Water Productivity Journal
Volume 3, Issue 1, 2023
journal homepage: http://www.waterproductivity.net/
EISSN: 2821-1103
PISSN: 2717-3062

Anthropocene Lithology and Hydropower search through North Eastern Ghats Hills, Odisha[1]

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Abstract

Introduction: The Proterozoic Eastern Ghats Mobile Belt (EGMB) fabric is an 1800km chain of broken and discontinuous hills that start from Jamankira in Odisha, taking a turn at Dhauli and runs up to the Cauvery River in Tamil Nadu. The northern EGMB is of length ≈400 km and emerges from Bhubaneswar. Northern EGB is dissimilar from the central and Southern EGB. The hills and the riverine system differ in their stratification lithology, minerals, rivers, forests, hot springs, and gigantic waterfalls. The NEGMB hills are remote, with hillocks, Jungles, poor communication, interstate conflicts, tribal population, and improper planning. The government has developed four hydropower units and irrigation infrastructures only and many are yet to be explored under limitations.

Materials and Methods: The evolvement, topography, drainage system, geologic structures, rock characteristics, and granite gneisses metamorphism, charnockite, Khondalite series, and granites occurring in the EGB Hills in Odisha, from Bhubaneswar to the end of South Odisha. The setting of mountainous hills does not allow long rivers to penetrate making large and small lagoons, and having almost *zero deltas* for a stretch of 382km along the coastal front up to Vishakhapatnam. All are serpentine rivers emerging from the hills and joining Lagoon, and BoB lack of coastal prioritization of Hydropower.

1. **Received:** 2022/08/11**; Received in revised form:** 2022/09/06**; Accepted:** 2022/10/13**; Published Online:** 2023/01/02

Cite this article: Mishra, S.P., Mishra, S. & Bera, D.K. (2023). Anthropocene Lithology and Hydropower search through North Eastern Ghats Hills, Odisha. *Water productivity journal*, 3(1): 75-104.

DOI: 10.22034/wpj.2023.170350

 Article type: Research Article **Published by:** Veresk Ettesal.

Results: The shear zones beyond NEGB hills are having several east-west running faults and their fragments. The shear zones, cartoons, faults, and grabens are part of them. They regulated the climate, rainfall, fluvial, mineral, igneous, and tectonic activities of the NEGB area. The findings are the NEGB hills have been utilized to exploit four major Hydel power projects due to their positioning in upper reaches in the southern fringes of Malkanagiri lithology. However many Hydro-power units can grow at various falls in the mountainous reaches of the Koraput, Kalahandi, and Malkanagiri districts of Odisha. There is a large gap between the Rushikulya River and the Vansadhara River i.e. from Khordha to Vishakhapatnam. There are also small streams within the Nagavali and the Sarada joining BoB. The Sarada, the Varaha; the Tandava, the Eluru; are a few rivulets between the Eluru and the Godavari decanting to the Bay of Bengal. It is the naked truth that the use of Photo Voltaic to power generation is renewable energy. After 20-25 years, a huge quantity of panels shall be generated non-destructible as e-waste. The Paris agreement in SDG-7, as an affordable and clean energy expansion, cannot find a place for disposal. Geothermal and Hydrogen as the source of renewable energy shall be expensive and difficult to afford economically by underdeveloped countries. The only renewable source is hydroelectric power, which not only solve the energy crisis during the Anthropocene epoch but also save agriculture through irrigation. The statistics for the utilization of water resources in Odisha, employing the topography of NEGMB is an enlightening source.

Conclusions: The major rivers originating from Baster, and Dharwar cartoon cannot join north of the Chilika coast to the left fringe of the Godavari Graben for a length of about 382km. These small rivers have no or little delta at their coastal reach with small serpentine rivers causing fast floods and depleting some brackish water lagoons like Chilika, Tampara, and Bendi lagoons. Further large numbers of waterfalls are yet to be exploited like Tirathgada, Chitrkota in Chhattisgarh, Hatipathar, Khasada, and Gandahati needs to be exploited either as tourist hotspots or large reservoir for multipurpose uses.

Keywords: Eastern Ghats Belt, Hydrology, East coast, Lithology, Hydel projects, Rivers, India.

1. Introduction

The Anthropocene epoch is assumed to be set from the year 1950, dominated by human activities over the geo-bio-hydrosphere. As result, the inaccessible areas are made accessible, and building skyscrapers; bumper agriculture, Dams, mines, and changes in the lacustrine environment are part of these diversities of Nature. Nature in past seems to be a unique landscape and assemblage of Scenic views. The canyons, coasts, rivers, mountains, lacustrine areas, volcanoes, sands, or caves need to be explored for anthropogenic use (Lewis *et al*., 2015; Mishra, 2017; Abhilas *et al*., 2022).

Peninsular India is protected in the east by the Eastern Ghats mountainous belt from the Bay of Bengal, in the west by Western Ghats (WGB Hills) mountains from the Arabian Sea, and north by the sky-touching Himalayan ranges. The major rivers and deltas of India lie parallel to the east coast about 2700km long, housing many large cities, river systems, and faunal diversities but not like the Himalayas or WGB hills. The thickly populated large deltas with a maximum width of 100km are regularly washed out by cyclones, rainfalls, high waves, tsunamis, and extreme weather events (EWEs). The geological and lithological studies of north EGB hills of length ~400km along the coastal track and apex of the 85^0 ridgelines show tectonic formation that indicates the strike-slip nature. They are part of the craton-mobile belt of the northern fringe of Bhubaneswar (Verma *et al*., 1985; Gupta *et al*., 2020; Mishra *et al*., 2021).

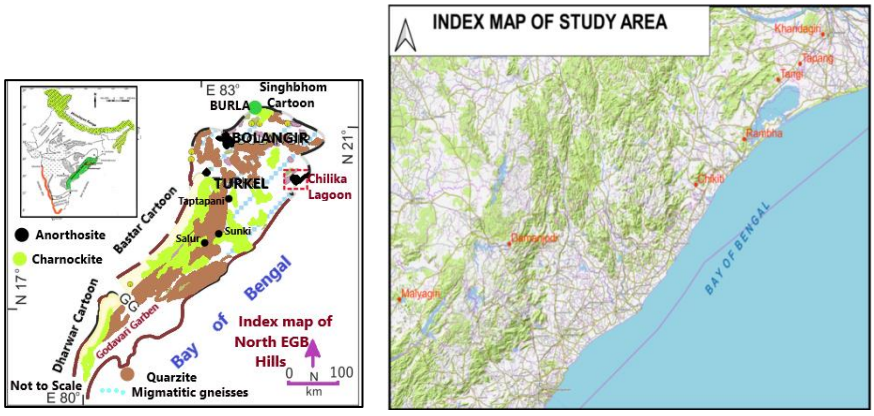

Fig 1(a) & (b). The index map of the study area (EGB Hills range) and the thematic map

The EGMB hills are divided into three segments North Eastern Ghats Mobile Belt (NEGMB) of Odisha, starting from Bhubaneswar on the northeast

fringe. The Central Eastern Ghats Mobile Belt (CEGMB), and Southern Eastern Ghats Mobile Belt (SEGMB) fringe runs from the Indian peninsula to Cape Comorin, (after Dobmeier & Raith, 2003). Odisha is classified as three distinct lithological crustal blocks, the north Orissa boundary faults (NOBF) along the Mahanadi rift, the North Eastern Ghats Mobile belt (NEGB), and the West Orissa Craton (WOC). The main east-flowing peninsular rivers are the Mahanadi, the Godavari, the Krishna, and the Cauvery, along with many rivulets that discharge along with a huge quantity of sediment to the Bay of Bengal directly or via a lagoon. Such large/small lagoons the Chilika, the Kolleru, the Pulikat, and the Bendi are also sandwiched between the EGMB making vast coastal plains, Fig 1(a) & Fig 1(b), (Sengupta *et al*., 2009; Mishra, a2017; Mishra *et al*., 2022)

Targeting the lithology, the anastomosis of the drainage system is discussed. The main objective argued based on rock formation and shifting of the Mahanadi basin southward and creating a typical drainage pattern in the north Eastern Ghats belt from Visakhapatnam to Puri NW corner of coastal length 382km and evaluation of drainage characteristics of small length rivers/rivulets emerging from EGMB and falling BoB. The present search is to study the rock types, structure, and lithological novelties. The study of the present hydropower advances and the plan for innovative energy sources have been mentioned after searching.

2. Geography

The EGB hills are an ancient orogenic belt-shaped by the fender-bender of the continental drift of crustal rocks of the Indian subcontinent during the Gondwana period of Archean Eon. The EGB hills extend from Jamankira near Sambalpur to Bhubaneswar and continue to parallel up to the eastern brinks of the Araku in AP, and then Nilagiri hills, Anamalai Mountains, and Palni Hills, etc. in Tamilnadu, (Mani, 1974). The EGB formation periods are dateable to two distinct convergence episodes. The first rifting occurred during ~ 2.0 Ga BP (before the present) due to rifting of the continent along the eastern shores of the Indian plate. The second type of evolvement is along the Andean-type subduction of continental edge by convergent plate movement at ~1.85 Ga BP. (Fig 1).

Longitudinally the lithe zones in NEGBMB, Odisha plunges the Western Charnockite Zone (20-30km wide up to Riamal, Talcher, and Odisha), Western Khondalite Zone (30-50km up to Bramhani valley), Central Migmatitic Zone (40-100km; Kalahandi, Phulbani, Rayagda and Ganjam

districts of Odisha), and Eastern Khondalite Zone (Puri and Khurdha districts Odisha). In the Chilika and its western coast, the dominant group consists of metapelites, migmatitic, and on the Balugaon side massif-form anorthosites. The geo-assembly is in Table 1.

Table 1. The lithe-stratigraphy of the ultrahigh temperate metamorphic rock of North EGB Hills

#	Lithe - Constituents	Rock type	Group of stones	Subgroups
1	Meta-sediments	Khondalite	High grade	450•5Myr
2	Charno-enderbite	Charnockite	mafic granulite's	443 ~: 8 Myr
3	Migmatitic	Granitic	gneisses leptynite/ granites,	900-1050 Myr
4	Alkaline Genesis	Precambrian	between car-tonic blocks	Mesoproterozoic (1400–1300 Ma)
5	Massif Type	Massif-type	anorthosites complexes	950–1000 Ma

(**Source:** Nanda *et al.*, 2009; Mahapatra *et al*., 2013; Ghosh *et al*., 2021; Pachuri *et al*., 2022)

3. Physiography

The EGB Hills are elder than the Western Ghats Hills. Their geologic formation history is connected to the breaking, rifting, and shifting of the Rodinia and Gondwana Supercontinent. Numerous squat hills of the NEGBMB are housed in the northern and southernmost edges of EGB. They are Biswanath Mundia (Hillock), Dhauli Pahada (Hilllock), and Udayagiri in and around Bhubaneswar, Sirumalai, and Karanthamalai hills of Tamilnadu. But towards the north of the Cauvery River, the hills are higher. They are Rollimalai, Panchaimalai, Kairayan hills, and chittering in Tamilnadu. The Nilagiri hills join the EGB and the WGB hills, Table 2.

Table 2. Geomorphology status of the Eastern Ghats mobile belt along the east coast of India

States	Share Area	Type of Forest	Rivers	Height of highest Hills
Odisha	~25%	Dry/semi-evergreen southern tropical dry mixed deciduous, Dry savannah, southern tropical dry scrub/ thorn; Carnatic umbrella; Southern sub-tropic hill/ thorn &Mangrove forests.	Baitarani, B-balanga, Rushikulya; Bahuda, Vansadhara, Palar, Nagavali, Sabari Champavati, Gosthani; Sarada; Tammileru; Sileru, Gundlakamma, Pennai, Yaru, Swarnamukhi, Kundu, Velar; Penna;(CWC year book).	1, 672m Deomali Peak
Andhra Pradesh	~40%			JindhagadaPeak Araku Valley (1690m)
Telangana	~05%			965mDoli Gutta
Karnataka	~05%			Kattahi betta; BR hills(1822m)
Tamil Nadu	~25%			Shervarayan Temple; height of 1, 623m

4. Review of literature

Enclosed between the Northern Odisha Cartoon, Baster cartoon, and Dharwar Cartoons, with variant biodiversity, ecosystem functions, and the Archean and Precambrian tectonic rocks are the Eastern Ghats Hills range. They are associated with strong linearity, ductile deformations events exhibit high-grade metamorphism skirting the Archean Cratonic blocks, (Lakes of India, 2022). CGMB has been divided into three zones, such as northern, central, and southern considering crustal shear zones in depth, (Chetty, 2001).

Eastern Ghats belt is a series of ancient orogenic discontinuous ranges of hills formed tectonically due to rifting and shifting of the part of the Rayner Complex of Antarctica, during the Proterozoic period 1.0 to 0.9 Ga Before present (BP) (Nasipuri *et al*., 2018). Various authors substantiated the evolvement of the EGB Hills date back to ~1600 Ma years BP, involving magmatism, sedimentation, metamorphism, and crustal anataxis and comprise of three broadly classified lithological groups (metapelitic granulites, charnockite-enderbite gneisses/ mafic granulite's, and migmatitic gneisses trending regionally NE-SW, (Kar *et al*., 2022).

The evolvement of the Eastern Ghats provinces are as a part of the Rayner complex of Antarctica and has formed by rifting and juxta-positioning at various times and events, approximately 983Ma BP, (Biswal *et al*., 2007; Chatterjee *et al*., 2008; Mishra *et al*., 2015; Nasipuri *et al*., 2018). The systematic study of Gravity-magnetic anomalies, the diversity, composition, and structure of dry tropical forests Fire alter in the Eastern Ghats. Difficulties are faced for systematic mapping of lithe-facies as non-availability of marker bands, tracing unconformities, covered thickly by weathering over a rock surface, and limited accessibility, (Banerjee, 1990; Basantray *et al*., 2022).

The NW of Chilika Lagoon houses sapphirine-spinel-bearing found in tectonically formed caves within the Khondalite and pelitic granulite's in the Kaithapalli (Rambha) area in the northern part of EGMB, (Prakash *et al*., 2019). The EGMB is a tectonically dynamic zone. It encompasses three provinces, the Eastern Ghats, the Jeypore, and the Krishna Provinces, along with the eastern brim of Peninsular India, with a low-velocity layer containing magma fluid at ~20 km of varying depth and susceptible to tremor, (Choudhury *et al*., 2016).

Eastwards tilt had occurred in the Indian landmass during its geologic formation. Along the east coast, large peninsular rivers have to cut the EGB to join the Bay of Bengal. They are the Mahanadi, the Godavari, the Krishna, and the Cauvery. Other rivers are small but their origin is from the east front of the

EGB and joins BoB. Some picturesque gorges have resulted from this passage. The Mahanadi graben, the Godavari graben, and Krishna trifurcate the EGB Hills range as North, central, and southern EGB hills (NGEB, CGEB, and SGEB), (Mishra, 2021).

5. Origin of EGMB south Odisha

The crash between the Lambert Terrane of East Antarctica and the Bastar–Dharwar craton, under ultra-high temperature (UHT) granulite facies metamorphism found in the Eastern Ghats occurred in About 1650 Ma BP, The 3rd event of collision occurred between 1500 to 1200 Ma BP. It was connected with the partition of the Vestfold Hills and another opening of the proto-Indian ocean, and the development of a sequence of basins towards the west of the Eastern Ghats areas are part of Khariar, Balimela, Upper Kolab, Indravati, upper Vansadhara, upper Nagavali and Sabari basins in Odisha (Mohanty, 2015; Guhey, *et al*., 2017). The Indravati, Upper Kolab, and Balimela Basins are 9000 km^2, in EGMB hills of South Odisha, and Chhattisgarh. They are rifts due to outcrop of Proterozoic sediments, in Koraput, Nabarangpur, Malkanagiri, and within Kanker, Baster, and Dantewara districts of Chhattisgarh, (Fig 2(a, b, c))

6. EGMB; a storehouse of Mineral

The northern EGB Hills in Odisha is rich in mineral resources beyond iron and Bauxite. The other rocks and minerals found in NEGB are (Table 3).

Table 3. Availability of ores on EGB Hills housed in Odisha with their volume of deposits[1]

EGB Supper group Rocks	District	Mineral	Location
Khondalites, Charnockites blanket, capping parent rocks on plateau tops.	Koraput, Rayagada, M-giri, K-handi	Bauxite (1810 MMT)	Panchpatmali, Pottangi, Maliparbat, Ballada, Kodingamali, Hatimali, Kak rimali, Chintamgundi, Kornapadi
Khondalite, Charnockite, Pyroxene, granulite host rock.	Debagarh	Copper (3.09 MMT)	Adasa
Beaches. Titanium, Zircon, Sillinite, Monazite: rare-earth	Ganjam	Titanium (226.24 MMT)	Gopalpur Sector, Chhatrapur Sector and Prayagi Sector (Chilika)
Khondalite calcaneus Quartzite, & calcgranulite as tabular body	Balangir and Rayagada	Total 119.81 (MMT)	**R-gada**: Nishikhal, Podakana, Khuri gaon, Anajori, Liliguma, Amba dola, Rukunibari, Loharapara, Bhalu maskaetc. **B-gir:** Champasar, Bhar atbahal, Rengali, Tamiya, Babja, Ucchabapali, Banipali, Gadashankar,

1. Source: https://www.odishaminerals.gov.in/Download/geology_mineral_resources_orissa.pdf

EGB Supper group Rocks	District	Mineral	Location
Meta-sedimentary, metal basics,	Debagarh	Odisha 3.09MM	Adarsh: Bengal Group intruded by pegmatites & quartz veins
Tin ore (Cassiterite) in Meta basics or Meta-sedimentary	Malkanagiri	Not assessed	Bijapadar, Vederupalli, Durmaguda, Mohapadar, Kurumpalli, Gurupada, Permanasu
Asbestos with granite Gneiss, nd amphibolite	Malkanagiri	Not assessed	MV-76, MV-114, MV-96, Uruvalley Baliguda, Maharajpali.
Limestone	Koraput, Nuapada, Malkanagiri Balangir	Total Odisha 1007.2MMT	**KPT:** Sunki, Dumajodi Kunda Jodi, Parasagudi, Binsuli, Gupteswar, **Mal-Giri:** Kottametta, Nandiveda, Uskalvagu **N-Pada:** Chandpala, Sagundunguri, Deobahal, Rohapadar, Gorramura. **B-gir:** Dhamandanga, Kuliadaha, Hial
EGB Hills houses other minerals in Odisha such as ***Graphite*** for multifarious uses in districts of Angul, Baragad, Balangir, Kalahandi, Kandhamal, and Nuapada, ***Quartz, and Quartzite*** (Angul, Gajapati, Nuapada, Ganjam, Nabarangpur, etc., and dimension stones in districts like Boudh, Baragada, Kandhamal, Koraput, Rayagada, Nuapada, Nabarangpur districts along with Precious and semiprecious stones like Gold, Diamond, sapphire Garnet, Aquamarine, etc.			
K-Handi: Kalahandi; K-put: Koraput; B-gir; N-Pada: Nuapada; K-mal; Kondhamal; Mal-giri: Malkanagiri			

7. Various Geological Features in situ

Based on Geological and tectonic considerations the NEGMB in Odisha, start from north of Similipal in the Mayurbhanj district and runs through Malkanagiri district covering 17 districts and an area of around 75, 000 km2. The entire EGB region has granulite terrains, mainly Khondalite and Charnockite sheets of rocks, intruded locally by the mafic-ultramafic suits, anorthosites, alkaline rocks, potassic granites, pegmatites, and quartz veins with Gondwana sediments. The areas under EGMB investigated are as follows:

Northern fringe EGB Hills

1) Khandagiri: (Lat20.2569°N, Long85.7792°E), The SOI topo sheet No. 73H/16RE:

2) Dhauli: 20.1978°N, 85.8436°E, The SOI toposheet No. 73H/16RE: 1:125,000

Central part of North EGB Hills

3) Tapang - Golabai: Lat-250 43’ N ; Long-85^0 47’ 5” E

4) Balugaon: Lat-190 5’ N, Long.-800 23’ E,

5) Banapur: Lat-19045’ 44” N; Long-85012’ 57” E)

6) Taratarini: (19.4889°N, 84.8991°E)

South-Western Part of NEGB

7) Gandahati, in Gajapati district: (18.8777°N, 84.2667°E)

8) Khasada Gajapati: (19.2433°N, 84.2411°E)

Southern fringe NEGB

9) Hatipathar, Nagavali River; Rayagda (19.17°N and 83.42°E; elevation: 207m)

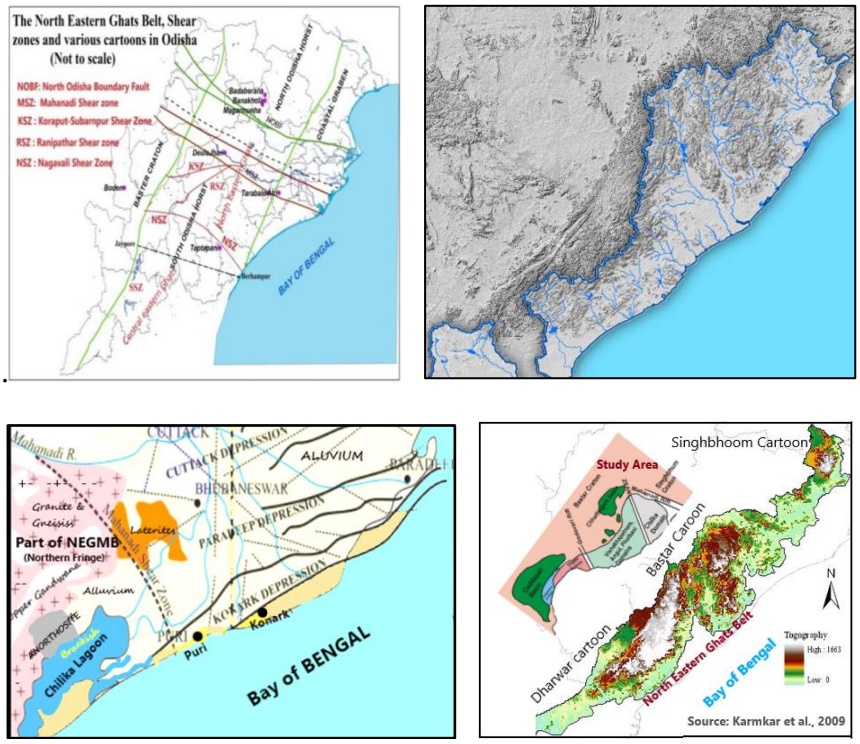

Fig 2(a). The shear zones, and cartoons in NEGB; **Fig 2(b).** The rivers in coastal NEGMB; **Fig 2(c).** The northern fringe of NEGMB (7D_MERO_Bhubaneshwar_Vamsadhara_ Rushikuliya_Nagavali_Sarada_WYB_2016-17.pdf and Karmakar *et al.*, 2009)

The Northern EGB Fringe: This region (Lat-20014'45" N; Long-85047'5" E with Altitude-43m (mean sea level (MSL). Dhauligiri, Khandagiri, and Udayagiri are located at a distance of 15km, 7km, and 7.2km from the temple city, Bhubaneswar, and the capital of Odisha.

8. Dhauligiri and Khandagiri

The study is for geological investigations around Dhauligiri and Khandagiri, Geological setup, Petrography, and Structure and geometry. Also, geographical studies for Structure, Stratigraphy, and geometry of rocks in the area are done. The pervasive structures, cleavage, and foliations on weathered rocks and their thickness and effect on water resources do not allow the river Kuakhai and

Daya rivers to affect the rock formations. Some small drains only can carry the runoff from the area. In the case of Dhauligiri, paleo sediments in past have made the land fertile. The groundwater and the ponds are conducive to fish culture in the area (Fig 3).

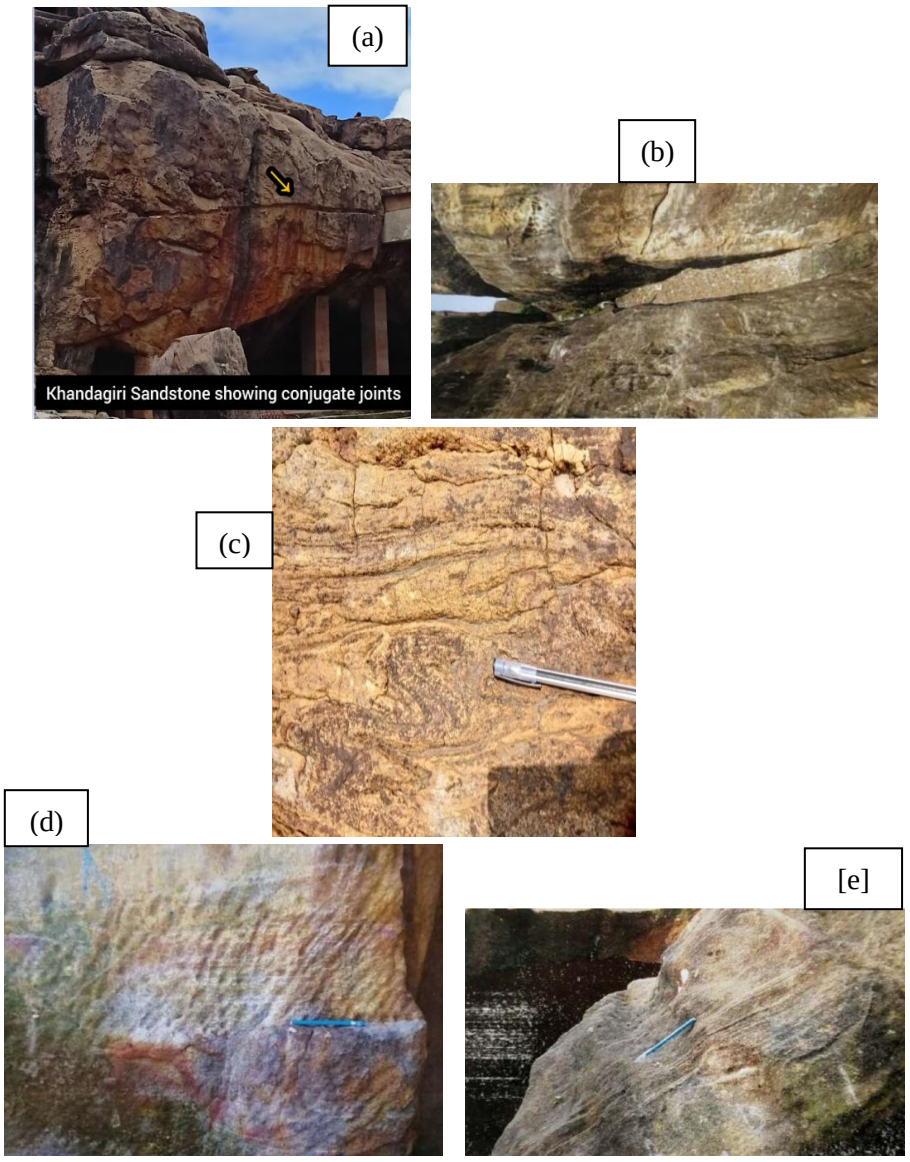

Fig.3. The Khandagiri- Udayagiri Hills showing (a) conjugate joint (b) the master joint (c) complex joint and well preserved (d) ripple marks (e) Bedding planes

8-1. Climate

This area comes under a humid dry tropical Savanna climate. The average annual rainfall of this area is 1000mm to 1443mm varying from south to north. The minimum temperature of the area has been recorded at approximately 8°C during January whereas the maximum temperature is about 45°C in May. Northern EGB Hills can protect orographic cyclonic storms slamming northern EGB Hills like Titili (Oct. 2018), the southern fringe of NEGMB, and Fani (April 2019) in the northern fringe of EGB. The effect of climate change and orogenic effects is prominent. Flora, Fauna, and Vegetation.

These low heightened hill ranges have a collection of tropical vegetation that is supporting thickly populated areas (Pas) in the canopy. Mostly the NEGB hill locks are bald or gradually becoming bald. A series of protected forests representing floral diversities and the number of permanent or fragile significant ecosystems maintaining varieties of flora, fauna, and avifauna are gradually reducing due to Anthropogenic, Industrial, institutional, and federal activities.

8-2. Physiography

The area comprises of series of small hillocks of steep slopes of height 30m to 90m above MSL. The Dhauligiri Hills is about 90m high on its southern. The north side of the Dhauli mound show closely spaced contours indicating a steep slope whereas the south and eastern side show little wider spaced contour indicating a gentle slope.

8-3. Geomorphology

The Dhauligiri hillocks are formed as a residual hill, standing as isolated amidst the first flood plain developed by the river Daya. There are two mounds and a valley along the hill slope. At the foothills, the river Daya is flowing cutting through the hillocks on both sides where the flow direction is changed. The general geomorphic trend is nearly E-W and sporadic flat top with a very steep slope. It is an elongated hillock as indicated by the contour lines. The extensive flood plain encircling Dhauligiri is an old alluvial terrain, supporting rich cultivation and high yield.

9. Geological setup of northern NEGMB

9-1. Lithology

The exposed rocks in the Khandagiri and Udayagiri are the Athagarh

Sandstones. They are terrigenous Sedimentary rocks composed of more than 70% sand and quartz particles. feldspar, micas, heavy minerals, and rock fragments. The lateritic rocks show over the sandstones. Latosols are the type of soil created from the laterites due to prolonged weathering. The sea level progradation and degradation with transgression due to shifting of SW monsoon, and later subsequent uplift is the reason behind the minimal deformation in the configuration of the hills. The rocks display sedimentary structures like ripples and bedding planes.

The Dhauligiri area forms a small part of the Eastern Ghats complex of the Precambrian age. It is exposed in this hill and divisible into three lithologic zones as Western Khondalite zone, the central migmatitic zone, and the Eastern Khondalite zone.

9-2. Petrography

Khondalite: It is of reddish brown colour with well-marked colour bands. Garnet is the quartz-feldspathic material a banded meta-sedimentary rock composed of Quartz, Feldspar, Garnet Sillimanite, and Biotite which are identified as megascopic. It can be an inter-banded field relationship with basic granulite /charnockite that varies in colour from light to deep brown with whitish patches. Feldspar and Granite grains show a high degree of alternation of prevalent Kaolinisation and ferrugenisation. The foliation in Khondalite is imparted by a parallel array of Sillimanite needles, Biotite flakes, and elongated Garnets, and Schistosity is also well-developed. The Khondalite is partly folded. Linear grooves are found in them due to the removal of garnet grain arranged in a particular direction.

Quartz: It is a coarse-grained rock, characterized by bedding and metamorphic banding, which are principally composed of Quartz. It is a greyish, white rock pitted with brown knots. The Quartzite band is set up to be concordant interlayered with weathered Khondalite on both sides.

9-3. Anorthosites

The Udayagiri housed in the northern fringe of EGB exhibits metamorphic Grenvillian granulite of 950–1000 Ma BP known as Udayagiri anorthosites complex, (UAC), consisting of anorthosites, leuconorite, and norite. They show prograde and retrograde of metamorphism before and after the anorthosites invasion, signifying their positioning, Anorthosites of Massif-type are found in the outskirts of the Chilika Lake area, and the Turkel area of Balangir of Odisha, (Mukherjee *et al*., 1999; Mohapatra *et al.*, 2013).

9-4. Structure and Geometry

The lithologic assemblage especially Khondalite shows different structural features. The rock has suffered high-grade metamorphism and well-marked development of the prominent gneiss. The different structural features are - bedding planes, foliation, Schistosity and gneiss, lineation, joints, folds, and faulting (Sharma *et al*., 2009).

Bedding plane and Axial plane foliation: The strike of the bedding plane foliation varies from N-S to S22W, with dip varying from 80 -84 due to W-ly and NW-ly. Whereas the Axial plane foliation is the strike of the axial plane foliation of this rock of this area varies from N65E to S65W having dip towards NW and sometimes Garnets are stretched parallel to the foliation plane. Various lineation is found in the northern EGMB, which may be internal, Mineral, Minor metamorphic folds, clear folds, Joints, Faults and sicken sides, etc.

9-5. Stratigraphic columns

The stratigraphy column from the frustum to bed plane is identified as alluvium or moorum, Laterite, Quartzite, Khondalite, and finally charnockite or hard granite black or coloured.

The topsoil the outskirt of Dhauli hills is either old or newly formed alluvium in the agricultural lands, comprising floodplain deposits. The immediate underlain is a bed of lateritic soil followed by 10m to 15m of porous laterite mines. Later the extension is either quartz or granite genesis.

Khondalite or Granites: are “inselbergs” and they are undergone high-grade metamorphism. Polyphase deformation and found in Khondalite and quartzite. The structures are bedding plane foliation, axial plane foliation, Schistosity, joints, and minor folds are common.

Tapang-Golabai Mundia: Lat-250 43’ N; Long-850 47’ 5” E with Altitude-46m (MSL)

The Golabai and Tapang Mundia are the hillocks coped with Lateritic sheets composed of alternate dark and white bands. Charnockites and gneisses dominated the lithology of the region.

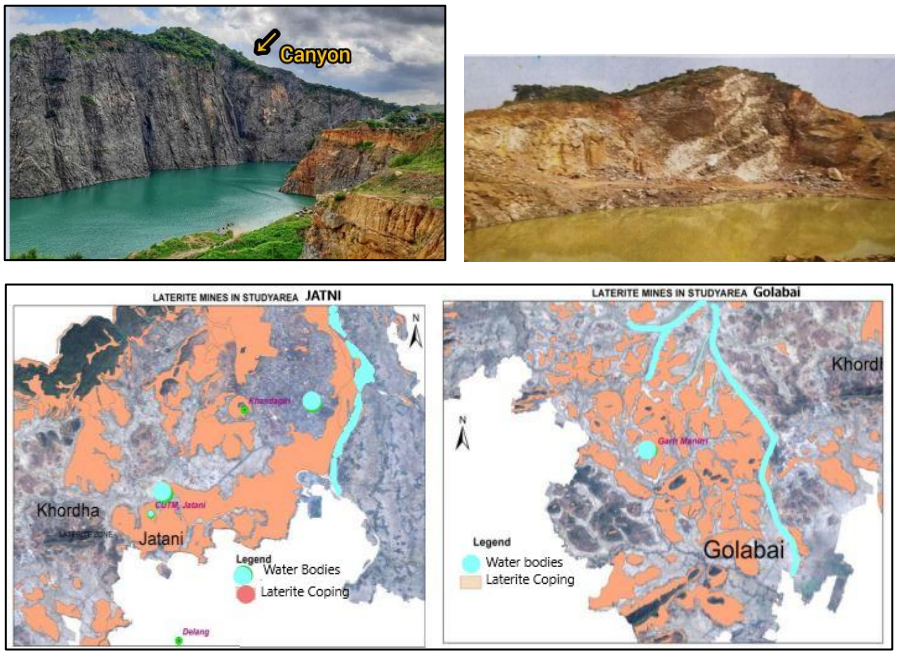

Fig. 4(a). Nijigarh, granite quarry at Tapang (paleo and moorum overburden); **Fig. 4(b).** Alternate bands of leptynite and charnockite; **Fig. 4(c).** The laterite coping and underlain by Quartz and other landforms at Jatni and Golabai in Khordha district

Charnockite is considered a meta-igneous rock, formed in water-deficient conditions. There was an abundant occurrence of leptynite (white patches) in the host gneiss. The rocks indicated the presence of garnet, quartz, biotite, and feldspars. Rocks are highly metamorphosed and thus show granoblastic texture. Quartz ribbons are also found in these metamorphic rocks. From the mineral assemblage, it is inferred that the rocks are formed in volatile deficient conditions (Granulite facies). Granulite facies are characteristics of the Eastern Ghats rocks caped by latterites. (Fig 4(a), Fig 4(b) & Fig 4(c)).

10. Banapur and Balugaon

Lat-190 5’ N, Long.-800 23’ E, Altitude-38m (above MSL) Petrography study of at Banapur-Balugaon. The northern EGMB has four settings of massive Anorthosites setting at Balangir (~400 km2), Chilika Lake (~250 km2), Jugsai Patna (16 km2), and Turkel (81 km2) massif. The phase of magmatism in anorthosites of the north EGMB varies as 1400 Ma BP 792 ± 2 Ma and 983 ± 2.5 Ma for the Chilika Lake complex and ca. 930 Ma for the Balangir complex. The massifs are hosted by a migmatitic garnet-ferrous felsic suite of

rocks that vary in composition from granite to monzonite through granodiorite, Fig. 5 (Chatterjee *et al*., 2008; Mohapatra *et al*., 2013).

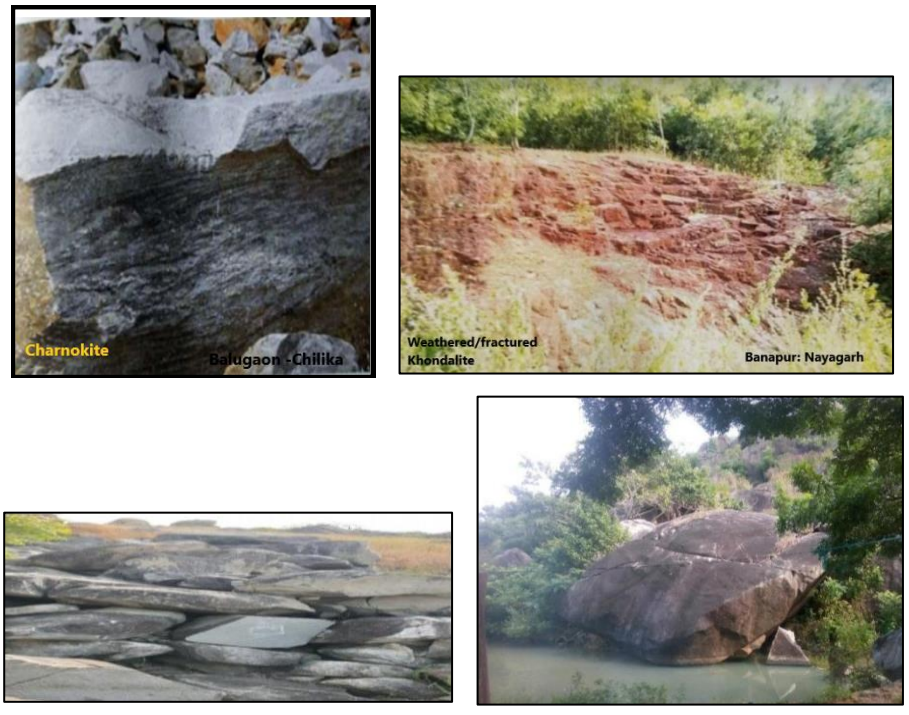

Fig.5. Bands of Charnockite preserved within a leptynite rock at Balugaon and Banapur

The hill ranges in and around Koraput in the geological past were a melting pocket. There were alternate bands of rocks representing alternate melts. We observed some fresh Khondalite was exposed amidst the luxurious vegetation. Khondalite is metaplastic rock containing quartz, garnets, rhodonite stone, and schists. It may also contain sillimanite and graphite. Anorthosites are phaneritic, intrusive rocks consisting of plagioclase feldspar (90-100%) and minimal mafic component. Pyroxene Ilmenite, Magnetite, and olive are most commonly present.

10-1. SW Odisha (Gandahati)

Gandahati (18.8777° N, and 84.2667° E) is a waterfall near Parlakhemundi, in Gajapati, which lies within the southern fringe of the Northern EGMB range of hills in Odisha. The perineal waterfall is 180.5 m above MSL, one of height 20 m, and over the rivulet Mahendra Tanaya.

Fig. 6(a). Geological settings of Gandahati Waterfall; **Fig. 6(b).** Porphyritic texture near Rayagada – R. Udayagiri; **Fig. 6(c).** Poly phase folding near Gandahati; **Fig. 6(d).** Cross beddings near R. Udayagiri (SH)

The texture of a rock is the size, shape, and arrangement of the grains (for sedimentary rocks) or crystals (for igneous and metamorphic rocks). Also of importance are the rock's extent of homogeneity (i.e., uniformity of composition throughout) and the degree of isotropy. About six main structural types of rocks phaneritic, porphyritic, pegmatite, aphanitic, glassy, and pyroclastic, are found here (Fig 6(a), Fig. 6(b), and Fig 6(c)).

10-2. Cross bedding

Cross-bedding over rocks is found in a fluvial environment Fig 6(d). If the bed material is mobile then it shows cross-stratification. Gandahati rocks have fairly consistent fixed angles cleavage and direction of cross-beds. They are cross-beds that range in depth from a few centimeters, up to hundreds of meters depending upon the deposition and the extension of the bed form. Cross-bedding is common in EGB stream deposits, tidal or, fluvial bed forms (in ripples/dunes).

10-3. Khasada Waterfall

Khasada waterfall (Lat.:19.2556058 N, Long.:84.2330967E) is located near Chandragiri of Gajapati, Odisha.

Fig. 7(a). Khasada Waterfall; **Fig. 7(b).** Biological weathering;
Fig. 7(c). Pot Holes and **7(d)** mounds near Khasada Waterfall, Gajapati

11. Potholes and mound formation

The potholes are even, bowl-shaped, or cylindrical hollow, (deeper than width), and are found engraved in the rocky fluvial bed. It is created by erosional turbulent forces in waterfalls particularly when the base is limestone, Fig 7 (a), Fig 7(b), Fig 7 (d), and Fig 7 (e).

11-1. Ripple Marks

Ripple marks are found on the surface of the rock bed, mono-directional or asymmetrical ripple marks in the gentle up-current slope and a steeper down-

current slope. They are generated in long term in aeolian and fluvial depositional environments and are significant in the bottom chunk of the rock where flow is of less quantity (Fig 8 (a) & Fig 8 (b)).

Fig. 8(a). Ripple mark near Khasada Waterfall (Vertical) and **Fig. 8(b).** Horizontal)

11-2. Hornblende Intrusions

The distinct sheet structures on rocks called Veins form when mineral constituents get deposited on the surface due to hydrothermal circulation. They are formed due to open-space filling and crack-seal growth. Hornblende is a rock-forming mineral in acidic and intermediate igneous rocks such as granite, diorite, syenite, andesite, and rhyolite. It is also found in metamorphic rocks such as gneiss and schist. These metamorphic rocks dark in color are easily identifiable in Khasada waterfall (Fig 7(a) & Fig 7(b)).

Fig. 9(a). Hornblende Veins near Khasada Waterfall

Fig. 9(b). Joint near Khasada Waterfall

11-3. Joints

A brittle-fracture surface in rocks along which little or no displacement has occurred is called a joint. Joints have smooth, clean surfaces, or they may be

scarred by slickensides, not extending large depths in the Earth's crust. They are upon weathering, become well-marked, mostly in soluble rocks like limestone. Solution by water percolating through joints has led to the formation of large caves and underground rivers like the naturally formed Gupteswar cave in Koraput. Quarrying operations are facilitated by the presence of a well-developed joint system. Sedimentary rocks usually show two sets of joints at right angles to one another. One set is extending extends in the direction of the dip and the other in the direction of the strike. The igneous rocks, jointing is generally quite irregular; but in granite, two vertical sets forming right angles to one another on the top surface and another set of cross joints approximately horizontal occur frequently in the Khasada rock stratum (Fig 9 (a) & Fig 9 (b)).

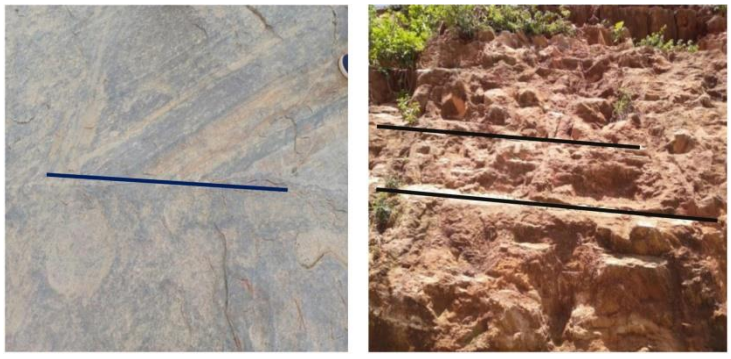

Fig 10 (a). Metamorphic Bedding near Khasada Waterfall

11-4. Metamorphic bedding

The bedding found in metamorphic rock that formed from sedimentary rock is evidence of extreme heat and pressure and is often quite distorted. Distortions may change the sedimentary bedding by compressing, inclining, folding, or other changes. One of the most common types of bedding is called graded bedding.

11-5. Quartzite veins

Originally Quartz is hard, non-foliated metamorphic rock comprising pure quartz sandstone and later converted into quartzite of white to grey. They can be of various shades of pink and red due to varying proportions of iron ore within. Other colours, such as yellow, green, blue, and orange, are due to other minerals. Quartz veins are mostly fracture related and have clear contact with their host rocks.

The crack might have formed during the folding of the rock in mountain-building processes, by shattering during tectonic events, by a decrease in pressure during the uplift of a rock, or because a rock cools down and shrinks. These quartzite veins are found in rock layers in the Khasada area and Mahendragarh, and Chheligarh areas (Fig 9(a)).

Metamorphic rocks vary in colours from clear to cloudy to milky white, as well as rose, blue, and smoky containing abundant quartz especially those produced from granites, sandstones, or shales. In particular, coarser-grained metamorphic gneiss is marked by distinct bands of quartz and other minerals. Pure quartzite of white to grey colour is less traceable in the area. They occur in various shades of pink and red (for % of hematite). Other colours, such as yellow, green, blue, and orange, are due to other minerals.

Fig. 9(a). Quartzite vein near Khasada Waterfall
Fig. 9(b). Clear unconformity Younger is overlain older

11-6. Unconformity

An unconformity is a contact between two rock units in which the upper unit is usually much younger than the lower unit. Unconformities are typically buried erosional surfaces that can represent a break in the geologic record of hundreds of millions of years or more. The Khasada fall has such a type of unconformity (Fig 8(b)). There are three kinds of unconformities: disconformities, non-conformities, and angular unconformities (Fig 9 (b)).

12. Tara Tarini, Ganjam

12-1. Layering and bedding

Layering, or bedding, is the sedimentary rock characteristic shown by the rocks at Taratarini in Ganjam Districts on the bank of the Rushikulya River.

These sedimentary rocks are formed particle by particle and bed by bed. The layers are piled one on top of the other, the lower layer is older than the upper one. The layers range from several millimeters to many meters in thickness and vary greatly in shape. Strata may range from thin sheets that cover many square kilometers to thick lens-like bodies that extend only a few meters laterally. Original stratification may be destroyed by plants or animals, by recrystallization of limestones, or by other disturbances after deposition as some rocks do not exhibit stratification (Fig 10(a)).

Fig. 10(a). Layering and bedding at Taratarini,
Fig. 10(b). Deterioration of rocks by physical weathering

Physical Weathering: Physical weathering is the process of the disintegration of rocks, minerals, and soils without chemical change through abrasion by temperature, frost, pressure, root action, and burrowing animals. The physical weathering forced to form cracks due increase in the exposed area to chemical action. Most of the rocks at Taratarini are weathered and cracked where plant roots sometimes enter cracks and increase the disintegration.

Biological weathering: Biological weathering is the weakening and subsequent disintegration of rock by plants, animals, and microbes. Biological weathering also means organic weathering. It is the disintegration of rocks as a result of the action of living organisms. Plants and animals have a significant effect on the rocks as they penetrate or burrow into the soil respectively. Biological weathering can work hand in hand with physical weathering by weakening rock or exposing it to the forces of physical or chemical weathering (Fig 10(b)).

13. The Riverine System Coasts along NEGB

The drainage system: The rivers originating from the hills of EGB and falling in the Bay of Bengal are 18 in number and the major rivers are the Budhabalanga, the Baitarani, the Rushikulya, the Vansadhara, the Nagavali, the Sarada, the Sileru, the Swarnmukhi, and the Penna rivers, (Mishra *et al*., 2016). Major east flowing Rivers not originated from the EGB Hills but tearing the series of EGB hills that joins the BoB seven including the Mahanadi, the Godavari, the Krishna, the Cauvery, and the Pennar, etc. The drainage anastomosis and sediment transport of anastomosed drainage through the EGB Hills range explain and longitudinal section depicting the tectonics in past, and the horizontal profile of the longevity of the drainage system, (Mishra, 2017; Seybold *et al*., 2022). The NEGMB rivers are small and independent rivers join the Bay of Bengal (BoB). They are the Rushikulya, the Bahuda, the Vansadhara, the Nagavali, the Sarada, the Varaha, the Tandava, the Eluru, the Gundalkamma, the Musi, the Paleru, the Manneru, and the Vogarivagu. After the Daya southern distributary of the Mahanadi joining BoB via the huge lagoon Chilika, only two small rivers of optimum length 250km and the list is in Table 4 and these small distributaries are *having almost zero deltas.*

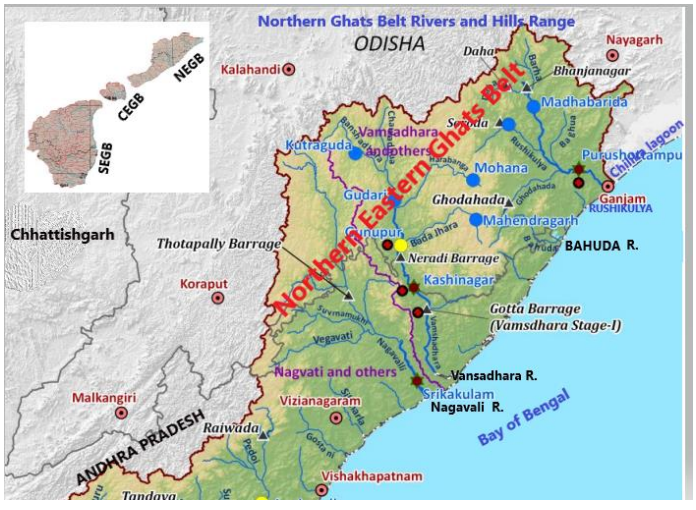

Fig. 10. Large gap from Chilika to Kakinada, but no major rivers (Source Modified CWC figure).

There is a large gap between the Rushikulya River and the Vansadhara River i.e. from Khordha to Vishakhapatnam. There are also small streams within the Nagavali and the Sarada joining BoB. The Sarada, the Varaha; the

Tandava, the Eluru; are a few rivulets between the Eluru and the Godavari decanting to the Bay of Bengal. The rivers are given in Table 4.

Table 4. The physiognomies of small delta-less rivers, originating from NEGB and falling BoB[1]

#	Rivers from NEGB Hills	Length of river	Basin area	Place/district of origin	Basin characteristics	Tributaries
		(Km)	Sq km	Near		
1	Daya/ Bhargovi via Chilika	60 from	~1998km^2 +Mahanadi flood Flow	Uttara near Bhubaneswar	Vast deltaic plain enclosed by Khordha EGBhills	Bhargovi, Ratnachira Makara, Luna,
2	Rushikulya	165Km	8963sqkm	Matabarhi	EGB Hills of Phulbani	Barhandi, Ghodahada, Bagh and Pathama
3	Bahuda	73km	1250	Ramgiri hills in Gajapati	Passing via Ganjam join BoB at Srikakulam	No tributaries
4	Vansadhara	254km	10830 (74% Odisha)	Lanjigarh of Kalahandi	Interstate join BoB at K- patnam	Chauldua, Phalphalia, Harbhangi, Sanna Nadhi & M-Tanaya;
5	Sarada	122km	2665	Andhra Pr.	Ravipalem Village	Pedderu
6	Nagavali	217	9510	Interstate	Lakh bahal village in Kalahandi	Janjhavati, Vottigedda, Suvarnamukhi, Voni gedda, Champavathi and Peddagedda

13-1. Discussion

Unanimously agreed upon that the EGB Hills located along east coast India, were a part of the Rayner block of Antarctica between 1.0-0.9 Ga BP and 0.6-0.5 Ga BP during Neoproterozoic /Early Paleozoic period (Nasipuri *et al*., 2018).

The portion of Northeastern Ghats Mobile belt (NEGMB) comprises primarily laterites coping, Khondalite, quartzite, granites, patches of Charnockite, and other formations of leptynite, gamet-biotite schists, basic granulite, gneisses, *etc*. underneath. The NEGMB rocks embrace the Precambrian granulite belt in association with anorthosites. The entire expanse is made up of numeral orders of supra-crustal (low-grade) granitic intrusion with or without Banded Iron Formation (BIF) or Bauxite.

The NEGMB between Mahanadi and Godavari graben partitioned by Chilika Lineament consists of many geological features like south Odisha horst, North Odisha Boundary Fault, Bedding planes, and axial plane foliation. The Mahanadi and Godavari stretch accommodate small sloppy serpentine rivers with almost zero or small deltas. They are Rushikulya, Bahuda, Vansadhara, Nagavali, and Sarada, and passing through hilly terrain has flash

1. **Source:** Mishra SP. Thesis, 2016, Integrated Hydrological Data Book CWC, 2012

floods. The upper stretch of the southern fringe of NEGMB has forests, vegetation, and hillocks with few reservoirs that can be converted to potential sources of hydropower. The only drawback is to moderate the flash floods, through proper modeling, (Schismenos *et al.*, 2022).

All types of geological kinks like deep sheeted faults, fractures, folds, and colourations, strike NE-SW-ly. They are found in the rocks of the EGMB. It is of late Proterozoic events (1.0 to 0.8Ga BP), (Mahalick *et al.*, 2022). The Nagavali - Vansadhara Basin shear zones (NVSZ) in western Odisha and the Mahanadi rift structure behave as penetrating points within the Gondwana formations (the Lambert Rift and the Napier Rayner boundary fault (NRBF)) of the Ender by Land of east Antarctica (Chetty *et al*., 2001).

The shear zones in the wide zone of the NEGB hills are affected by several east-west running faults and their fragments. The shear zones, cartoons, and grabens are part of the fault zone. They control the climate, rainfall, fluvial, mineral, igneous, and tectonic activities of the NEGB area where Gondwana graben in which coal-bearing sediments were deposited covering the contacts. The basement for the EGB rocks isotopic and/or litho-tectonic subdivisions of the belt. They indicate UHT metamorphism and timing of juxtaposition of the mobile belt, (Dasgupta, 2019).

The mountains in and around Chilika are part of the EGB range (Sarkar *et al.*, 2012). The mountain Hillocks are rocky and act as spurs to accumulate sediment; physically the Chilika Lineament is separating Chilika into two sectors Southern and northern with the formation of a neck at Krishna Prasad. The rocks of Soleri, Valeri, Magarmunha, Kalijai, Chadheihaga, and Magarmunha islands act as spurs that are reducing in width geospatially.

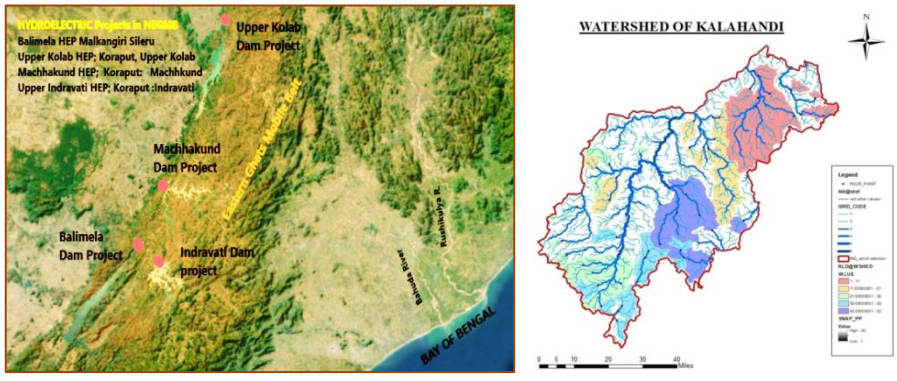

Fig. 11. The number of Hydel projects constructed over NEGMB and a few numbers under planning in NEGB by Odisha.

13-2. The limitations

The northern expanse of NEGMB hills is less inaccessible with poor communication, mostly dwelling places of aboriginals, forests, undulated hillocks, poor transport, etc. The area is lagging behind water resources development due to interstate conflicts, finance, proper governance, and Naxalite dominance. Last two to three decades, the areas have been explored and developed by the government resulting in four hydropower and irrigation infrastructures. Very few published literature are available against the hydropower development in NEGMB Odisha, except state Government sources reflected in Table 5.

Table 5. The active, closed, and under planning and investigation for hydropower generation in EGB mountainous hills of south Odisha[1]

#	Name of the HE power project	River	District	Active project
	Projects in operation			MW
1	Balimela	Sileru	Malkanagiri	510 MW
2	Upper Kolab	Upper Kolab	Koraput	320 MW
3	Upper Indravati	Indravati	Malkanagiri	600 MW
4	Machkund	Sileru	Koraput	60 MW
	About to close Projects			Closed
5	Potteru Small Hydro Electric Project of 1976 (Closed state)	Potteru (Saberi)	Malkanagiri	06MW
	Projects under Planning			(Projected)
6	Middle Kolab Hydro Electric Project (proposed)	Kolab (Jouranallha with Kolab)	Dumajori vil., Koraput	200 MW
7	Tel Integrated Project	Tel tributary	Nawarangapur	50 MW
8	Lower Vansadhara Project	Join Badanallah ofBansadhara	Tovapodar village Rayagada	18 MW
9	Salki Hydroelectric Project	Where salki joins pilasalki	Phulabani	165 MW
10	Khadago Project	Khadgo river at Ghurabali	Kalahandi	100 MW

In addition, OHPC has intended to install a Pumped Storage Power Station (PSPS) at Balimela, Upper Kolab & Upper Indravati Hydro Electric Projects and the status is under survey and investigation. Kalahandi, Koraput, and Malkanagiri have many project sites where reservoirs are possible but at the cost of dense forests. Some waterfalls can be attempted for a multipurpose project. The Odisha Hydro Power Project (OHPC) has planned to exploit the

1. http://www.ohpcltd.com/Home/Projects

water energy sector where amply available. Those districts are in NEGMB's southern fringe areas in Koraput, Kalahandi, and Malkanagiri districts in Odisha.

It is the naked truth that the use of Photo Voltaic to power generation is renewable energy. After 20-25 years, a huge quantity of panels shall be generated non-destructible as e-waste. The Paris agreement in SDG-7, as an affordable and clean energy expansion, cannot find a place for disposal. Geothermal and Hydrogen as the source of renewable energy shall be expensive and difficult to afford economically by underdeveloped countries. The only renewable source is hydroelectric power, which not only solve the energy crisis during the Anthropocene epoch but also save agriculture through irrigation. The statistics for the utilization of water resources in Odisha, employing the topography of NEGMB is an enlightening source.

Landsat TM images, reconnaissance field go over, and the existing geological maps of NEGMB, India, disclose major ductile shear zones (SZ). The SZs exhibit distinct stretching lineation, mylonitic foliation, grain size reduction, signatures of alkaline, metamorphic anorthosites, and granitic magmatism. The terrane distribution in the NEGMB is matching with thrust tectonic, amalgamation, and accretion, (Chetty, 2001; Nanda, 2009).

14. Conclusions

The dams and reservoirs at rivers Upper Kolab, Upper Indravati, and Sabari have been properly utilized across the meandering in the southwestern part of NEGMB as UKHEP, UIHEP, BDP, and Machhakund Power projects. The major rivers originating from Baster, and Dharwar cartoon cannot join north of the Chilika coast to the left fringe of the Godavari Graben for a length of about 382km. These small rivers have no or little delta at their coastal reach with small serpentine rivers causing fast floods and depleting some brackish water lagoons like Chilika, Tampara, and Bendi lagoons. Further large numbers of waterfalls are yet to be exploited like Tirathgada, Chitrkota in Chhattisgarh, Hatipathar, Khasada, and Gandahati needs to be exploited either as tourist hotspots or large reservoir for multipurpose uses.

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