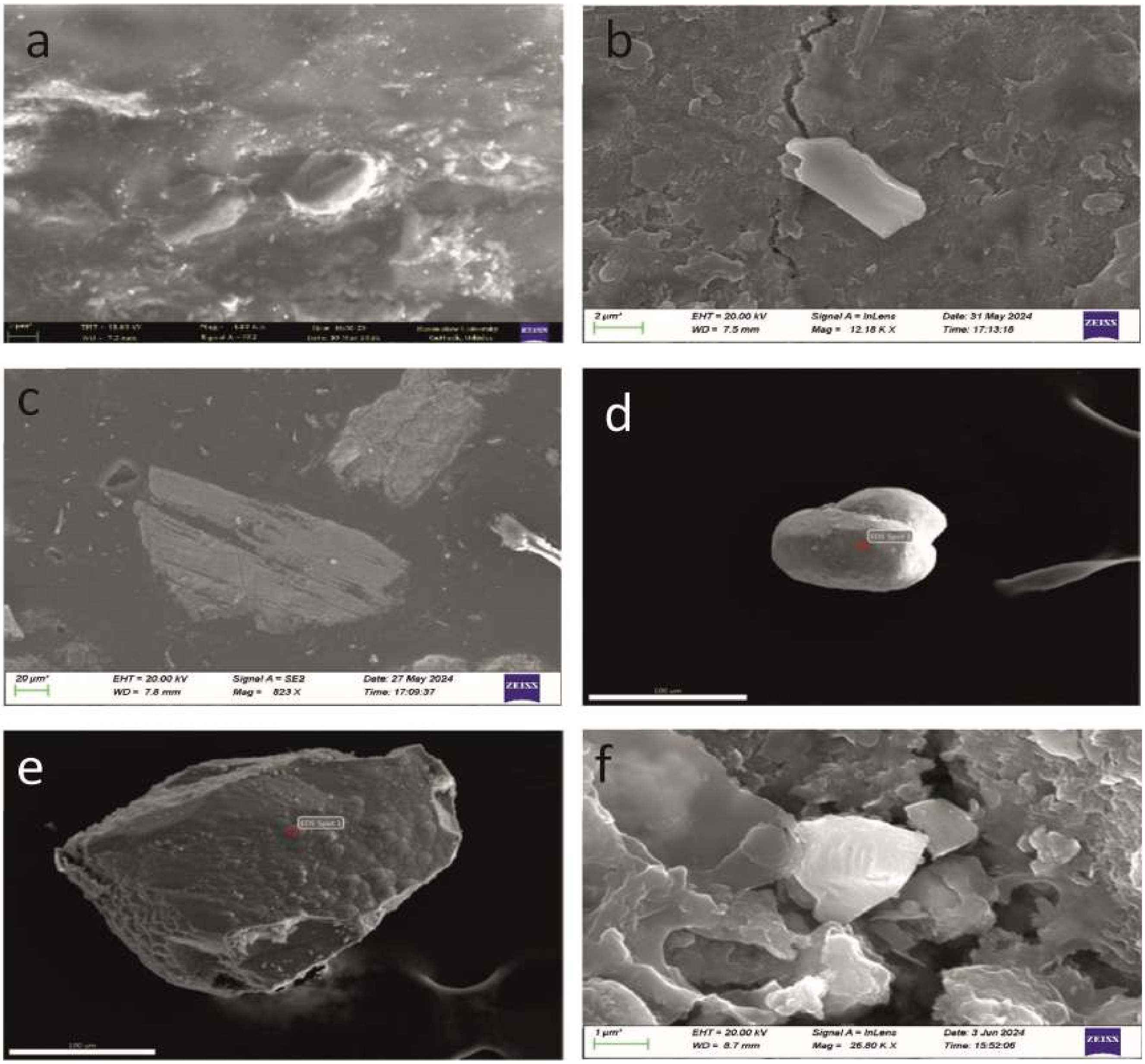

Fig. 1: Electron-micrographs of different silicate minerals from coal: a) Detrital quartz grains modified during diagenesis, b) A subhedral grain of orthoclase in a clay matrix c) Kaolinite showing well developed cleavage d) A detrital grain of zircon showing twinning e) An irregular piece of garnet showing micronodules on its surface f) Mn-silicate mineral (rhodonite?) present within clay

Clay Minerals

Clay minerals comprising of kaolinite, illite, chlorite, etc. form the most dominant component of inorganic constituent which includes 60-80% of mineral matter (Renton, 1982; Taylor et al., 1998; Ward, 1984). Analysis of Talcher coal indicates the presence of kaolinite (Fig. 1c) of authigenic or detrital nature (Renton, 1982; Ward, 2002).

Zircon

Zircon is one of the most ubiquitous accessory minerals in coal (Dia et al., 2021), It is mostly derived by erosional activity of provenance or is of pyroclastic origin (Dai et al., 2017; Rimmer, 1991; Zhou et al., 2000) or may be authigenic in origin (Dai et al., 2014). In Talcher coal, the zircons (Fig. 1d) are mostly derived from weathering and erosional activity depicted from its length : width ratio (Dia et al., 2021). In Talcher, zircons with 2:1 length-to-width ratios indicate derivation from granitic-gneissic terrains of the Singhbhum Craton and the Eastern Ghats Belt, modified by weathering, erosion and recycling. Their morphology reflects polycyclic provenance, confirming inputs from both igneous and metamorphic parentages.

Garnet

Garnet is also one of the ubiquitous accessory minerals in coal and has been reported in form of spessartine, uvarovite, pyrope, almandine, Ti-V-garnet and Cr-V-garnet (Dia et al., 2021). In Talcher, occurrence of pyrope (Fig. 1e) as accessory phase has been observed. Gondwana basins in Odisha received detritus not only from nearby granites and greenstone belts but also from cratonic roots and granulite terrains. Pyrope garnets have possibly been derived from high-grade metamorphic belts, viz., the Eastern Ghats Belt adjoining he Gondwana basin, where garnet bearing granulites and lamproites are well exposed.

Rhodonite

Mn silicate is a very rarely occurring mineral phase in coal. Among them mesolite, garnets, epidote, pyroxenes, amphiboles, chlorites and pennantite (Finkelman et al., 2019) are some known occurrences. In Talcher, occurrence of rhodonite as rare phase has been observed (Fig. 1f). The Eastern Ghats and Gangpur Group of rocks have abundant manganese silicate minerals like rhodonite, bustamite, spessartine, tephroite etc. So, the Mn-silicate associated with Talcher coal might have a detrital parentage to these rocks or might have precipitated from Mn-bearing solutions from them.

Oxides:

Magnetite and Hematite

Magnetite, hematite and goethite are common minerals of iron present in coal (Dia et al., 2021). They may be of detrital, diagenetic or epigenetic in nature. In Talcher, occurrence of hematite along with magnetite phase indicates a detrital origin of the Fe-oxide phases (Fig. 2a and b) indicating diagenetic process the coal has undergone.

Hollandite

Hollandite is a rare oxide phase present in coal and has been reported from Jharia coal basin and may be due to lamproites intrusion (Kaur and Mitchell, 2024). In Talcher, rare occurrence of hollandite group of minerals has been observed (Fig. 2c). The hollandite is rich in cerium which indicates that the Ba-Mn precipitation from solution might have scavenged the cerium from solution.

Ilmenite

Ilmenite is one the common Fe-Ti accessory detritus phases of coal (Dia et al., 2021). This usually occurs as a single phase or immiscible phase with magnetite. In Talcher, both the types of phases were observed (Fig. 2d). The ilmenite is highly altered and have given rise to leucoxenes.

Carbonate:

Carbonate group of minerals are syngenetic or epigenetic mineral phases of coal (Renton, 1982; Saxby 2000) and different groups can form through precipitation during each diagenetic phase (Renton, 1982).

The carbonate of authigenic origin, occur as precipitate in pore infillings, nodules or cleat and fracture fills of coal beds (Ward, 2016). In Talcher, the principal carbonate minerals, viz., calcite, siderite, aragonite and ankerite were observed (Fig. 3 a-d). Calcite and ankerite may be in nodular forms while aragonite shows acicular form. The siderite is in knee bent texture.

Other minerals

Apart from the above discussed minerals of silicates, oxides and carbonates few other groups of minerals also occur in minor quantities. These include sulphates, phosphates and halides. In the present study area, gypsum, occurring as an elongated crystal,

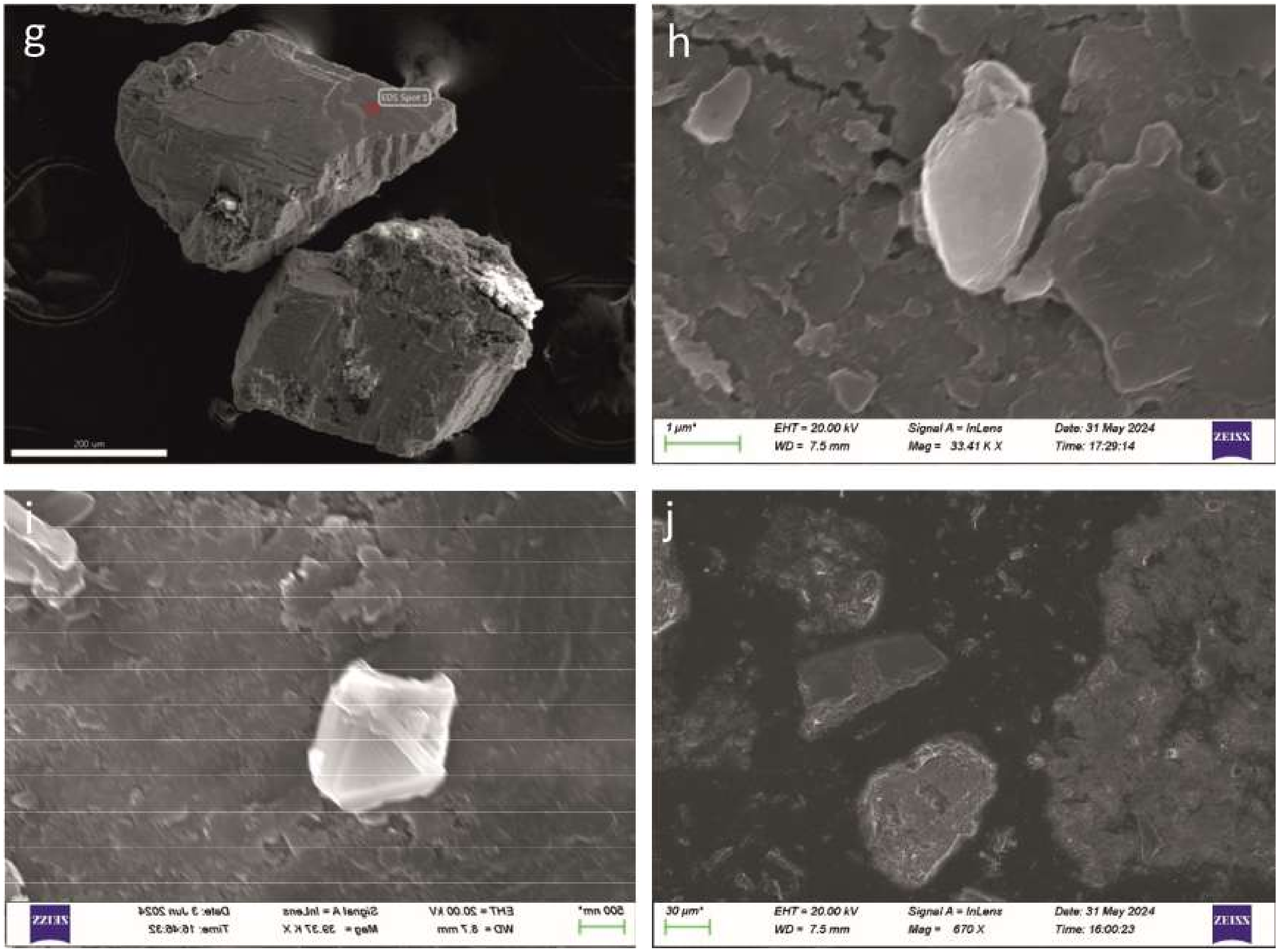

Fig. 2: Electron-micrographs of different oxide minerals from coal: g) Two euhedral grains of magnetite showing distinct cleavage, h) Diagenetically grown hematite in a clay matrix, i) A small grain of hollandite over clay, j) Subhedral grains of ilmenite often altered to leucoxene

probably formed hydrothermally (Fig. 4a). Melanterite, a rare secondary sulphate mineral, formed from oxidation of primary sulphide minerals like pyrite and marcasite (Fig.4b). Apatite usually occurs in three different forms, viz., chlorapatite, fluorapatite and hydroxyapatite, out of which the later was reported from the present study area to have a diagenetic parentage, occurring as a small globular crystal (Fig. 4c). A number of ions are usually associated with pore water and sub-surface water circulating particularly through the coal beds. Very rare but significant mineral phases are often precipitated from the solution amongst which sodium and potassium chlorides are common. Euhedral sylvite crystals were observed in voids associated with the Talcher coal, believed to have been formed from halogen rich solutions.

Conclusions

The SEM study of texture and micromorphology of mineral matter associated with Talcher coal revealed the presence of a multitude of mineral phases comprising of silicates, oxides, carbonates, sulphates, phosphates and halides.

While the silicates and oxides were mostly contributed from a detrital source, the carbonates, sulphates, halides and phosphates were either product of diagenesis or precipitated from hydrothermal solutions. The sum total of the mineral phase associated

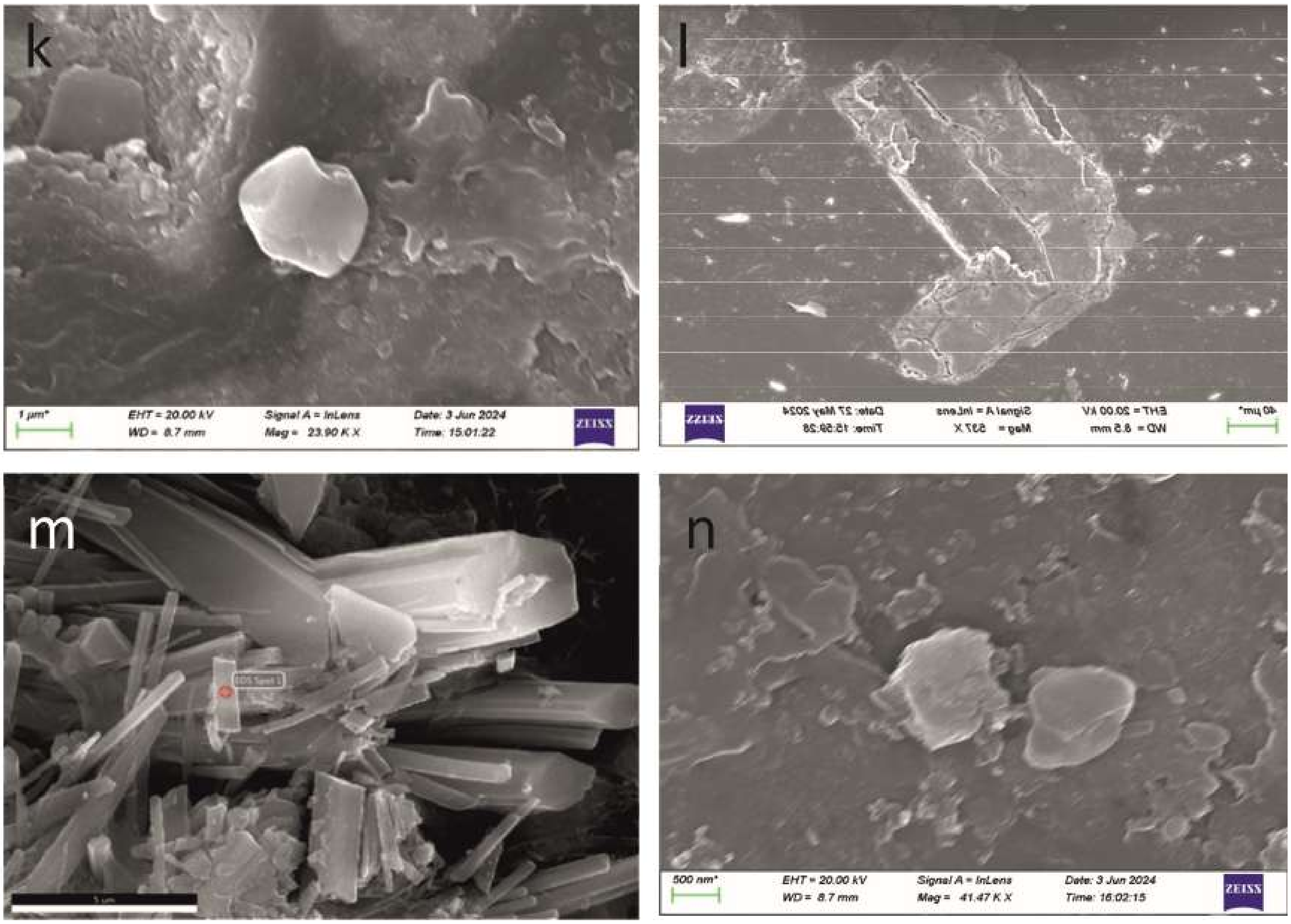

Fig. 3: Electron-micrographs of different carbonate minerals from coal: k) A small grain of calcite in clay, l) An altered siderite showing knee-bend twin, m) Acicular crystallites of aragonite present in a large void, n) Two small crystals of ankerite present over clay

with the Talcher coal indicated that none of the environmentally hazardous trace minerals are present in significant amount.

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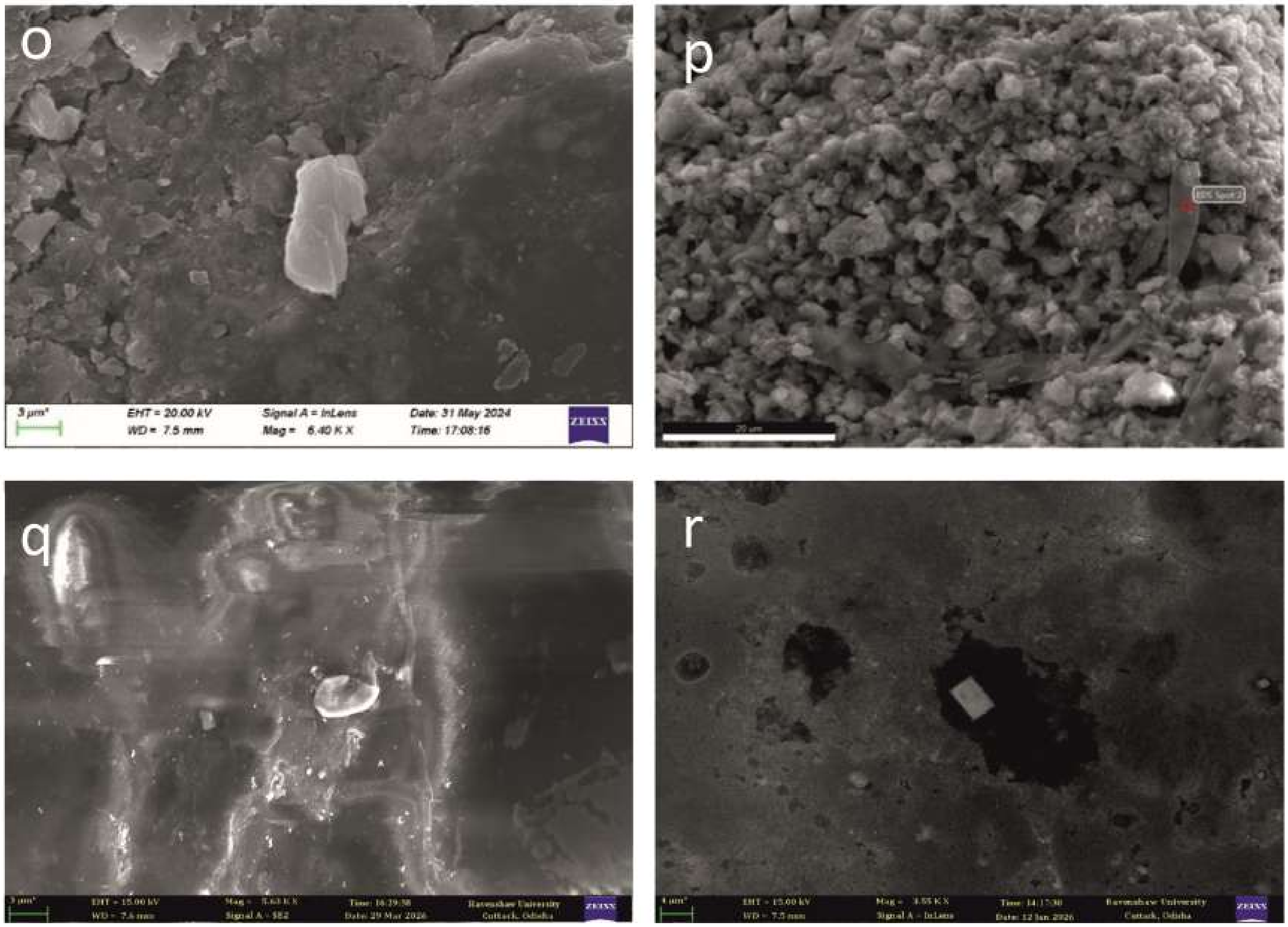

Fig. 4: Electron-micrographs of different associated minerals from coal: o) A tabular grain of gypsum in clay matrix, p) Acicular grains of melanterite associated with micro-pyrite, q) A diagenetic crystal of fluorapatite showing overgrowth, r) A euhedral crystal of sylvite grown in a void

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SGAT Bulletin
Vol. 27, No. 1, June 2026, pp. 79-80

EARTHY CHRONICLE: IN SEARCH OF PYRITE, WE LANDED IN THE PIRATE'S DEN

J. Swami Nath
Former Director General, GSI

In the early forties, about the closing stages of World War II, there were little or few opportunities for graduates in geology to take it as a profession for livelihood. The Geological Survey of India then had no periodic recruitment policy as in later years and a few openings were available with private companies like Tata, Birla and Bird. To seek a job in one of these private companies I was travelling in a crowded Calcutta tram to Dalhousie Square on a chilly December morning in 1944. At Elgin Road an elderly couple boarded the tram and I offered my seat to the lady. The elderly gentleman thanked me on behalf of the lady and noticed the book 'The Geology of India and Burma' by M. S. Krishnan in my hand and enquired if I was a student. I explained my mission that morning. Before getting down he informed me some help may be available for what I was seeking, if he cared to call at 5, Loudon Court, Moira Street at 8 a.m. the next day. Next day at appointed time I realized, I stood at the home of Sir Cyril S. Fox., Retired Director, GSI. He got me a job in a private mine and later I applied for and joined GSI.

Field work for me had its own charm along with its attendant hardships. It kept me physically and mentally fit and developed in me an innate strength to face unforeseen difficult situations. It inculcated in me the ability to get on with those around me amicably. In short, it shaped me for my life's ordeals ahead. Amidst the occupational hazards in the profession of a geologist, a few instances inter alia have left an indelible impression in my mind, which I now look back with wonder.

After joining GSI, I was posted in Jaipur office of GSI, in Rajasthan. In the mid-fifties I was a member of the geological party of the GSI in Jaisalmer district of Western Rajasthan, where the Jurassic Formation was almost flat (1 to 2 degrees). About 15 km northeast of Jaisalmer town, my colleague J. G. Krishnamurthy and I were on a traverse, during the course of which we came across a dry sandy river bed, about 2 km in length, 10 to 12 m in width, bounded by vertical walls, 3-4 m in depth, in the otherwise featureless plain. The depression triggered our geological curiosity to investigate. We selected a location on the southeastern rim, jumped on to the sandy river bed below and landed safely on all fours, got up and as we faced the northwestern wall, we froze at the unexpected sight we beheld. It took us some time to collect ourselves and there slowly emerged before us a huge tall figure seated on a charpoy (stringed cot) with his broad chest criss-crossed by belts of bullets, and to his right within reach, two gleaming rifles rested inclined on the charpoy. His face was hidden behind his long coiled luxuriant moustache, but his two sparkling eyes were visible. He supported a bright coloured turban on his stately head, adorned by one or two silver chains that hung like festoons. Some metres away were two camels leisurely chewing their cuds. Behind him was a cavern from which smoke was emanating. He made the first move by a stern nod of his head and beckoned us to sit beside him on the charpoy. He enquired what we were up to at that God forsaken place, at that unearthly hour – a question we were in no position to ask him. We immediately realized by his authoritative way of enquiry;

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that he must be a notorious dacoit. Our discomfiture grew for we were in khaki field uniform with compass and other instruments hanging about us. He could have easily mistaken us for police patrol. It was his goodness to have given us the chance to identify ourselves and state our mission, instead of pushing the two bullets into our frail vegetarian torso. We explained our purpose of going to that river bed. Having convinced himself that we were harmless creatures, he offered us bajra roti with a big chunk of butter brought by a servant from the cavern behind. We were in no mood to eat due to fright, but not to offend him, we made a semblance of enjoying his repast.

When taking leave of him, we politely offered him to drop him in our jeep, if he was going our way. He was equally polite in his refusal and pointed out to the two camels that would take him to Mijallar some tens of kilometers to the southeast, where he intended to abduct a rich man's son and demand a mighty ransom. We were in no position to preach but simply to thank him for his hospitality and our great good luck for deliverance from his clutches unscathed.

Excerpts from *Reminiscences*, 150th year GSI, 2001, Looking back by J. Swami Nath 2001.

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SGAT Bulletin
Vol. 27, No. 1, June 2026, pp. 81-82

Book Review:

EARTH, ETHICS AND THE ILLUSION OF PROGRESS

by Dr. K. C. Sahu, Formerly Professor, IIT, Bombay

A two-hundred-eighty-four-page love letter to our collective vainglory. Written in lucid eloquence that makes you feel thoroughly sophisticated while realizing we are actively flushing our future down the drain, this masterpiece is loaded with thought-provoking analogies. It beautifully paints the tantrums nature is throwing, as we aspire to build a robust infrastructure. In an era dominated by chest-thumping narratives of technological salvation, the recently published volume ***Earth, Ethics and the Illusion of Progress*** by Prof K. C. Sahu arrives as a profound and sobering philosophical intervention. The book serves as both a grand testament to our planet's geological majesty and a fierce indictment of the industrial machinery actively dismantling its basic ecosystems. At its core, the author challenges the modern definition of development, arguing that what humanity labels "progress" is often merely an advanced mechanism for ecological exploitation.

The narrative initially works on establishing the grandeur of planetary Earth, painting a vivid picture of a dynamic, self-regulating organism operating on a deep time cycle. However, this awe-inspiring balance is being fundamentally disrupted. The author contends that modern humanity is aggressively "fiddling with Earth," treating a highly sensitive, interconnected planetary apparatus as a passive warehouse of commodities.

This crisis places modern Earth Science at a historical crossroads. Rather than serving purely as an instrument for resource extraction and engineering efficiency to fuel unmitigated global warming, the author argues that geosciences must urgently pivot toward an ethical framework that prioritizes conservation and stewardship. A significant portion of the book focuses on the acute physical wounds inflicted by urbanization and heavy industrial production. The author effectively argues that current patterns of rapid urbanization are fundamentally unsustainable, draining localized resources while generating catastrophic waste streams. This is nowhere more apparent than in the meticulous examination of heavy metal toxicity-specifically chromium and arsenic pollution-which contaminate vital aquifers and impact agricultural soils.

The critique deepens as the book examines the persistence of the coal paradigm. Thermal power plants continue to anchor global energy grids at an astronomical ecological cost. The author moves beyond the standard critique of greenhouse gas emissions to highlight the localized horrors of fly ash disposal-massive, toxic particulate landscapes that contaminate air and leach heavy metals into surrounding water tables. Through case studies, the book skilfully illustrates how our immediate energy demands jeopardize long-term ecological survival.

Refreshingly, the book balances its apocalyptic warnings with a rigorous analysis of alternative technologies, free from utopian romanticism. The author dissects the economic realities of renewable infrastructure, evaluating the true lifecycle cost of solar energy including the ecological footprint of rare-earth mining and photovoltaic panel disposal. Similarly, the text explores cutting-edge chemical engineering, specifically the potential of splitting water for green hydrogen as a clean fuel matrix. Yet, the author remains deeply sceptical of massive, heavy-handed geoengineering schemes. A compelling chapter on interlinking rivers exposes the profound dangers of altering natural hydro-geomorphology, demonstrating how disrupting riverine dynamics can trigger unforeseen ecological collapses downstream. Instead of these vainglorious alterations, the author calls for a U-turn to

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recognising how soil, water, and clay have historically stood in the quiet, sustainable service of Man when managed with humility or else in author's words: "We can only raise our hands to Nature and realise that the Sixth Extinction has appeared on the horizon."

Ultimately, ***Earth, Ethics and the Illusion of Progress*** redefines the fundamental relationship between Homo Sapiens and Environment. It demands that we bury our anthropocentric arrogance and replace it with an earth-centric ethical system. The volume is an essential read for scientists, policymakers and environmentalists alike. It serves as a stark reminder that if humanity does not learn to align its economic frameworks with the immutable laws of the Earth, the planet will inevitably correct the imbalance at the cost of our civilization. The language is simple and crisp with a dash of humour; it makes an absolutely readable material. The illustrations perhaps ring the bell, sometimes, of the graphic refurbishing.

It's a truly moving read for anyone who enjoys discovering exactly how our brilliant aspirations are backfiring on a planetary scale.

Reviewed by
Dr. B. M. Faruque

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➢ SGAT News

State Level Environment-cum-Mineral Awareness Programme, 2025-26

Regional Environment-cum-Mineral Awareness Programmes (EMAPs) were successfully completed in 12 regions by 30th January 2026. The State-Level EMAP was held on 24th and 25th March 2026 at Bhubaneswar, with the following winning teams from the eleven regions participating.

- Daitari High School, Daitari
- Atomic Energy Central School, Matikhalo
- Delhi Public School, Damanjodi
- Dalmia Vidya Mandir, Rajgangpur
- Aditya Birla Public School, Oshapada
- Tata DAV Public School, Noamundi
- Rabindra Vidya Niketan, Keonjhar
- DAV Public School, Pokhariput, Bhubaneswar
- Kerala Public School, Anladuba, Rairangpur
- DAV Public School, MCL, Jagannath Area, Talcher
- DAV Public School, MCL, Bandhabahal

Due to some unavoidable reasons Bimlagarh High School, Tensa could not participate. The following educational and awareness-building activities were organised for the participating students.

- Visits to Kala Bhoomi, Bhubaneswar Meteorological Centre, Regional Science Centre, Prehistoric Life Park, and Regional Museum of Natural History
- Written Test
- Interactive Meet
- Identification of Plant and Mineral Specimens, and Photographs
- Elocution
- Oral Quiz

The field visits, evaluations and tests were coordinated by Anup Kumar Raut, Khitish Patnaik, Sujit Kumar Mohanty, Mayadhar Behera, Ramanath Praharaj, Jayant Kumar Nanda, Girija Prasad Mohapatra, Dr. Tilottama Basa, Jyotiranjan Patnaik, Tapas Rath among others, with overall supervision by Shri Trilochan Mohanta, Vice-President, SGAT.

The Valedictory and Prize distribution ceremony was held on 25th afternoon where Dr. Aurobindo Behera, IAS (Retd.), Former Secretary and Member of the Board of Revenue, Govt. of Odisha graced the occasion as Chief Guest where as both Dr. Jaya Krushna Panigrahi, Professor, Sri Jayadev College of Education and Technology & Working President, Orissa Environmental Society and Shri Sunit Kumar Patel, Executive Director (Mines & Metal Business), The World Group, Bhubaneswar, Odisha shared the dais as Guest of Honours. This time, Miss Navya Namasya Kar, Class IX, Unit VIII, DAV School joined the dais as Youth Icon. Shri Alok Bihari Panigrahi, President SGAT presided over the session.

Besides other members and guests, members of Late B. K. Mohanty's family-his son, daughter, and niece were present to witness the function.

The winners of different events were as follows.

- **Elocution:** Miss D. S. Aditi, DAV Public School, Pokhariput, Bhubaneswar (First), Master Ayushman Giri of Delhi Public School, Damanjodi (Second) and Miss Lipsarani Acharya of Rabindra Vidya Niketan, Keonjhar (Third)
- **Written Test:** Master Hitesh Patra, Atomic Energy Central School, Matikhalo (First), Master Jyoti Prakash Prusty of Aditya Birla Public School, Oshapada (Second) and Master Bishnu Prasad Patra of Atomic Energy Central School, Matikhalo (Third)
- **Identification (Rocks, minerals and plants):** DAV Public School, MCL, Jagannath Area, Talcher represented by Master Ashutosh Mohanty and Master Debesh Ranjan Moharana (First), Atomic Energy Central School,

Matikhalo represented by Master Bishnu Prasad Patra and Master Hitesh Patra (Second) and Delhi Public School, Damanjodi represented by Master Ayushman Giri and Miss Shreyasi Padhihari (Third)

- **Oral Quiz:** Delhi Public School, Damanjodi represented by Master Ayushman Giri and Miss Shreyasi Padhihari, Rabindra Vidya Niketan, Keonjhar represented by Miss Anushka Sahu and Miss Lipsarani Acharya and DAV Public School, Pokhariput, Bhubaneswar represented by Master Anwesh Mishra and Miss D. S. Aditi. All the three teams were adjudged joint winners of First Prize in this category.

The **Overall Best Team of the State Level EMAP 2026** was won by Master Ayushman Giri and Miss Shreyashi Padhihari, Delhi Public School, Damanjodi. They received the first **B. K. Mohanty Memorial Trophy**, instituted and given away by the family members of Late B. K. Mohanty. Atomic Energy Central School, Matikhalo represented by Master Bishnu Prasad Patra and Master Hitesh Patra and DAV Public School, MCL, Jagannath Area, Talcher represented by Master Ashutosh Mohanty and Master Debesh Ranjan Moharana emerged as the Overall Second and Third teams respectively.

The State-Level EMAP, 26 was sponsored mainly by M/s Gitarani Mohanty and co-sponsored by SNM Group and Rungta and Sons Pvt. Ltd.

45th Annual General Body Meeting of SGAT

The 45th Annual General Body Meeting (AGBM) of the Society of Geoscientists and Allied Technologists (SGAT) was held at 06:30 p.m. on 21st December 2025 in the Conference Hall of SGAT building, VIP Area, Bhubaneswar. This time the AGB Meeting was held on hybrid mode on Zoom platform and linking it with YouTube. The meeting was presided over by Shri G.S. Khuntia, President of the Society.

At the outset, the house observed a one-minute silence to pay homage to the departed members:

- Bijoy Kumar Jena (30.11.1950 -21.01.2025)
- Prabhakar Rout (11.06.1942 –-04.03.2025)
- Prof. Anil Kumar Paul (10.03.1944 – 20.09.2025)

Shri Sujit Kumar Mohanty, Vice-President welcomed all the members, all the distinguished awardees, guests and speaker of the K. S. Mahapatra Lecture present physically in the venue and those who joined online. He presented the agenda items of the programme and sought the co-operation of all members to make the event a success.

Proceedings of the 44th Annual General Body Meeting held on 22nd December, 2024, as circulated on the 28th February 2025 and incorporated in the Annual Report of 2024-25, were confirmed.

Shri Trilochan Mohanta, General Secretary, presented the Annual Report of the Society for 2024-25 and proposed the Action Plan for 2025-26, which were approved after due discussion.

The Audited Annual Accounts of the Society for the financial year ending on 31st March 2025 and the Budget Proposal for 2025-26, presented by Shri Anup Kumar Raut, Treasurer, were also approved by the General Body. Shri Bhabani Prasad Padhi, Chartered Accountant, RDA & Associates, was appointed as the Auditor for the Financial Year 2025-26 (Assessment Year 2026-27).

This was followed by the release of the December, 2025 (Volume 26, No. 2) issue of SGAT Bulletin by Shri Ghana Shyama Khuntia, President, SGAT.

In his Presidential Address, Shri Ghana Shyama Khuntia highlighted different activities of SGAT, particularly the EMAP and MDAP programmes and their bearing on the school and university students. He thanked all the Council members who kept him busy and also stood by his side during his tenure of two years as President of the society. He also suggested that the next Council should form various committees to prioritize its activities for further expansion of the society.

The K. S. Mahapatra Memorial Lecture

The prestigious K.S. Mahapatra Memorial Lecture was delivered online by Shri Ranjan Kumar Sinha, Former Controller General, Indian Bureau of Mines. He talked on the topic "Iron-Ore Scenario - Wake-up Call for Miners & Warning Bell for Steelmakers". At the outset Shri Sinha thanked the organizers for giving him an opportunity to deliver the K. S. Mahapatra Memorial Lecture.

Shri Sinha talked about the iron ore resources of the country and their distribution in different states. He said that Odisha is having the maximum resources so far as haematite is concerned. He also made a comparison of the reserve and resource figures of 1st April 2015 and 1st April 2020, where there was 7% increase only in the resource figures. He gave the present scenario of production in which Odisha contributes 55% of India's output. From 2019-20 to 2024-25 there was a constant growth of about 4% iron ore production, except during the COVID period in 2020-21. In state-wise production, Odisha has been far ahead of other states. The National Steel Policy 2017 envisages 300 MT of steel production. The present per capita consumption of steel is hardly 100 kg, which the policy envisages to increase to 160 kg. By 2030, demand for steel, through construction and infrastructure will be 60-65% of total demand. There should be steady mine auctions, rising out puts from Odisha blocks and Central PSUs, capacity expansions, growth in beneficiation and pelletisation along with logistic upgrades. He presented the status of auctioned iron ore blocks, policy and price impact, year-wise demand scenario from FY 2026 to FY 2035 indicating that there may be huge difference between production and requirement from FY 2030 to FY 2035. For the way forward, Shri Sinha suggested that the miners should accelerate beneficiation/ pelletisation and de-risk evacuations; the steelmakers should secure long-term linkages, blend strategies and invest in DR-grade feed; and the Policymakers should provide stable legal framework, faster statutory clearances for early operation of auction blocks etc.

SGAT Awards, 2025

The following distinguished professionals were conferred SGAT Awards for their outstanding contributions:

- B. K. Mohanty Memorial SGAT Award for Lifetime Achievement 2025: This time the award was conferred on two renowned Mining Industrialists of Odisha, Shri Kshirod Chandra Pradhan and Shri Rajib Lochan Mohanty jointly.
- SGAT Award of Excellence, 2025: Prof. Kalachand Sain, CSIR-NGRI, Hyderabad
- Sitaram Rungta Memorial Award, 2025: Prof. Sisir Kanti Mondal, Department of Geological Sciences, Jadavpur University, Kolkata
- H. H. Read Memorial Award, 2025: Dr M. Ram Mohan, Geochemistry Division, CSIR-NGRI, Hyderabad
- Best Paper Award, 2025: Prof. Jayanta Kumar Pati, National Centre of Experimental Mineralogy and Petrology, Allahabad University, Prayagraj

Election 2025-27

The results of the election of office bearers and members of the Executive Council for the term 2025-27 (see the second page of this bulletin) were announced by Shri Ghana Shyama Khuntia, President, SGAT.

Shri Alok Bihari Panigrahi, President Elect, SGAT, expressed his sincere gratitude for the trust and confidence reposed in him by the members. He stated that SGAT has long served as a platform for knowledge sharing, professional growth and ethical practices, with flagship programmes like EMAP and MDAP creating a national impact among school and college students. He appreciated the contributions of the outgoing Council and highlighted SGAT's role in bringing together professionals, academicians, researchers and students to advance technical capabilities and serve society.

Outlining his vision as President, he emphasized mentoring young professionals and students, strengthening industry-academia collaboration, promoting continuous professional development through seminars and workshops, and ensuring effective utilisation of SGAT infrastructure. He called upon all members to work together with integrity, professionalism and teamwork to further enhance the reputation and impact of SGAT. He thanked everyone for the honour and expressed confidence in a productive and inspiring journey ahead.

The 45th Annual General Body Meeting ended with vote of thanks from Shri Jadaba Nanda Das, Joint Secretary."

SGAT Fraternity Presentation Programme

The 6th Lecture of the Fraternity Presentation Programme (FPP) was held online on the 8th of January 2026 in hybrid mode (Zoom and YouTube). Shri Soubhagya Kumar Tripathy delivered a talk on "Red Mud (Bauxite Residue) Utilisation for Road Construction in Odisha and Jharkhand-A Global Perspective towards Policy Formulation". The talk was very well appreciated by all the participants.

The 7th Lecture of the Fraternity Presentation Programme (FPP) was held online on the 13th of January 2026 in hybrid mode (Zoom and YouTube). Prof. M. L. Dora, Department of Environmental Sciences, JNU delivered a talk on "Vanadium as a Critical Mineral: Global Metallogeny, Deposit Diversity, and India's Emerging Resource Potential and Exploration Significance". The talk was very well attended and was very well appreciated by all the participants.

The 8th Lecture of the Fraternity Presentation Programme (FPP) was held in hybrid (both physical as well as Zoom, Microsoft Team and YouTube) mode on the 28th of May 2026, the physical venue being the SGAT building, Bhubaneswar. Shri Piyush Srivastava, Former Chief, Natural Resource Division (NRD), Tata Steel delivered a talk on "Digital technologies to improve mine productivity, efficiency and safety". Shri Srivastava was joined online by his co-speaker, Shri N. Saha, NRD, Tata Steel, Jamshedpur. The talk was also very well attended and was very well appreciated by all the participants.

Comments/ Suggestions of the Society of Geoscientists and Allied Technologists (SGAT) on the following proposals were considered by the Sub-Committee on Mining and Environment.

1. MoM Notification No. M.VI-1/7/2025-Mines VI, dated.07.01.2026 on the Additional proposal in the Mines and Minerals (Development and Regulation) Amendment Bill, 2026 for Public Consultation.
2. MoM Notification No. M.VI-16/6/2026-Mines VI, dated.23.01.2026 on the Amendment of the Mineral (Auction) Rules, 2015 for faster operationalization of mines
3. MoM Notification No. M.VI-16/35/2026-Mines VI dated 19th March, 2026 on the Draft Mineral Exchange (Regulation) Rules, 2026

Suggestions of SGAT, as decided by the Sub-Committee, were sent to the Ministry of Mines, Govt. of India, New Delhi before the due dates.

62nd Meeting of the State Geological Programming Board (SGPB)

The proposals for the forthcoming 62nd Meeting of the State Geological Programming Board (SGPB), prepared by Shri G. P. Mohapatra, Dr B. M. Faruque and Shri G. C. Das, were sent to the Director of Mines and Geology, Odisha on 04 May 2026.

Invited special online lecture

An invited special online (Zoom) lecture was arranged on the 19th of June 2026 at 06:30 p.m. Dr. Manoranjan Mishra, Professor and Head, Department of Geography, Fakir Mohan University, Balasore delivered the lecture on "Future Shock to Future Ready: Navigating Climate Uncertainty in Odisha". The talk was simple but very informative and highlighted various problems that needs to be mitigated in advance. It was well appreciated by all who attended the lecture.

Release of SGAT Bulletin December 2025 (Volume 26, No. 2) by the office bearers of SGAT during the 45th AGB Meeting

Dr M Ram Mohan, Chief Scientist Geochemistry Division, CSIR-NGRI receiving the H. H. Read Memorial Award 2025 in presence of his spouse from Shri Girija Prasad Mohapatra, Former Former Addl. DG, GSI during the 45th AGB Meeting

Dr Sisir Kanti Mondal, Prof. of Geology, Jadavpur University receiving the Sitaram Rungta Memorial Award 2025 in presence of his spouse and son from Dr Veerendra Pratap Upadhyay, Former Advisor, MoEF & CC during the 45th AGB Meeting

Prof. Kalachand Sain, J. C. Bose National Fellow at CSIR-NGRI, Hyderabad receiving the SGAT Award of Excellence, 2025 in presence of his spouse from Shri Ghana Shyama Khuntia, President, SGAT during the 45th AGB Meeting

Shri Rajib Lochan Mohanty, Chairman, M/s M. G. Mohanty receiving the B. K. Mohanty Memorial SGAT Award for Lifetime Achievement 2025 in presence of his son from the office bearers of SGAT during the 45th AGB Meeting

Shri Khirod Chandra Pradhan, Chairman, M/s KCP Iron P Ltd. being presented the B. K. Mohanty Memorial SGAT Award for Lifetime Achievement 2025 at his residence by the office bearers of SGAT on 22.12.2025

Participants of SLEMAP 2026 in front of SGAT building on 24.3.2026

Participants of SLEMAP 2026 in front of Kala Bhoomi Odisha Crafts Museum, Bhubaneswar on 24.3.2026

Guests on dais (From left to right: J. N. Das, General Secretary, SGAT; J. K. Panigrahi, Working President, OES; Dr Aurobindo Behera, IAS (Retd.), Former Secretary and Member, Board of Revenue, Govt. of Odisha; A. B. Panigrahi, President, SGAT; S. K. Patel, Executive Director (Mines & Metal Business), The World Group; and Navya Namasya Kar, Youth Icon) on 25.3.2026

Ashutosh Mohanty and Debesh Ranjan Moharana of DAV Public School, MCL, Jagannath Area, Talcher receiving the Overall Third Team Trophy from Chief Guest, Dr Aurobindo Behera, IAS (Retd.) on 25.3.2026

Bishnu Prasad Patra and Hitesh Patra of Atomic Energy Central School, Matikhalo receiving the Overall Second Team Trophy from Chief Guest, Dr Aurobindo Behera, IAS (Retd.) on 25.3.2026

Ayushman Giri and Shreyasi Padhihari of Delhi Public School, Damanjodi receiving the B. K. Mohanty Memorial Trophy from the family members of Late B. K. Mohanty and the Guests on 25.3.2026

➢ **News About Members**

Honorary Members

Dr. Vijay Prasad Dimri, Former Director, CSIR-NGRI and a Honorary Memebr of SGAT who has delivered a talk in our Distinguished Lecture Series, has been bestowed with prestigious Christiaan Huygens Medal 2026 in the category of Data Sciences by the European Geosciences Union (EGU) Geosciences Instrumentation and Data Systems Division for his outstanding contributions to exploration geophysics, particularly establishing scaling properties of potential fields through fractal and spectral analysis. He has written books like Fractal Models in Exploration Geophysics - Applications to Hydrocarbon Reservoirs (2012), Fractal Solution for Understanding Complex Systems in Earth Sciences (2016), Reservoir Characterization, and Modeling and Quantitative Interpretation: Recent Workflows to Emerging Technologies (2023). His upcoming book on Tsunami Modelling is in press.

Dr. Shailesh Naik, Former Secretary to the Government of India in the Ministry of Earth Sciences (MoES) and an Honorary Member of SGAT, is currently the Director of the National Institute of Advanced Studies (NIAS) in Bengaluru.

Dr. Naik received the following awards.

- INSA Distinguished Lecture Fellowship (2025) under Earth & Environmental Sciences for outstanding contributions in building the National Tsunami Warning System and advancement of the Blue Economy of the Coastal Region of India besides, notable contributions like improving the understanding of Polar Science, geoscience, Ocean Science and Ocean-modelling, resources and technology.
- Brock Gold Medal-2026, for outstanding landmark in evolution of the photogrammetry, remote sensing and spatial information sciences by the International Society for Photogrammetry and Remote Sensing, Czech Republic (July 2026)

Dr. Naik has been nominated as the Distinguished Honorary Professor, Department of Earth Sciences, IIT Gandhinagar for the session 2026-28, as a Member of the prestigious International Science Council (ISC) National Committee for Scientific Committee on Antarctic Research (SCAR), INSA, for the period from 1 January 2026 to 31 December. 2028 and Honorary Member of Asian Association of Remote Sensing (AARS) for his outstanding contribution.

Dr. Shailesh Naik has authored an editorial article ‘Towards the Stewardship of the Third Pole: The Himalaya in the *Journal of Indian Society of Remote Sensing during* 2026 (https://doi.org/10.1007/s12524-025-02415-5).

He has co-authored an article “Observed anomalous chlorophyll-a bloom in the northern Arabian Sea during winter 2008” in *Environmental Research Communications volume-8 in* 2026, 015023 (https://doi.org/10.1088/2515-7620/ae39b) along with P. C. Mohammed Munzil, Prince Prakash, R. R. Rao, Hasibur Rahaman, Aneesh A Lotliker, T. M. Balakrishnan Nair and M. Ravichandran.

Members

Prof. K. C. Sahu published a book titled “Earth, Ethics and Illusion of Progress,”published by BFC, Lucknow.

Dr. Prabhakar Sangurmath, Former Director at the Hutti Gold Mines Company Limited has been nominated

1. to the Board of Directors, Karnataka State Minerals Corporation Ltd. (KSMCL), a Government of Karnataka Undertaking, Bengaluru
2. as an Assessor for the Accreditation Scheme for Prospecting/Exploration Agency (APA) and Mining Plan Preparation Agency (MPPA), NABET, Quality Council of India Government of India, New Delhi

3. as Executive Council Member, Karnataka Science & Technology Academy (KSTA), Government of Karnataka, Bengaluru and
4. as Member (and alternate Chairperson), PRC , National Institute of Rock Mechanics (NIRM), Ministry of Mines, Government of India, New Delhi.

Dr. Debadutta Mohanty, S*enior Principal Scientist, CSIR-Central Institute of Mining and Fuels Research (CIMFR), is the* Guest Editor for the upcoming collection 'Developing Sustainable Communities through Monitoring and Mitigation of Short-Lived Climate Pollutants from Different Sectors' of Discover Sustainability Journal, Springer Nature. https://link.springer.com/collections/iiehcjgeeg

Dr. Mohanty delivered a talk titled 'Can reducing methane emissions build a healthier, more sustainable future?' in the webinar hosted by UN Inter-Parliamentary Union (IPU) in collaboration with the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) and the United Nations Economic Commission for Europe and a lecture on 'Challenges and Efforts in Methane Mitigation in Indian Context' in Regional Policy Dialogue on Methane Emissions Reduction for Climate Action in Asia and the Pacific – 13th Asia-Pacific Forum on Sustainable Development held during 23-27 February 2026 at United Nations Conference Centre, Bangkok as invited Speaker.

Dr. Mohanty also delivered keynote address on 'Multiphysics Simulation in Understanding Unconventional Gas Reservoirs' on COMSOL Day on 27 February 2026 at Hyatt Centric, Kolkata organized by COMSOL Multiphysics Pvt. Ltd.

Shri Jayanta Kumar Nanda, former Dy. Director General, Geological Survey of India published two research papers as a co-author.

1. Divyajyoti D. Rana, Dewashish Upadhyay, Jayanta Kumar Nanda**,** Mousumi Bhattacharjee (2026) U-Pb zircon-monazite-apatite geochronology and zircon Hf isotope composition of syenite-clinopyroxenite suite from Nayagarh (Odisha) of the Eastern Ghats Province. Precambrian Research 437 (2026) 108065 (https://doi.org/10.1016/j.precamres.2026.108065).
2. Om Prakash Pandey, Klaus Mezger, Dewashish Upadhyay, Jayanta Kumar Nanda, Froukje M. van der Zwan (2026) Crustal growth and reworking across the Singhbhum Craton–Rengali Province boundary: Zircon U Pb geochronological constraints. Geochemistry 86 (2026) 126420 (https://doi.org/10.1016/j.chemer.2026.126420)

Dr. Sundara Narayan Patro, President, Orissa Environmental Society, was, conferred with Odisha Vanyaprani Mitra Award by the Ever Green Forum in recognition of his lifetime contribution to biodiversity and wildlife conservation on 1.3.2026, the World Wildlife Day. The award carried a cash prize of rupees one lakh.

Shri R. N. Padhi, former Dy. Director General, Geological Survey of India received Healthy Senior Supervisor Citizen Award from Central Government Health Scheme Beneficiary Welfare Association.

Dr. Manoranjan Mohanty, Former Dy. Director General, Geological Survey of India and Jt. Secretary, SGAT has been nominated as a Member of the Accreditation Committee of the National Accreditation Board for Education and Training (NABET), Quality Council of India for a two-year term starting from the 5th of May, 2026.

Shri Sisir Chandra Rath, former Director General, GSI has been felicitated by Institution of Geoscientists Odisha as an Eminent Geoscientists on 24 December 2025.

Shri Girija Prasad Mohapatra, former Additional Director General, Geological Survey of India has been felicitated by Institution of Geoscientists Odisha as an Eminent Geoscientists on 24 December 2025.

Shri Rabi Narayan Patra, former Additional Director General, Geological Survey of India has been felicitated by Institution of Geoscientists Odisha as an Eminent Geoscientists on 24 December 2025.

Dr. K Sarveswara Rao wrote an interesting article titled "Odisha's Gold reserve can spur entrepreneurial opportunity" in the 29th Anniversary issue of the news paper New Indian Express as a special Feature in the Bhubabeswar Expression under the New Sunday Express on the 3rd of May 2026.

Shri S. V. Satyanarayana, Former Director of GSI co-authored a book "All About Diamonds in a Nutshell" with Shri K. Srinivasa Rao. It was published by Natural History Society of India, and released in a ceremony at the GSI, Southern Region, Hyderabad.

Dr. S. K. Wadhawan, Former Director General, GSI and presently Adjunct Professor, Amrita Vishwa Vidyapeetham, Kerala, presented the scientific Keynote paper on "Rehabilitation and Restoration of Degraded Landscapes due to Landslides – Challenges and Implementation Strategies" at the International Conference of the Engineering Geology and Environment - EGCON, and published in ISEG Special Publication No. 15 on Keynote Papers. pp. 33-70. https://doi.org/10.64944/iseg-sp 15/07

He co-authored and published a scientific paper entitled, "Mundakkai-Chooralmala Landslide: Assessment of Initiation, Progression, and Impact' in a high Impact Factor International Journal, Scientific Reports | 15:26961 | https://doi.org/10.1038/s41598-025-07828-3

Dr. S. K. Wadhawan authored the article "Significant Role of Sacred Spaces for Conservation of Geodiversity - Interconnectedness and Sustainable Futures", SGAT Bulletin Vol. 26, No. 2, pp. 66-74. 0972-2173/2026-2 © SGAT, Bhubaneswar.

He also published a Chapter on "Desert Margins as Climate Change Hotspots: Insights from the Thar Desert's Environmental Evolution During the Late Quaternary" in Geological Magazine GEO-0021 Cambridge University Press.

Dr. S. K. Wadhawan also published an article on "Landslides – Multi-Hazards Dynamics and Disaster Risk Reduction Through Integrated Participatory Community Approaches" in the Jour. Geol. Soc. India 100 (8): 1214-1215 https://doi.org/10.17491/jgsi/2024/173971 [Wadhawan, Sudesh Kumar]

Shri Subhajyoti Das, Eminent Scientist and Former Director, CGWB was felicitated as a Veteran Hydrogeologist by Dr Sudhansu Shekhar, Secretary, Indian National Committee of International Association of Hydrogeologist (INC of IAH), acknowledging his lifelong dedication and outstanding contributions to the field of hydrogeology and groundwater management in India at his Bengaluru residence on 17 April 2026.

Dr. Danda Srinivas Rao (Retd. Chief Scientist of CSIR-IMMT, Bhubaneswar & former Professor & Dean of AcSIR) has attended as Guest of Honour & was felicitated by his own Alma Mater, Govt. Queen of the Missions High School, Berhampur on the 19th of January 2026 on the School's Annual Prize Distribution Day.

Dr. D. S. Rao was felicitated by Alumni Association of the Dept. of Geology, Utkal University on the 21st of Feb. 2026.

Dr. D. S. Rao was the Chief Guest at the National Science Day (29th Feb. 2026) & Geologists Day (4th April 2026) Celebrations at Khallikote Unitary University, Berhampur and delivered talks for motivating the students.

Dr. D. S. Rao was the mentor in the "National Seminar on Geosciences" held at Khallikote Unitary University during 28th & 29th of April 2026.

Dr. Shreerup Goswami, Professor, Department of Geology, Utkal University, Bhubaneswar, has been independently verified and ranked among the World's Top 5% Scientists in the 2025 SciRank Global Registry, based on rigorous bibliometric analysis.

➢ **New Members**

The following members were admitted as Life Members of SGAT.

926 **Dr. Kalachand Sain**
J C Bose National Fellow
CSIR-NGRI, Uppal Road
Hyderabad-500007

927 **Shri Himanshu Sekhar Biswal**
Dy. Vice President (Mines)
CAPRI GLOBAL LTD. Flat No. 403
Fourth Floor Surekha Orchid Apartment
Sishu Vihar, Patia, Bhubaneswar-751024

928 **Dr. Swatirupa Pani**
Woman Scientist
CSIR-Institute of Minerals
and Materials Technology
Bhubaneswar-751013

929 **Dr. Sharada Prasad Mohanty**
Professor (Retired)
IIT (ISM), Dhanbad
HIG-2/114, Satyasai Enclave
Khandagiri Bhubaneswar-751030 Odisha

930 **Dr. B. K. Sahu**
Deputy Director General (Retd.)
GSI, 1062, K-3A, Kalinga Nagar
P.O.: Ghatikia, Bhubaneswar-751029

931 **Shri Kanhu Charan Sahu**
Dy. Director General (Retd.), GSI
P. N. 966B, Prakruti Vihar
Baramunda, Bhubaneswar-751003

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OBITUARY

ARINDAM DASH
(01.12.1945-24.06.2026)

Shri Arindam Dash, former Joint Director, Directorate of Mines and Geology, Odisha, was born on the 1st of December 1945 in Athamallik as the 6th son of Krupasindhu Rayguru and Padmamali Devi. He passed matriculation from local school, Pre-University and Pre-Professional from Angul Science College, and obtained his M.Sc. (Geology) degree from Ravenshaw College in 1970. An outstanding student, he was highly regarded by his teachers for his academic brilliance and sincerity.

Shri Dash began his career with the Orissa Lift Irrigation Corporation before joining as a Geologist at the Sambalpur Zonal Office of the Directorate of Mining and Geology, Odisha in July 1972. During his long and distinguished service, he worked extensively across Odisha in mineral investigation, exploration, and resource evaluation. His notable contributions include the investigation of rare-metal-bearing pegmatite swarms in Angul, particularly for columbite; exploration of base-metal deposits in Padampur of Bargarh district; assessment of iron ore and bauxite deposits around Koira in Sundargarh district; and evaluation of coal resources in the Talcher coalfield. His exploration reports were widely appreciated for their technical rigor and high academic standards.

A brilliant scholar and an accomplished field geologist, Shri Dash was known for his sharp intellect, professional competence, and keen observational skills. He possessed a lively personality, an engaging sense of humour, and a deep appreciation for nature. A man of strong principles and uncompromising integrity, he upheld truth and fairness throughout his life. Though firm in his convictions, he was compassionate, affectionate, and ever willing to extend support to colleagues and friends in times of need.

Shri Dash remained deeply attached to his home district of Dhenkanal and took immense pride in the Directorate of Mines and Geology, Odisha, where he served with distinction. His contributions to the geological profession and his warm human qualities earned him the respect and affection of all who had the privilege of knowing him.

Shri Arindam Dash left for heavenly abode on the 24th of June 2026 leaving behind a rich legacy of professional excellence, integrity, and friendship. Members of the Society of Geoscientists and Allied Technologists mourn his demise and convey their heartfelt condolences to his wife Mrs. Banalata Dash, sons Anupam & Abinash and daughter Lopamudra and pray to the Almighty to grant eternal peace to his noble soul and strength to his bereaved family to bear this irreparable loss.

Members of SGAT

SUBMISSION OF ARTICLES FOR SGAT BULLETIN
(Instruction to Authors)

Submission of manuscript implies that the same is **original work**, unpublished and is not being considered for publication elsewhere. Each manuscript must be a soft copy of the entire material prepared in Microsoft Word. Manuscripts in Portable Document Format will not be accepted.

The figures, if any, may be submitted separately in high resolution in JPEG/ TIFF/ BMP format.

Both the text files and figures of the manuscript may be submitted by e mail.

Journal Format: A-4 size

Language: English

Manuscripts: Manuscripts should be computer typed soft copies in double spacing with wide margins in A-4 size (Font size: 12-point, Times New Roman). The title page should include the title of the paper, name(s) of author(s) and affiliation(s). The title should be as brief as possible. An informative **Abstract** of not more than 500 words is to be included in the beginning. Not more than 5 key words are to be listed at the end of the abstract. Text of research papers and review articles should not exceed 5,000 words. The short communication is for quick publication and should not exceed 1,500 words.

Headings: Different headings should be in the following format.

(a) **Title:** Centrally aligned, bold, capital

(b) **Author (s):** Centrally aligned, short name, bold, first letter of all words in capital letter followed by communication address (Not Bold, Italic). include Email ID of corresponding author only.

(c) **Abstract:** Secondary heading left aligned bold. Abstract text: Justified aligned, italic.

(d) **Key words:** Left aligned.

(e) **Primary heading:** Left aligned, bold, capital

(f) **Secondary heading:** Left aligned, first letter of each word capital

(g) **Tertiary heading:** Left aligned, first letter of first word capital

(h) **Acknowledgements:** Left aligned, bold, first letter capital

(i) **References:** Left aligned, bold, first letter capital

(j) **Figure Caption:** Left aligned, first letter of first word capital, below the figure.

(k) **Coloured figures:** Authors are requested to avoid including coloured photos or figures where colour is used without any scientific connotation.

(l) If colour is not used as index in a figure, it will be printed in black and white, by default.

(m) **Table Caption:** Centrally aligned, first letter of first word capital, at the top of the table

(n) **Tables:** Each table must be provided with a brief caption and must be numbered in the order in which they appear in the text. Table should be organised within A-4 size and should be neatly typed for direct reproduction. Use of 10 points Times New Roman/ Arial Font for table is recommended. Tables must be in **editable format** (word/excel). Tables as Raster images/JPEG format will not be accepted.

(o) **Illustrations:** All illustrations should be numbered consecutively and referred to in the text. They should conform to A-4 size and carry short captions. Text inside figure should be large enough to accommodate reduction up to 50%.

(p) **Photographs** should be of good quality with excellent contrast.

References:

(a) References in the text should be with the name of the author(s) followed by the year of publication in parenthesis, i.e., Patnaik (1996); Patnaik & Mishra (2002); Nayak et al. (2001)

(b) Reference list at the end of the manuscript should be in **alphabetical order**, in the following format:

Sehgal, R. K. and Nanda, A. C. (2002) Palaeoenvironment and Palaeoecology of the lowerand middle Siwalik sub-groups of a part of North- western Himalayas. Jr. Geol. Soc. Ind., vol. 59, pp. 517-529

(c) Articles from the books should follow the following format.

Windley, B. F. and Razakamanana, T. (1996) The Madagascar – India connection in a Gondwana framework (In Santosh, M. and Yoshida, M. Eds.). The Archaean and Proterozoic terrains of South India within East Gondwana. Gond. Res. Group Mem. No. 3, Field Sci. Publ., OSAKA, pp. 25-37.

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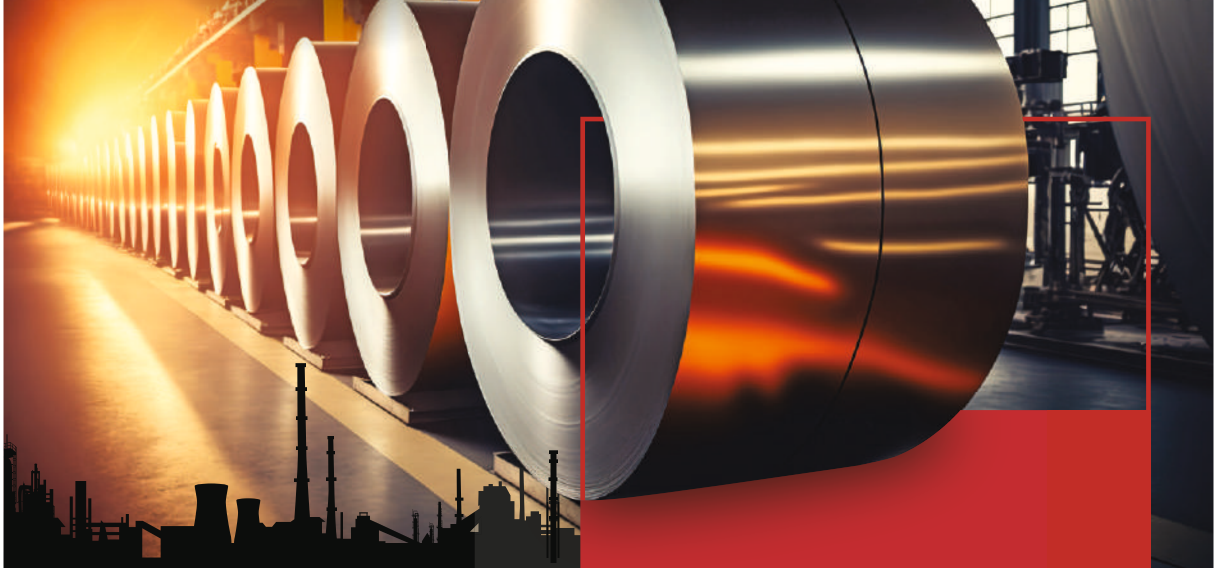

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