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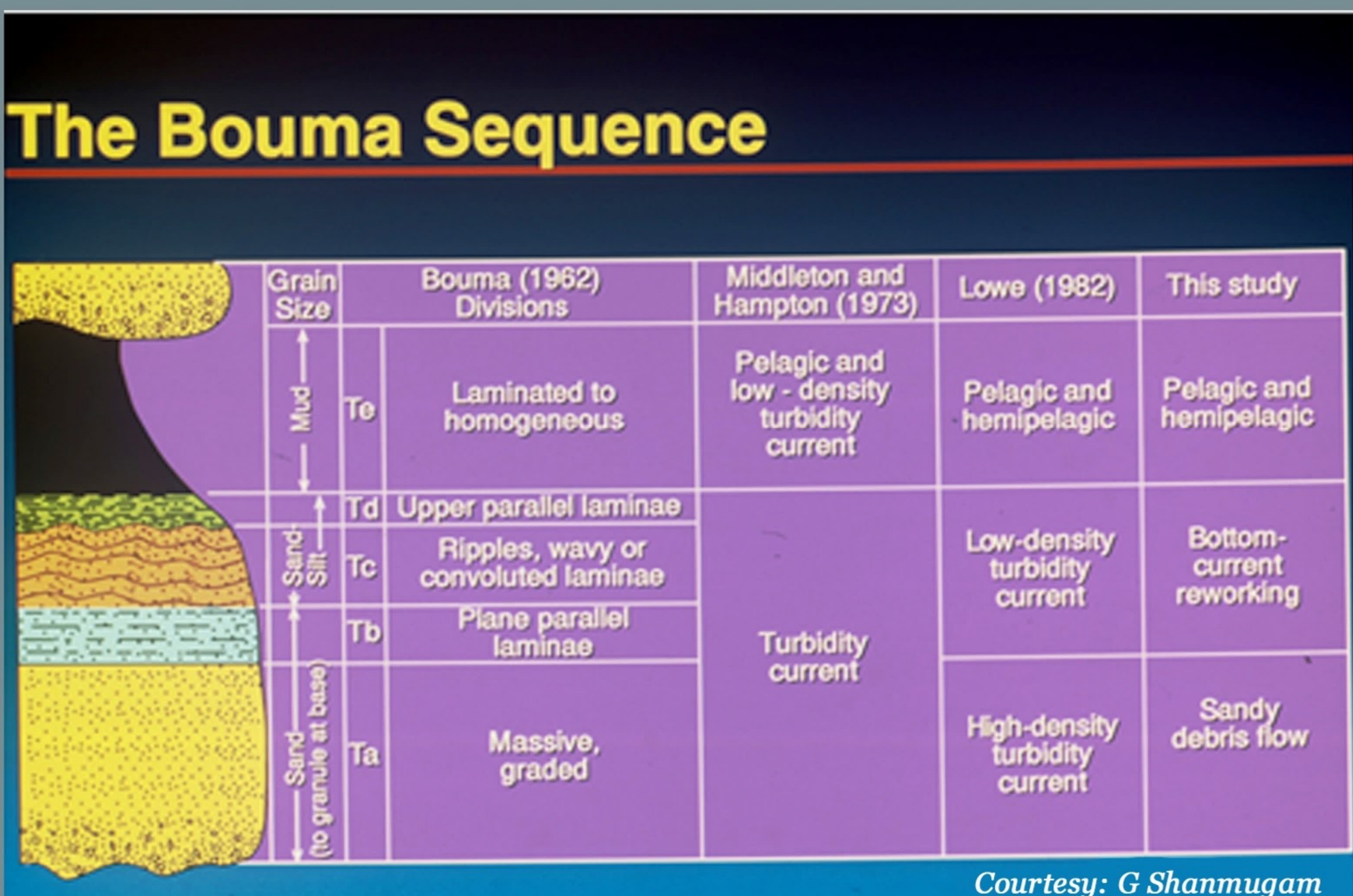

Courtesy: G Shanmugam

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Protection and Conservation of our Geodiversity: Geoheritage Tourism Parks

Earth is endowed with unique geological features which are significant in tracing the expression of its evolutionary history through 4.5 billion years of its age. The chronicals of this evolutionay history are inscribed in these unique physical features (landscapes) providing an insight into earth science. These physical features document evidences of the past narratives of geology, processes of formation of earth, past ecosystems and climate record, and evolution of biotic and abiotic spheres. "Geodiversity" is the major abiotic component supporting landscapes, biodiversity, and ecosystems. Broadly speaking Geodiversity is the geological expression that holds enormous potential with *examples representing major stages of earth's history, including the record of life, significant past and on-going geological processes in the development of landforms, or significant geomorphic or physiographic feature of aesthetic significance*. Studying these elements of Geodiversity allows us to trace the evolutionary history and understand its natural environment for better resources management. Geodiversity of a place is classified as "Geoheritage" site when a certain uniqueness or value is attributed to it. For example, Geoheritage sites encompass significant elements which possess geological, educational, scientific, aesthetic and cultural values.

Societies and cultures have always been influenced by the geology and landscape of site specific regions. For example Indian Subcontinent is blessed with captivating landforms which have played a key role in shaping its civilization and rich cultural diversity. The subcontinent exhibits imprints of varied geological processes evolved through geological ages and is a storehouse of interesting geological features of aesthetic and educational values. India has rich Geodiversity with geophysical attributes, eventful geological history and rich cultural heritage. The diversified territory of India comprises of rocks and landscapes of various geological periods spread over the entire span of geological time scale. It extends right from oldest Eoarchean era to Cenozoic era, including evidences of earliest fossil records from plants, vertebrates, invertebrates and stromatolites. The richness of various rock formations, geophysical features and fossil record, and structural events in the country occur at the diverse geosites offering scientific and aesthetic interest. India exhibits imprints of varied geological processes evolving earth through space and time and is a storehouse of interesting geological features. There is an increasing interest in the development of Geoparks as an initiative aimed at promoting knowledge and earth science education. Efforts are being made for preservation of geological heritage, natural conservation and geo-tourism as an alternative means of local development, particularly in indigenous communities. Geological Survey of India has already enlisted some of those locales as 'National Geological Monuments'**.** But none of the reference stratigraphic sections in the country has been included in this list. The Permian-Triassic boundary sections in Kashmir and Spiti are the best potential sites to qualify for the reference "Stratigraphic Bounday" sections of the world for preservation of the record of mass extinction of "Great Dying" also know as "Mother of Mass Extinctions". The Kashmr section at Guryul Ravine was a candidate for Global Stratotype Sections and Points (GSSP) along with three Chinese sections including Meishan D section in South China (now GSSP for Permian-Triassic boundary) for defining the international geologic time scale. China has established 10 such GSSPs in the country and unfortunately India has none.

The Geoheritage features are vulnerable if once destroyed cannot be recreated. Unique geological landscapes have evolved through millions of years and have witnessed the downfall of several civilizations. In the present age, many anthropogenic activities, natural hazards and climate changes have rendered them vulnerable to rapid deterioration. As a result, much of our landscapes have already been destroyed and many more are likely to be detereorated beyond recognition in the course of development. During the recent years protection of geological and geomorphic features has received appropriate attention inernationally. These efforts of protection and preservation of geological and geophysical features have resuted in newly coined concepts of Geodiversity, Geosites, Geomonuments, and Geoparks.

Preservation of Geodiversity rests in "Geoheritage and Geoconservation". Geoconservation is preservation for heritage, science, or educational purposes and aesthetic values. Geoconservation measures include identification, protection, and management of valuable elements of Geodiversity and their preservation as tourist-friendly educational Geoparks. Internationally, a number of agencies are working for the protection of geo-heritage sites, viz, 1) Global Geoparks Network (GGN) which works under the aegis of UNESCO. GGN provides developmental framework which integrates conservation of geological heritage sites with sustainable economic development. 2) The International Union for Conservation of Nature -

World Commission on Protected Areas (IUCN - WCPA) has a specialised group (Geo-heritage Specialist Group) which assists the conservation and management of protected geoheritage sites. 3) A European agency ProGEO, in association with IUGS & UNESCO is focused on the conservation of the Geological Heritage in Europe. The fourth world conservation Conference (2008) held in Spain was a major mile stone in the efforts of protection and preservation of Geoheritage. In this conference a resolution was adopted by IUCN regarding conservation of Geodiversity and Geoheritage. Folowing this resolution in June 2015, IUCN-WCPA organised its first international Geoheritage conference in China. This conference focused on conservation and management of geoheritage sites and resolved that geoharitage sites be promoted and developed as Geotourism parks.

Tourism plays a major role in showcasing the country's culture internationally. In the Indian context of late, significant initiatives have been taken in promoting tourism even in remotest parts of the country. It is imperative that the tourist map of India should be enriched by the inclusion of the geological monuments, geoheritage sites, reference straigraphic sites and the alike, so that the scientists and tourists from within the country (India) and overseas can have an insight in the geological past - the formation of the landmass, the orogeny, the palaeoenvironment and the paleo - flora and fauna particularly of extinction events preserved in the country across the stratigraphic sequence boundaries. Workshops need to organised for the students, technocrsts and general citizenry focusing on principal objectives of presenting Geoparks from the perspective of UNESCO for the preservation of Geodiversity. We need to generate conscience among local authorities and natural resource managers, about the importance of geo-conservation and how it can become a strategy in local development. We need to encourage the creation of local groups for promotion and creation of Geoparks in the country for conservation of our rich Geodiversity and Geoheritage.

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The Peer-Review Problem: a sedimentological perspective

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Abstract:

Albert Einstein, one of the greatest physicists of all time, had a deep disdain for peer review. The peer-review process, introduced over a thousand years ago in Syria and fully formalized by the Royal Society of London during 1665-1752, is an integral part of quality control in publishing articles and in awarding research grants. However, there are many lingering problems, which include: 1) anointed experts, 2) blind peer reviews, 3) delays, 4) orthodoxy, 5) bias, 6) groupthink, 7) Peer rejection of ideas (including Nobel-Prize winners), 8) inconsistency, 9) politics, 10) fake peer review and plagiarism, 11) "Sham peer review" in the U.S. medical community, 12) settling old scores, 13) online publications, 14) acknowledgements, 15) controversies in geological sciences, and 16) imbalance of peer reviewers in the biomedical research. Transparency, which is the underpinning trait of science journalism, is lost in the secrecy of blind peer review. Under the blind peer review, there are at least eight examples of scientific papers that were rejected before going on to win a Nobel Prize. Furthermore, there are 33 striking cases of peer rejection in science, including the notorious theory of "continental drift" by Alfred Wegener. My own examples of papers in process sedimentology and petroleum geology show that the same manuscript was rejected by one journal, but was accepted by another, suggesting that the blind peer review is obsolete. A solution is to adopt an Open Peer Review (OPR). Barring an open peer review, an alternative path is to publishing the entire peer-review comments and recommended decisions of all reviewers (anonymous and identified) at the end of a paper. This practice not only would force the anonymous reviewer to be objective and accountable but also would allow the entire peer-review process to be transparent.

Keywords: Blind peer review; Fake peer review; Open peer review; Biomedical literature; Nobel-Prize winners; Orthodoxy; Plagiarism; Peer rejection; Bias; Copernicus; Galilei; Oldenberg; The Royal Society; Journal of Sedimentary Research

Introduction

The issue of peer review is much more strident in medical, biomedical, and other natural sciences than in geological sciences. The practice of peer review, since it was first introduced by a physician named Shaq bin Ali al-Rahway of Syria (854-931 CE) (Kelly, 2014), has become a self-regulating mechanism for controlling quality of articles in journals by experts (peers) in a given domain. At present in 2022, journals adopt a double-blind review process in which the identities of both the author and the reviewer are masked in maintaining objectivity. Although popular, the peer-review process is not without problems. For example, Richard Smith, MD, former editor of the British Medical Journal, stated that "So we have little evidence on the effectiveness of peer review, but we have considerable evidence on its defects. In addition to being poor at detecting gross defects and almost useless for detecting fraud it is slow, expensive, profligate of academic time, highly subjective, something of a lottery, prone to bias, and easily abused." Richard Horton (2000), the current Editor-in-Chief of **The Lancet**, a weekly peer-reviewed general medical journal, has written in the **Medical Journal of Australia** that "The mistake, of course, is to have thought that peer review was any more than a crude means of discovering the acceptability - not the validity - of a new finding. Editors and scientists alike insist on the pivotal importance of peer review. We portray peer review to the public as a quasi-sacred process that helps to make science our most objective truth teller. But we know that the system of peer review is biased, unjust, unaccountable, incomplete, easily fixed, often insulting, usually ignorant, occasionally foolish, and frequently wrong."

During the past 50 years, in publishing over 200 peer-reviewed works, I have encountered many peer-review problems in geological journals. The peer review is so deeply entrenched in publishing articles and in awarding research grants; it is impractical to abolish the entire peer-review system today. However, it is possible to improve the system. Therefore, the purpose of this article is to identify inherent problems associated with peer-review process (Wennerås and World, 1997; Ronnie, 2003; Smith, 2006; Scissor, 2016; Jana, 2019, among others) and to provide solutions to improve the current system. However, this article is not a comprehensive review of peer review per se. Furthermore, I have commonly used my own publications and experiences in this review because I am most familiar with them, but geoscientists who publish could probably supply multiple examples of their own. This review is an attempt to explore peer-review problems with a geological/sedimentological perspective.

Historical events

The history of peer review has been discussed by many scholars and publishing organizations (van Rooney et al., 1999; Biagioli, 2002; Spier, 2002; Kennefick, 2005; Benos et al., 2007; Kelly et al., 2014; Shema, 2014; Vyas and Hozain, 2014; Baldwin, 2015, 2019; Belluz and Hoffman, 2015; Scissor, 2016; Dinerstein, 2017; Ronnie and Flanagan, 2018; Jana, 2019; Al-Mousawi, 2020; Elsevier, 2021; Roy, 2021; Wikipedia, 2021; Hoffman, 2022; among others). From these and other sources, I have selected some historical events dealing with scientific development and peer review. Although broad in scope, I have included the birth of some key journals in geological sciences worldwide:

1) **5th Century BCE**: Introduction of the concept of peer review as a method of evaluating written work in ancient Greece (Kelly et al., 2014; Roy, 2021).
2) **25-220 CE**: Documentation of first paper-making process in China (Wikipedia, 2021).
3) **854-931 CE**: First description of the process of peer review by a physician named Shaq bin Ali al-Rahway in Syria. He described in great details the process in his book **Ethics of the Physician** (Al Kawi, 1997; Ajlouni and Al-Khalidi, 1997; Kelly et al., 2014).
4) **1398-1468**: **Johannes Gutenberg** invented the printing press at around 1440, which revolutionized the world in publications (Roy, 2021).
5) **19 February 1473 – 24 May 1543**: **Nicolaus Copernicus** was a mathematician, astronomer, and Catholic canon, who formulated a model of the universe that placed the Sun rather than Earth at its center. His theory was subjected to peer review and rebuked by the Catholic Church (Wikipedia, 2021).
6) 15 February 1564-8 January 1642: Galileo Galilei was an astronomer, physicist and engineer, from Pisa, Italy. Galileo has been called the "father of modern science". His publications were delayed due to peer review. He was under house arrest for heresy until his death (1616-1642} for his following of Copernican theory that the Earth revolves around the Sun. On 31 October 1992, Pope John Paul II acknowledged that the Church had erred in condemning Galileo (Wikipedia, 2021).
7) **1620**: Francis Bacon wrote the work **Novum Organum**, which is considered to be the basis for shaping the Scientific Method (Spier, 2002).
8) **1662**: The birth of **The Royal Society of London** to formalize a system of discussion and debate (Roy, 2021).
9) **1665**: **The Philosophical Transactions** of the Royal Society of London, which was the first journal to introduce steps to formalize the peer review process under the editorship of Henry Oldenburg (Elsevier, 2021), who was the legendary secretary of the Royal Society of London (Baldwin, 2015). During 2015, the journal celebrated the 350th anniversary of **Philosophical Transactions** (now called **the Philosophical Transactions of the Royal Society**). It is considered to be the world's first science journal.
10) **1665**: The Journal **des sçavans** was the first scientific journal to systematically publish research results in France (Liumbruno et al., 2012).
11) **1731**: The first peer-reviewed publication called the **"Medical Essays and Observations"** was published by the Royal Society of Edinburgh (Kelly et al., 2014).
12) **1752**: The Royal Society of London's development of a "Committee on Papers" to

oversee the review of text for publication in the journal **Philosophical Transactions** (Baldwin, 2015). This was the final step in fully formalizing the peer-review process.

13) **1760s**: The French journal **Académie Royale des Sciences** adopted peer review (Al-Mousawi, 2020).
14) **1800**: The birth of the **Library of Congress** (**LC**), which is the national library of the United States. https://www.loc.gov/about/history-of-the-library/# Retrieved 10 December 2021.
15) **1818**: The birth of the "**American Journal of Science"** (**AJS**) at Yale University. With peer review (visit journal website). It has been the United States of America's longest-running scientific journal, having been published continuously since its conception in 1818 by Professor Benjamin Silliman, who edited and financed it himself. Until 1880.
16) **1831**: William Whewell who is considered to be the inventor of peer review by some science historians (Al-Mousawi, 2020). He was also the one who first proposed an open peer review (Roy, 2021).
17) **1823**: The birth of the British medical journal "**The Lancet"** (Elsevier). It is a weekly peer-reviewed general medical journal. It is among the world's oldest and best-known general medical journals. It was founded in 1823 by Thomas Wakley, an English surgeon who named it after the surgical instrument called a lancet (scalpel). https://www.thelancet.com/lancet/about Retrieved 21 December 2021.
18) **1839**: The birth of the "**Proceedings of the Yorkshire Geological Society**" with peer review (visit journal website).
19) **1845**: The birth of the "**Journal of the Geological Society (London)**" with peer review (visit journal website).
20) **1864**: The birth of the "**Geological Magazine**" at the Cambridge University with peer review (visit journal website).
21) **1883**: The birth of the "**Bulletin of the U, S. Geological Survey No. 1**" with peer review (visit journal website).
22) **1890**: The birth of the "**Geological Society of America Bulletin**" with peer review (visit journal website).
23) **1893**: The birth of the "**Journal of Geology"** at the University of Chicago with peer review (visit journal website).
24) 1893: The "**British Medical Journal"** adopted the practice of assessing submitted manuscripts using external referees (Al-Mousawi, 2020).
25) **1896**: The birth of 'The **South African Journal of Geology"** with peer review (visit journal website).
26) **1896**: The birth of 'The **Journal of Geophysical Research"** with peer review (visit journal website). Former names: Terrestrial Magnetism (1896–1898), Terrestrial Magnetism and Atmospheric Electricity (1899–1948)
27) **1912**: The concept of "**Continental Drift",** fully developed by Alfred Wegener (1912), was originally rejected by his peers due to lack of driving mechanism**.** With the advent of plate tectonic mechanisms or sea-floor spreading (Vine and Mathews, 1963), the Wegener's concept was eventually accepted by experts.
28) **1916**: The birth of the journal "**American Mineralogist**" with peer review (visit journal website).
29) **1917**: The birth of the "**AAPG Bulletin**" {American Association of Petroleum Geologists) with peer review (visit journal website).
30) **1931**: The birth of the "**Journal of Sedimentary Petrology**" (1931-1993) with peer review (visit journal website). The journal was renamed to its present name "the **Journal of Sedimentary Research**" by its parent organization SEPM (the Society of Economic Paleontologists and Mineralogists**),** which is currently known as The Society for Sedimentary Geology.
31) **1936**: Albert Einstein was extremely offended that his manuscript was sent out to be refereed by the editor of **Physical Review (**John T. Tate). Einstein withdrew the manuscript protesting that he had not authorized the editor to do so with a strongly worded letter (see Kennefick, 2015).
32) 1940: The "**Journal of the American Medical Association**" (JAMA) started to use outside referees (Roy, 2021).

33) 1945: The birth of the "**Geological Survey of Canada's Bulletin**" "GEOSCAN" with peer review (visit journal website).
34) **1950**: The birth of the journal "**Geochimica et Cosmochimica Acta"** (Elsevier) with peer review (visit journal website).
35) **1951**: The birth of the "**Geological Journal**" (Wiley) with peer review (visit journal website).
36) **1952**: The "**Joint Commission on Accreditation of Healthcare Organizations"** (JCAHO). This act began requiring physician peer review at all United States hospitals (Goldberg, 1984). However, abuse of peer review has persisted.
37) **1953**: The birth of the journal "**Dee-Sea Research**" with peer review (visit journal website).
38) **1962**: The birth of the journal "**Sedimentology**" (Wiley) with peer review (visit journal website).
39) **1964**: The birth of the journal "**Marine Geology**" (Elsevier) with peer review (visit journal website).
40) **1965**: The birth of the "**Scottish Journal of Geology**" with peer review (visit journal website).
41) **1966**: The birth of the journal "**Earth-Science Reviews**" (Elsevier) with peer review (visit journal website).
42) **1966**: The birth of the journal "Earth **and Planetary Science Letters**" (Elsevier) with peer review (visit journal website).
43) **1967**: The birth of the journal "**Sedimentary Geology**" (Elsevier) with peer review (visit journal website).
44) **1973**: The birth of the journal "**Geology**" (GSA) with peer review (visit journal website).
45) **1973**: The journal **"Nature"** introduced external peer review (Baldwin, 2015).
46) **1976**: The journal **"The Lancet"** introduced external peer review (Al-Mousawi, 2020).
47) **1984**: The birth of the journal "**Marine and Petroleum Geology**" (Elsevier) with peer review (visit journal website).
48) **1986**: The "**Health Care Quality Improvement Act"** (HCQIA). In order to legislatively strengthen the role of peer review in the medical community across the United States, the U. S. Congress enacted the **HCQIA** (Curran, 1989). However, abuse of peer review has persisted.
49) **1988**: The birth of the journal "**Natural Hazards**" (Springer Nature) with peer review (visit journal website).
50) **1989**: The birth of the **World Wide Web** (Wikipedia, 2021).
51) **2006:** The birth of PLOS **One**, which is a peer-reviewed open access scientific journal published by the Public Library of Science (PLOS). The journal covers primary research from any discipline within science and medicine (visit journal website).
52) **2008**: The birth of the journal "**Petroleum Exploration and Development**" (PED) (Elsevier) with peer review started in 2009.
53) **2011**: The UK Government House of Commons Science and Technology Committee's report on **peer review system** for academic publications was published on 28 July 2011 (The Geological Society, 2011).
54) **2012**: The birth of the "**Journal of Palaeogeography**" (Elsevier) with peer review (visit journal website).
55) **2014**: The birth of **F1000Research, which** is an open access, open peer-review scientific publishing platform, covering the life sciences, owned by Taylor & Francis (visit platform website).
56) **2017:** Emergent and future innovations in peer review (Tenant et al., 2017).
57) **2018**: The birth of the "**Journal of the Indian Association of Sedimentologists**" (**JIAS**) with peer review (visit journal website).
58) **2022**: The **Ninth Peer Review Congress** in September 2022. According to Veronique Kiermer, Chief Scientific Officer, PLOS, every four year since 1989, the **Peer Review Congress** has brought together researchers, journal editors and all those who participate in the reporting and publication of scientific research, in order to share their own data and processes under scrutiny openly by peers. https://theplosblog.plos.org/2021/09/ninth-international-congress-on-peer-review-and-scientific-publication-call-for-abstracts/ Retrieved 11 December 2021.

Peer-review problems

Peer review is the underpinning quality-control mechanism in publishing articles and awarding grants. It is imperative that this process is not tainted by reviewer bias. Unfortunately, "History is replete with evidences of many important, original and innovative papers, many of which even earned the **Nobel Prize** as well at a later time, which had been rejected by the referees under peer review system" (Roy, 2021). Richard Horton (2015), the current Editor-in-Chief of The Lancet, stated that "The case against science is straightforward: much of the scientific literature, perhaps half, may simply be untrue. Afflicted by studies with small sample sizes, tiny effects, invalid exploratory analyses, and flagrant conflicts of interest, together with an obsession for pursuing fashionable trends of dubious importance, science has taken a turn towards darkness". Although there are many issues associated with the quality of science publications compounded by peer-review problems, I have selected the following key ones for this review:

Anointed experts

The problem with peer review stems from the basic question "Who are reviewers?" Ronnie and Flanagin (2018) answered the question as "Editors like anointing colleagues as experts, reviewers appreciate peer review because it tends to confirm their own impressions of themselves as experts, and no one has created a better system to vet the validity of scientific reports. Authors may complain but also may be grateful for expert appraisal and criticism and subsequent improvement in their manuscripts. They realize that their work has been taken seriously and recognize that the incorporation of reviewers democratizes beyond the editor this part of the scientific enterprise." In other words, there are no standard tests to qualify one as being an expert reviewer in a given field. The selection process of a reviewer by an editor is mostly subjective. A related problem is that once someone is anointed to be an editorial board member of a journal for a specific field (e.g., deep-water environments), he or she may be asked to review a manuscript on an unrelated field (e.g., carbonate diagenesis) depending on circumstances and the need. In such cases, the reviewer tends to focus on mundane matters, such as a manuscript failing to adhere to journal format, missing references, typos, etc. than dealing with science content. But under the blind peer review system, the reader will never know the true expertise of the blind reviewer. Here, the science (quality) suffers.

Blind peer review

The two common modes of peer review are single- and double-blind reviews. In the single-blind peer review, the authors do not know the identity of the reviewers, but the reviewers know who the authors are. In the double-blind peer review, neither the authors nor the reviewers know each other's identities. The single-blind peer review is the traditional mode. However, the double-blind mode is also common. According to Al-Mousawi (2020), the first peer-reviewed publication is considered to be the "Medical Essays and Observations" published by the Royal Society of Edinburgh in 1731. The society adhered to the following peer-review process: "Memoirs sent by correspondence are distributed

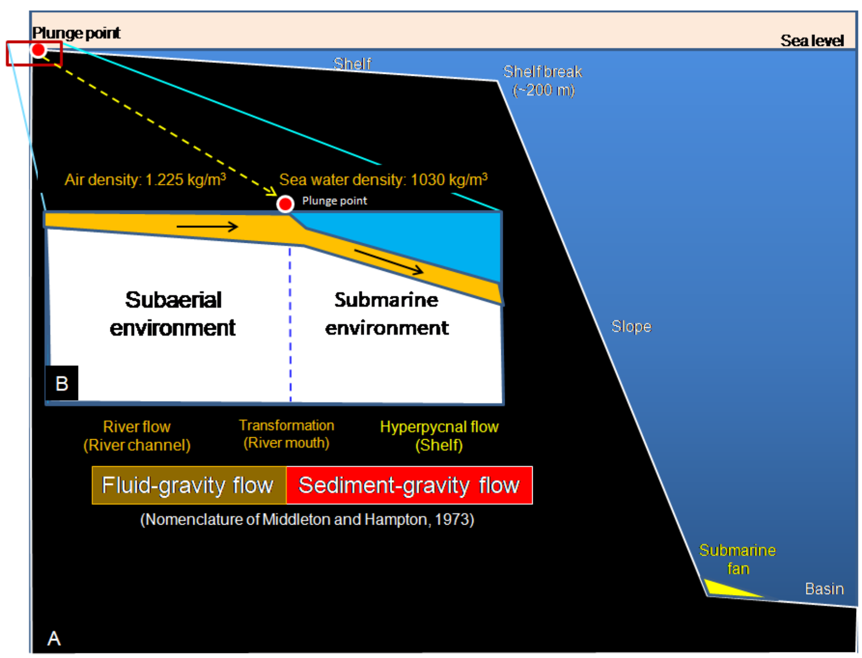

Figure 1. Generation of hyperpycnal flows near the shoreline. A. Continental margin. B. Close-up view showing plunge point (red dot) and hyperpycnal flows near the shoreline. From Shanmugam {2021a). Open Access.

according to the subject matter to those members who are most versed in these matters. The report of their identity is not known to the author.” This publication appears to be the birth of blind peer review.

Although the intention behind the double-blind review is good, in practice, it is dysfunctional. For example, Shanmugam (2021a) published an article on deep-water processes in the Journal of Palaeogeography. It was subjected to the double-blind review. However, the author has 23 self-citations, which were necessary in covering the past contributions. In this case, the reviewer should have known that the anonymous author is likely to be “Shanmugam”. Similarly, anonymous reviewers often suggest that the author should cite certain articles published by the reviewer, revealing his/her identity to the author. Another common practice is to use the “Track changes” menu in a Microsoft Word document by a blind reviewer. However, under this menu, some reviewers unwittingly reveal their identities by their initials or nick names posted along with their comments. In the 70s and 80s, I used to detect the identity of an anonymous reviewer by his or her handwriting styles using review comments by a pen posted on the manuscript paper pages. According to Benos et al. (2007), “Removing an author's name cannot remove biases against unconventional methodology, radical new ideas, negative results, or results that contradict a reviewer's viewpoints.” Clearly, the blind peer review system is defective. A solution is to abolish the blind peer review altogether and adopt an open peer review. All future peer reviews must be transparent in which both authors and reviewers must be identified by name with e-mail address and phone numbers during the peer review. Such a transparent world is critical for creating an academic environment, which would allow authors and reviewers to communicate openly with each other as amicable colleagues, not as adversaries.

The "Toruń portrait" (anonymous, c. 1580) Poland

1636 portrait by Justus Sustermans Italy

Figure 2. Portraits of Nicolaus Copernicus (1473-1543) and Galileo Galilei (1564-1642). Wikipedia (2021). Public Domain.

Delays

Although most journals have a set time limit of 2 to 3 weeks for review of an article, some reviewers take up to six months. Let me provide an example from my archives of delayed manuscripts. I submitted a comment on a paper by Steel et al. (2016) to the GSA Bulletin on May 22, 2017 (MS # 831848). My comment, which dealt with hyperpycnal flows and hyperpycnites, was entitled “Highstand shelf fans: The role of buoyancy reversal in the deposition of a new type of shelf sand body: Comment.” On August 28, 2017, I contacted the GSA Bulletin office to find out the status of my manuscript. The journal office informed me that the editor-in-charge (anonymous) was too busy with other matters and did not have a chance to send my manuscript out for a peer-review. Because most journals reach a decision to accept or reject in three months after submission, I promptly withdrew my manuscript from GSA from further consideration. This disappointing event was the incentive for me to conduct a comprehensive study of hyperpycnal flows at river mouths around the world, including the Yellow and Yangtze Rivers in China.

I have published a review article entitled “The hyperpycnite problem” (Shanmugam, 2018), which included my main points from the withdrawn manuscript (Fig. 1). My review article, “The hyperpycnite problem,” had resulted in my publishing four other offshoot publications, including a book chapter (Shanmugam, 2021b). This is an example of turning obstacles into opportunities!

Orthodoxy

Historically, negative peer reviews of scientific works had resulted in serious penalties, including house arrests and even deaths. Dinerstein (2017) articulated the problem of failing to preserve the orthodoxy of the time with the following statement: "When Guttenberg's press created the opportunity for scientific information to be more widely shared it was followed, eventually, by one of the earliest forms of peer review – scientific criticism by the Church. Copernicus and Galileo both underwent an early form of peer review, and their work was even banned, Copernicus for four years and Galileo's work until 1758, when telescopes better proved heliocentricity (it was proved beyond doubt in 1838.) Their peer review ordeal was relatively tame compared to Miguel Servatus, who was burned at the stake for his beliefs about the Trinity. He was later applauded for his work understanding pulmonary circulation, the idea that blood from the right side of the heart traveled through the lungs to the left side of the heart." (Fig. 2).

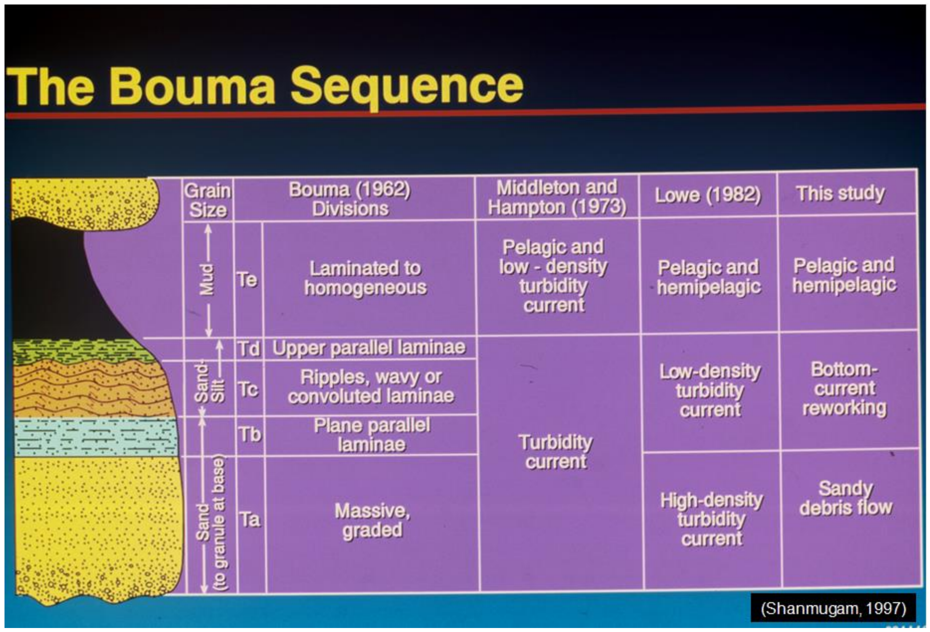

Figure 3. The Bouma Sequence. Note differences in interpretations. From Shanmugam (1997). This turbidite facies model is obsolete (Shanmugam, 2021a).

In the 21st century, peer-review related penalties are much less severe, confining to rejection of manuscripts (Section 3.7), rejection of funding grants, and retraction of published articles (Section 3.10). For example, the geologic orthodoxy in North America was that the Ouachita Flysch was composed of turbidites (Briggs and Cline, 1967). However, our (Shanmugam and Moiola, 1995) controversial reinterpretation of it as debrites was originally rejected by the GSA Bulletin, but was later accepted by the AAPG Bulletin. Not surprisingly, this paper had resulted in 42 printed pages of discussions and replies in the AAPG Bulletin by some of the leading authorities in the field, which included:

Bouma et al. (1997)
Coleman (1997)
D'Agostino and Jordan (1997)
Lowe (1997)
Slatt et al. (1997).

We promptly responded (Shanmugam and Moiola, 1997). No other paper in the history of the AAPG Bulletin, since its founding in 1917, has generated this much controversy.

Bias

Peer-review bias against women has been well documented. Christine Wennerås and Agnes World (1997), in the first-ever analysis of peer-review scores for postdoctoral fellowship applications in Sweden, have shown that the system is riddled with prejudice. For example, women were awarded 44% of biomedical PhDs but held a mere 25% of the postdoctoral positions and only 7% of professorial positions. The authors argued that the policy of secrecy in peer-review evaluation must be abandoned.

According to Smith (2006), the editorial peer review process has been strongly biased against `negative studies' (i.e. studies that find flaws with a certain popular concept or model). Importantly, reviewers have their own bias against certain authors and/or concepts. Let me provide a personal experience on this matter. Arnold H. Bouma (1962) used the Annot Sandstone [Grès d' Annot Formation (Eocene–Oligocene)], exposed in the Peira-Cava Area and vicinity of the French Maritime Alps, for developing the first turbidite facies model. This model is popularly known as "the Bouma Sequence" (Fig. 3). In questioning the basic tenet of the model, I submitted a manuscript entitled “The Bouma Sequence and the turbidite mind set” to the AAPG Bulletin. The Bulletin selected A. H. Bouma as the reviewer who promptly rejected the manuscript. Then, I submitted the same manuscript to Earth-Science Reviews (ESR). G. M. Friedman, who was the Editor of ESR, selected J. E. Sanders as the reviewer who accepted my paper (Shanmugam, 1997; Sanders 1965) is a pioneer in turbidite research. The point is that selection of unbiased reviewers is paramount in securing effective peer-review comments.

Groupthink

Groupthink, closely related to bias discussed above, is in direct conflict with scientific progress. This is because that scientific progress is often made by departing from conventional wisdom. Conventional wisdom, however, often dictates what is being published by major scientific journals today; geologic publications are no exception. Thus, conventional wisdom can have negative effects on the peer-review process and on scientific progress.

Revolutions in the thinking on continental drift (Wegener, 1912), terrestrial sources for oil in Australia (Shanmugam, 1985), fan deltas and braid deltas (McPherson et al., 1987), chert dissolution along erosional unconformities in Alaska (Shanmugam and Higgins, 1988), ten turbidite myths (Shanmugam, 2002), sedimentary basins (Shanmugam, 20222a), and groupthink on deep-sea research (Shanmugam, 2022b) are just seven of many examples where conventional geologic wisdom has proved to be wrong. Progress in science is made through the introduction and successful testing of new ideas, many of which are bound to displace and overthrow conventional ideas. Unfortunately, many reviewers are so tied to the conventional wisdom that they feel duty-bound to go to extraordinary measures to find reasons for rejecting a manuscript with unconventional ideas (Shanmugam, 1986).

Steve Jobs, the co-founder of Apple Computer, who said that “Your time is limited, so don’t waste it living someone else’s life. Don’t be trapped by dogma – which is living with the results of other people’s thinking. Don’t let the noise of other’s opinions drown out your own inner voice. And most important, have the courage to follow your heart and intuition. They somehow already know what you truly want to become. Everything else is secondary.” https://www.managingcommunities.com/2009/05/25/steve-jobs-dont-be-trapped-by-dogma-which-is-living-with-the-results-of-other-peoples-thinking/ Retrieved 22 December 2021.

Peer rejection of ideas (including Nobel-prize winners)

Braben (2020) in his book “Scientific Freedom” makes a convincing argument that the process of peer review is the primary obstacle for breakthrough ideas in science. In supporting this notion, Ricón (2020) has compiled 33 striking cases of peer rejection in science, including the theory of “continental drift” by Alfred Wegener. These cases were originally rejected during peer review, but were subsequently accepted by the science community. Selected examples are:

1) The ornithine cycle,
2) Jet engines,
3) mRNA vaccines,
4) Airplanes,
5) The structure of DNA,
6) Nuclear Magnetic Resonance (NMR) (see below under Nobel Prize),
7) Lasers,
8) Clustering analysis,
9) Continental drift, and
10) Darwinism.

in addition, there are scientific papers that were rejected by journals before going on to win a Nobel prize. Selected examples are (Macdonald, 2016; Efron, 2019):

1) **Hans Krebs**: Won the 1937 Nobel Prize for citric acid cycle. His paper was previously rejected by Nature, but he resubmitted it to the Dutch journal Enzymologia, which published the paper;
2) **Enrico Fermi**: Won the 1938 Nobel Prize for weak interaction. His paper was previously rejected by Nature, but he resubmitted it to the German journal Zeitschrift für Physik, which published his work.
3) **Murray Gell-Mann**: Won the 1953 Nobel Prize for classifying the elementary particles. His paper was previously rejected by Physical Review.
4) **Rosalyn Yalow**: Won the 1977 Nobel Prize for radioimmunoassay. Her paper

was previously rejected by The Journal of Clinical Investigation, but she persisted and later submitted a revised version of the paper to the same journal.

5) **Richard Ernst**: Won the 1991 Nobel Prize for describing nuclear magnetic resonance (NMR) spectroscopy (NMR spectroscopy). His paper was previously rejected twice by the Journal of Chemical Physics, before finally being accepted and published in the Review of Scientific Instruments.
6) **Kary Mullis**: Won (jointly) the 1993 Nobel Prize for polymerase chain reaction (PCR) method. His paper was previously rejected by two journals, namely Science and Nature. Finally, he resubmitted it to the journal Methods in Enzymology and got it published.
7) **Dan Shechtman**: Won the 2011 Nobel Prize for quasicrystals. His paper was previously rejected by Physical Review Letters. He then submitted his work to the journal Metallurgic Transactions, which published the paper
8) **Peter Higgs**: Won the 2013 Nobel Prize for the Higgs Model. His paper was previously rejected by Physics Letters. He then resubmitted it to the journal Physical Review, and got it published.

Throughout this article, I have cited examples of my own papers that were originally rejected by one journal, but were subsequently accepted by another. There is no logic to this bizarre phenomenon in peer review of articles. Nathan Efron (2019) in his editorial entitled "The shame of rejection (not)" to Clinical and Experimental Optometry explained this phenomenon best: "There are two morals of this story. First, it must be remembered that 'beauty is in the eye of the beholder'. Translated into journal peer review-speak – the scientific worth of a paper will be viewed differently by different reviewers. Just because a paper is rejected does not necessarily mean it is worthless… which brings me to the second, consequential moral: if your paper is rejected by Clinical and Experimental Optometry – or any other journal for that matter – do not despair; just shrug your shoulders, draw in a deep breath, take note of the comments of the reviewers of your paper, and submit elsewhere. You never know what might happen next." In other words, peer review is nothing more than a sophisticated gambling in the game of publications!

The corollary to peer rejection, of course, is equally puzzling. For example, the same reviewers who rejected papers of Nobel-Prize winning caliber were also the ones who accepted other papers for publications. Some of those published papers probably went on to win "outstanding paper" awards!

Inconsistency

In peer-review process, it is a common occurrence that two journals or two reviewers for the same journal can reach opposing decisions, one to accept the manuscript and the other to reject the manuscript. A classic case of opposing decisions

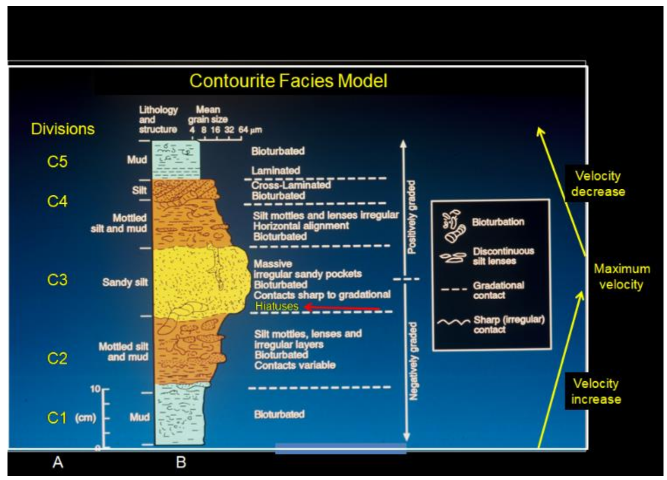

Figure 4. (A) Revised contourite facies model with five divisions (C1–C5) proposed by Stow and Faugères (2008); (B) Original contourite facies model by Gonthier et al. (1984). From Shanmugam (2016). This contourite facies model is obsolete (Shanmugam, 2021a). Fair usage.

between two journals occurred to my manuscript on "Manganese distribution in the carbonate fraction of shallow and deep marine lithofacies, Middle Ordovician, eastern Tennessee" (Shanmugam and Benedict, 1983). First, an SEPM journal rejected it. Second, an Elsevier journal accepted it as submitted without revision.

Second example is a paper on "The landslide problem". It was rejected by the Journal of Sedimentary Research, but was accepted by the Jounal of Palaeogeography (Shanmugam, 2015).

Third example is a paper on "The contourite problem" (Fig. 4). It was rejected by the AAPG

Bulletin, but was accepted as a book chapter by Elsevier (Shanmugam, 2016). Sometimes, a rejection can be used turn an obstacle into an opportunity. For example, at the time when the AAPG Bulletin rejected my paper, I received an invitation to contribute a book chapter to the thematic volume "“Sediment provenance”, edited by Rajat Mazumder (2016). His invitation provided me an opportunity to discuss the significance of deep-water bottom currents and their current directions in interpreting provenance of ancient contourites. I simply added this part on provenance to the rejected paper and got it published as a book chapter.

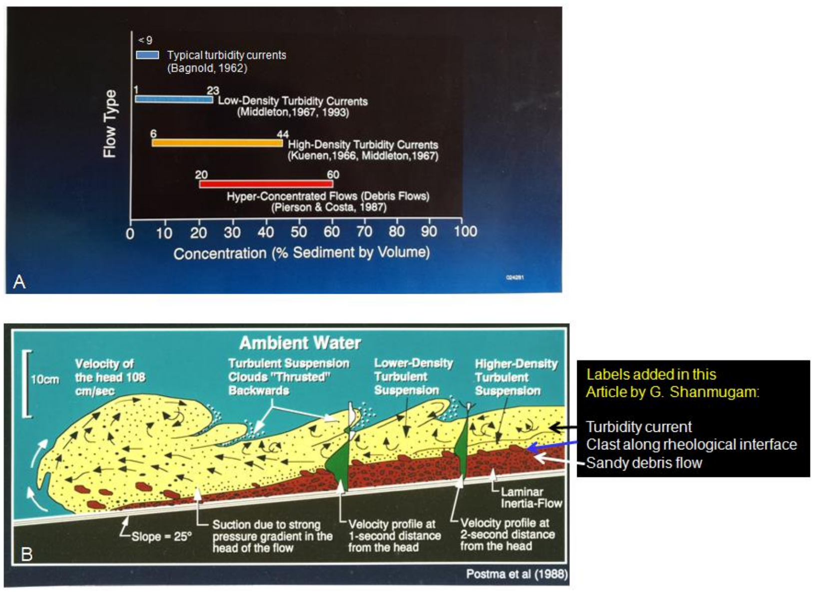

Figure 5. (A) Plot of sediment concentration for different flow types. Note overlap in sediment concentration among low-density, turbidity currents, high-density turbidity currents, and hyperconcentrated flows or debris flows. (B) Experimental stratified flows with a basal laminar-inertia flow and an upper (turbulent) turbidity current that have been termed as "high-density turbidity currents" (HDTC) by Postma et al. (1988). From Shanmugam (2021a). Fair usage.

My fourth example is a paper entitled 'High-density turbidity currents: are they sandy debris flows?' (Fig. 5) (Shanmugam, 1996). As the title suggests that the paper is highly controversial. Prof. John Southard (1995, MIT), who was the editor of the Journal of Sedimentary Research, decided to publish the paper despite mixed reviews (one positive and one negative). Southard informed me that this paper should trigger several academic debates and that should bring some clarity to the controversy. However, no one debated the issue. Six years after its publication, a survey was published by the International Association of Sedimentologists (IAS). Accordingly, my paper 'High-density turbidity currents: are they sandy debris flows?' had achieved the status of the single most cited paper in sedimentological research published in three world-renowned periodicals - Journal of Sedimentary Research, Sedimentology, and Sedimentary Geology - during the survey period of 1996-2003 (Source: International Association of Sedimentologists Newsletter, August 2003) (Racki, 2003). Researchers, who had spent several years on conducting studies on a topic and on writing a paper, are simply not going to discard the paper just because it was rejected by a journal. In my case, all rejected papers got published.

The fourth example raises some serious doubts about the peer-review process. The editor could have simply rejected the manuscript, which would have deprived the reader of this concept. This example also stresses the importance of the editor who should possess adequate knowledge on a given topic to make meaningful decisions on manuscripts with mixed reviews. Fortunately, the editor (Southard) happened to be a world-renowned expert on fluid mechanics (Middleton and Southard, 1977) and who held a full professorship at the Massachusetts Institute of Technology (MIT), when he handled my manuscript. Unfortunately, most editors simply perform a managerial task of assembling review comments and making an obvious decision. Also, it is unrealistic to expect an editor to be an expert on many fields.

Politics

The phenomenon of "Climate change" has become a formidable political force in controlling articles to be published and in awarding research grants. For example, articles and research proposals that do not favor climate change are likely to be rejected during the peer-review process. Scholars have addressed this phenomenon both in government testimony and in publications (Lindzen, 2010; Van der lingen, 2018).

Fake peer review and plagiarism

Gao and Zhou (2017) addressed the issue of fake peer review in science journals. For example, this scheme works in steps:

1) Fake or fraudulent peer review can result when editors rely on authors' recommended reviewers.
2) Although the recommended reviewer names are genuine but they have a fake e-mail address that only the author knows.
3) Consequently, the fake e-mail ID enables the authors to write a favorable review of their own paper.

Recently, Springer Nature geosciences journal has retracted 44 articles filled with gibberish. Most of them had questionable peer-review practices. An example of a nonsensical published article title is: "Distribution of earthquake activity in mountain area based on embedded system and physical fitness detection of basketball." This title is truly absurd. https://retractionwatch.com/2021/11/04/springer-nature-geosciences-journal-retracts-44-articles-filled-with-gibberish/ Retrieved 1 December, 2021

Blind peer reviews provide an ideal ground for stealing intellectual properties in terms of raw data and ideas. Plagiarism and fraud cases have been discussed elsewhere (Benos et al., 2007; Triggle and Triggle, 2017; Al-Khatibb, 2019).

"Sham peer review" in the U.S. medical community

Despite the passing of various government acts, such as **JCAHO** in 1952 and **HCQIA** in 1986, In the United States (see Sction 2), there has been a significant abuse of peer review process in the medical community. This perversion is called "Sham peer review" (Pfifferling et al., 2008). Vyas and Hozain (2014) discussed the history behind "sham peer review". This is a review called for by either a single, or group of physicians, conducted in order to lead to adverse action taken by the review committee.

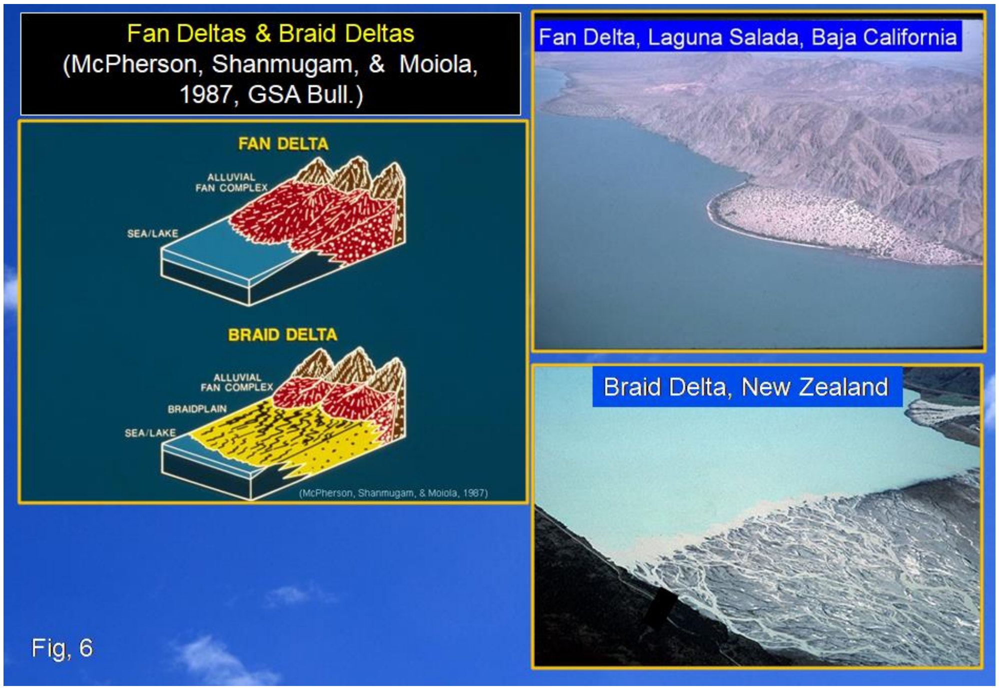

Figure 6. Distinction between fan deltas and braid deltas near the shoreline. Photographs are courtesy of J. G. McPherson.

Settling old scores

The phrase simply means to harm someone because they have harmed you in the past: Reviewers often use the blind-review to settle some old scores with their opponents. For example, McPherson, Shanmugam, and Moiola (1987) submitted a manuscript on "Fan deltas and Braid deltas" to GSA Bulletin. An anonymous reviewer of the manuscript had some strong comments about my papers on deep-water turbidites that I published in other journals earlier. Ironically, those review comments were totally irrelevant to the manuscript under review on shallow-water fan deltas and braid deltas (Fig. 6). It is worth noting that our paper on braid deltas has become one of the most cited papers on deltas.

Online publications

During the last decade, there has been a proliferation of online journals and blogs. The COVID-19 lockdowns have further accelerated online publications and Zoom conferences. The problem is that unlike the conventional print journals with established editorial boards and methods, the details of online journals and their peer-review methods are not always transparent. Plus, one can post an article, without peer review, on online platforms, such as Research Gate. The relative ease with which one can publish new ideas online quickly has attracted potential authors to online journals. This diversion of contributions from print journals to online journals seems to dilute the overall quality of articles in some cases. On the other hand, there are good quality online publications (e.g., Kelly et al., 2014; Kirkland, 2014; Belluz and Hoffman, 2015; Tennant et al., 2017; Baldwin, 2019; Al-Mousawi, 2020; Roy, 2021; among others). The advantages of online publications are that they are not only fast but also free. In both print and online publications, quality matters.

Acknowledgements

Peer review is a serious and time-consuming endeavor. In some cases, I have spent two or three full days in reviewing a manuscript. Let me cite two examples from which I benefited, namely Shanmugam (2012a and 2022c). The 2012a article was on “Paleo-tsunami deposits” and the 2022 book review was on “River Planet by Martin Gibling”. In each case, two anonymous reviewers were involved. These four reviewers were prompt, thorough, and provided detailed review comments. Consequently, the quality of my two publications improved considerably. Unfortunately, I could not acknowledge them by their names because they remained anonymous. It’s a pity!

Controversies in geological sciences

Interpretations of geologic units dating back millions of years are, by design, likely to yield differences of opinions and controversies. Not surprisingly, I have participated in 38 published academic discussions and replies during the past 38 years. All of them were peer-reviewed (Shanmugam, 2021b, his Table 6.3). In addition, I have commented on two articles published in the Earth-Science Reviews in 2022 (Shanmugam, 2022d, e). Clearly, it is problematic to expect an objective peer review on a controversial paper under the conventional blind peer review. On the other hand, academic discussions are a viable solution to the prevailing peer-review problems.

Imbalance of peer reviewers in the biomedical research

In a French study of peer review in the biomedical literature, Kovanis et al. (2016) have reported the following key points that are relevant to the theme of my article:

1) Surprisingly, 20% of the researchers performed 69% to 94% of the reviews.
2) Among researchers actually contributing to peer review, 70% dedicated 1% or less of their research work-time to peer review while 5% dedicated 13% or more of it.
3) An estimated 63.4 million hours were devoted to peer review in 2015, among which 18.9 million hours were provided by the top 5% contributing reviewers.
4) There is a considerable imbalance in the distribution of the peer-review effort across the scientific community.
5) Finally, various individual interactions between authors, editors and reviewers may reduce to some extent the number of reviewers who are available to editors at any point.

In summary, this study by Kovanis et al. (2016) suggests that only a small group of the available experts were doing most of the peer review in biomedical research. Such an imbalance of peer reviewers could explain the deficiency of quality in peer review.

A solution: Open Peer Review (OPR)

The basic tenet of science, which is discovering truth, requires scientists to be fully transparent. In this context, Al-Mousawi (2020) stated that “Looking ahead, I believe the focus on transparency in peer review will gain even more momentum and will soon become the ‘norm. Innovations will be contingent on what technology is available, but in the end, I believe the biggest hurdle we still need to overcome is a cultural one. There is still a lot of resistance from a small proportion of the research community towards transparency, and it will naturally take time to alleviate their fears around a fully transparent process.” Similarly, the Public

Library of Science (PLOS} also advocates "Open Peer Review" (OPR) because it promotes (1) quality, (2) enrichment, (3) credit, and (4) accountability in advancing science (Chen, 2021). For example**, F1000Research** is an open access, open peer-review scientific publishing platform covering the life sciences (see Al-Mousawi, 2020). In this process/model, the peer reviewer's names and comments are visible on the site. As part of its open science model, the data behind each article are also published and are downloadable.

Today, many scholarly journals employ versions of Open Peer Review in their day-to-day practice, including BMJ, BMC, Royal Society Open Science, Nature Communications, the PLOS journals, among others. Wolfram et al. (2020) have documented that the growth of Open Peer Review (OPR) journals by discipline groups is improving, in particular, the growth of Medical and Health Sciences among the science group since 2017 (Fig. 7). However, Journals in geological sciences are still reluctant to adopt OPR. Selected publishers of OPR journals are:

1) MDPI (Multidisciplinary Digital Publishing Institute) (Switzerland),
2) SDI (Solitaire Diamond Institute) (India),
3) BMC (BioMed Central) (UK),
4) Frontiers Media S.A. (Switzerland),
5) Kowsar (The Netherlands),
6) Wiley (USA),
7) Copernicus publications (Germany),
8) PLOS (Public Library of Science) (USA),
9) Elsevier (The Netherlands), and
10) EMBO (The European Molecular Biology Organization) Press (Germany).

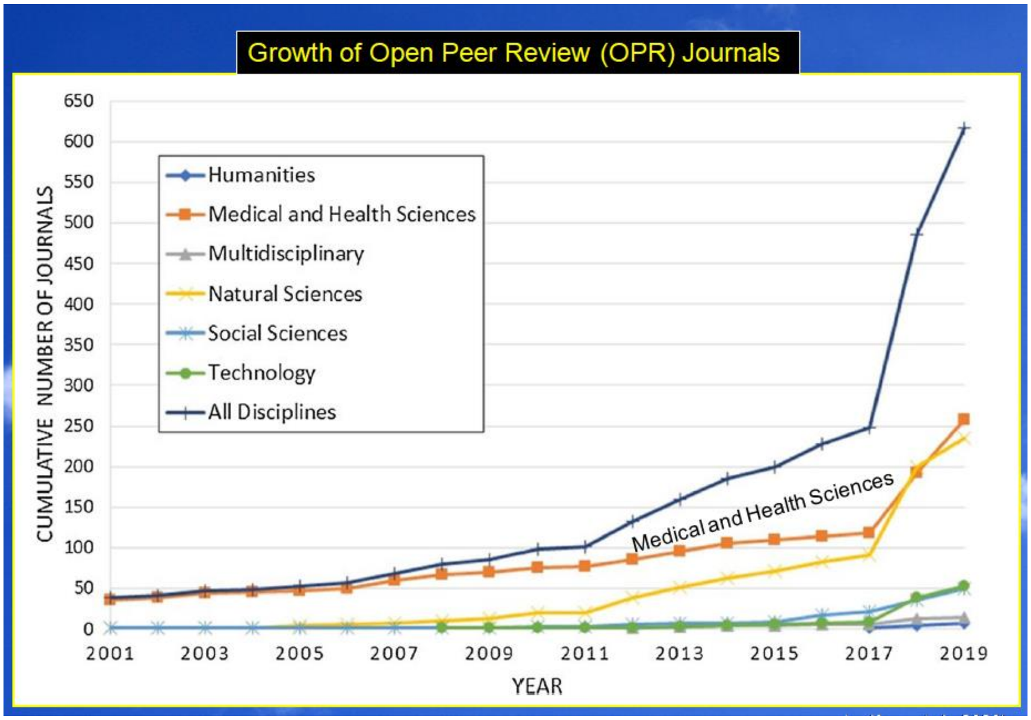

Figure 7. Growth of Open Peer Review (OPR) journals by discipline groups. Note the growth of Medical and Health Sciences since 2017. From Wolfram et al. (2020).

Although an open peer review is nothing new (McGiffert, 1988; Van Rooney et al., 1999), there has been resistance. One reason is the fear of retaliation. For example, there could be negative career consequences for critical reviewers who happen to be junior researchers and who depend on research grants. However, such fears are not supported by data (Justice et al., 1988; Van Rooyen et al., 1988).

Until we overcome this obstacle, an interim alternative is to make some improvements to existing peer-review process.

Suggested steps for improvements

1. In the published paper, the entire peer-review comments and recommended decisions of anonymous reviewers should be published at the end of a paper as "History of peer review".
2. This would force the anonymous reviewer to be objective and accountable for his or her comments and recommendations.
3. This would also allow the author to respond precisely to comments made point-by-point by the reviewer.

4. Most importantly, this would allow the reader to appreciate the entire review history from both sides, namely the reviewer side and the author side.

Open Peer Review (OPR) should not be confused with Open Access (OA) journals. They are not one and the same. OPR deals with the review process of an article in a journal whereas OA refers to the availability of an article in a journal. For example, an article accepted under blind review process can be published under OA.

Application of OPR in Petroleum Exploration

The Open Peer Review (OPR) has direct application to petroleum exploration. I know well from my years with Mobil Oil Company (1978-2000), petroleum exploration in frontier areas is a challenging business that requires the best and innovative ideas from everyone involved and it requires being ahead of others in the industry. With that perspective, it is only natural to think through the parallels of peer-reviewed publishing in academia with internal peer review of exploration ideas in the industry. In fact, OPR is already in practice in the industry.

Concluding remarks

The current system of blind peer review is obsolete. This is because there are at least 8 examples of scientific papers that were rejected before going on to win a Nobel Prize. As an active researcher in sedimentology and petroleum geology, many of my own examples show that the same manuscript, which was rejected by one journal, got accepted by another journal without any revisions. Also, there are no practical ways to hide the identities of the reviewer and the author. The current blind review process is an illusion. A solution is to adopt Open Peer Review IOPR). Many publishers have already adopted OPR in some medical and natural sciences. There is resistance from journals in geological sciences to OPR. Barring an open peer review in geological sciences, an alternative path is to publishing the entire peer-review comments and decisions of all reviewers (anonymous and identified) at the end of a paper. This practice not only would force the anonymous reviewer to be objective and accountable but also would allow the entire peer-review process to be transparent to the reader.

Abbreviations and Explanations

AAPG: American Association of Petroleum Geologists;
AJS: American Journal of Science;
BCE: Before Common Era
BCRS: Bottom-current reworked sands;
BMC: BioMed Central;
BMJ: British Medical Journal
CE: Common Era
EMBO: The European Molecular Biology Organization (Germany)
ESR: Earth-Science Reviews
F1000Research: Open Access publishing platform owned by Taylor & Francis
GSA: Geological Society of America;
HCQIA: The "Health Care Quality Improvement Act" was enacted by the U. S. Congress in 1986 in order to legislatively strengthen the role of peer review in the medical community.
HDTC: High-density turbidity currents;
IIT: Indian Institute of Technology;
JAMA: Journal of the American Medical Association;
JIAS: Journal of the Indian Association of Sedimentologists
JCAHO: The "Joint Commission on Accreditation of Healthcare Organizations". This 1952 act began requiring physician peer review at all United States hospitals.
JOP: Journal of Palaeogeography;
JSR: Journal of Sedimentary Research;
LC: Library of Congress of the US;
MDPI: Multidisciplinary Digital Publishing Institute (Switzerland);
MIT: Massachusetts Institute of Technology;
MPG: Marine and Petroleum Geology;
MTD: Mass-transport deposits;
NASA: National Aeronautics and Space Administration;
OPR: Open Peer Review;
PED: Petroleum Exploration and Development
PLOS: Public Library of Science;
SDI: Solitaire Diamond Institute (India);
SEPM: The Society for Sedimentary Geology;
US: United States;
USA: United States of America;
Vox: It is an American news and opinion website owned by Vox Media. The website was founded in April 2014 (Visit media website).

Acknowledgements

I thank Prof. G. M. Bhat, Managing Editor of JIAS, Jammu University, India, for encouraging me to submit this Editorial. I also thank Dr. Bashir Ahmad Lone, Co-Managing Editor of JIAS, Jammu University, India, for final processing and formatting of the manuscript. My sincere thanks to Dr. D. W. Kirkland (Retired Mobil Scientist) for a critical and helpful review of the manuscript. As always, I am thankful to my wife, Jean Shanmugam, for her general comments.

About the Author

G. Shanmugam is a person of Indian origin. He was born in 1944 in Sirkazhi, Madras Presidency, British India. He emigrated to the U.S. in 1970 and became a naturalized U. S. citizen in 1990. He has been married to his American wife, Jean, since 1976. They live in Irving, Texas. He is a pragmatic and an iconoclastic deep-water process sedimentologist. His primary contributions are aimed at documenting the volumetric importance of sandy mass-transport deposits and bottom-current reworked sands in deep-water petroleum reservoirs worldwide and at dispelling the popular myth that most deep-water sands are turbidites. Importantly, he debunked the myths of facies models on high-density turbidites (Shanmugam, 1996), tsunamites (Shanmugam, 2006b), landslides (Shanmugam, 2015), seismites (Shanmugam, 2016b), contourites (Shanmugam, 2016a, 2017), hyperpycnites (Shanmugam, 2018), and hybridites (Shanmugam, 2021a). . He has over 380 published works, including two volumes of Elsevier's Handbook of Petroleum Exploration and Production (Shanmugam, 2006a and 2012b) and their Chinese editions. His most recent Elsevier book "Mass Transport, Gravity Flows, and Bottom Currents" contains 540 case studies covering environments on Earth, Mars, and Jupiter, but with a majority on deep-water processes on Earth (Shanmugam, 2021b).

Professional Preparation

1978: Ph.D., Geology, University of Tennessee, Knoxville, TN., U.S.
1972: M.S., Geology, Ohio University, Athens, OH., U.S.
1968: M.Sc., Applied Geology, Department of Civil Engineering, IIT-Bombay, India
1965: B.Sc., Geology and Chemistry, Annamalai University, Tamil Nadu, South India
Note: He served as a research scholar under the Council of Scientific and Industrial Research (CSIR), Government of India, at IIT Bombay during 1968–1970.

OHIO University June 8, 2022 News

See his story on his scientific contributions under "Alumni/Friends" category at: https://www.ohio.edu/news/2022/06/alumnus-ganapathy-shanmugam-admonishes-scientists-against-deep-sea-groupthink-provides

1978-2000: Employment with Mobil Research and Development Corporation, Dallas,Texas

2000-Present: Adjunct Professor, the University of Texas at Arlington

2010-2011: Scientific Advisor: Research Institute of Petroleum Exploration and Development (RIPED) of PetroChina, Beijing, China

2000- Present: Petroleum Consulting: Reliance, ONGC, China University of Petroleum in Qingdao, Yangchang Oil Field in Yanan.

1997 AAPG Annual Convention Debate Panelist, Dallas, Texas, USA
Topic: Processes of Deep-Water Clastic Sedimentation and Their Reservoir Implications: What Can We Predict?
Moderator: H. E. Clifton.

Panelists: A.H. Bouma, J.E. Damuth, D.R. Lowe, G. Parker, and **G. Shanmugam**

Organizer of International Deep-Water Sandstone Workshops: 15
Examples:

- the UK Department of Trade and Industry (DTI) in Scotland (1995 and 1997);
- Petrobras, Mobil, and Unocal in Brazil and in Dallas, Texas (1998 and 1999);
- Oil and Natural Gas Corporation (ONGC) in India (2002 and 2004);
- Reliance Industries Ltd. in India (2006–09);
- Research Institute of Petroleum Exploration and Development (RIPED), PetroChina in Beijing (2009–10);
- Yanchang Oilfield Exploration and Development, Research Institute of Yan'an Branch (China) (2014);
- China University of Petroleum, Qingdao, China (2014).

Organizer of clastic facies field course (3 weeks) for Saudi Aramco, Dhaharan, Saudi Arabia:

1990 (3-21 November), Saudi Aramco, Saudi Arabia. Field area includes Qassim and vicinity. Modern and anient deposits were investigated in the field. Seismic profiles, well logs, and cores from petroleum-producing fields were used in class exercises

International invited speaker: 87

2018-Present: Editorial Board

- Associate Editor-in-Chief of the Journal of Palaeogeography (Springer)
- Editorial Board Member of the Petroleum Exploration and Development (Elsevier).
- Editorial Board Member of the Journal of Indian Association of Sedimentologists.

Research

He conducted outcrop studies of deepwater deposits in the Southern Appalachians (Tennessee, United States), Ouachita Mountains (Arkansas and Oklahoma, United States), and Peira Cava area (French Maritime Alps, SE France). He described deep-water strata using conventional cores and outcrops (1:20 to 1:50 scale), which include 32 deepwater sandstone petroleum reservoirs worldwide, totaling over 10,000 m in cumulative thickness during 1974–2011.

He also conducted field studies of coal deposits in Victoria (Australia), coniferous rain forests in the North Island (New Zealand), limestone karst in Guilin (China), fluvial deposits in Gujarat (India), 2004 Indian Ocean Tsunami-related coastal deposits in Tamil Nadu (India), shallow-marine deposits in Qassim area (Saudi Arabia), and estuarine deposits in the Oriente Basin (Ecuador). He would like to acknowledge a select group of world-renowned editors, associate editors, and reviewers who evaluated my contributions during the past 50 years:

1 J. Southard (Journal of Sedimentary Research)
2 P. McCarthy (Journal of Sedimentary Research)
3 C. North (Journal of Sedimentary Research)
4 P.J. Talling (Journal of Sedimentary Research)
5 G.A. Smith (Journal of Sedimentary Research)
6 G. Postma (Journal of Sedimentary Research)
7 D.J.W. Piper (Journal of Sedimentary Research)
8 Martin Gibling (Journal of Sedimentary Research)
9 O.H. Pilkey (Journal of Sedimentary Petrology)
10 Jean Lajoie (Journal of Sedimentary Petrology)
11 G. Kelling (Sedimentary Geology)
12 A.D. Miall (Sedimentary Geology and Earth-Science Reviews)
13 G.D. Klein (Earth-Science Reviews)
14 G.M. Friedman (Earth-Science Reviews and History of Geologic Pioneers)
15 André Strasser (Earth-Science Reviews)
16 A. Negri (Earth-Science Reviews)
17 Jingping Xu (Earth-Science Reviews)
18 R. Steinmetz (AAPG Bulletin)
19 J.A. Helwig (AAPG Bulletin)
20 S.A. Longacre (AAPG Bulletin)
21 K.T. Biddle (AAPG Bulletin)
22 N.F. Hurley (AAPG Bulletin)
23 E.A. Mancini (AAPG Bulletin)
24 G.M. Gillis (AAPG Bulletin)
25 M. Sweet (AAPG Bulletin)
26 Barry J. Katz (AAPG Bulletin)
27 D.G. Roberts (Marine and Petroleum Geology)
28 E.M. Moores (Geology)
29 H.T. Mullins (Geology)

30 R.E. Arvidson and M.E. Bickford (Geology)
31 R.D. Hatcher, Jr. and W.A. Thomas (GSA Bulletin)
32 J.D. Collinson (Sedimentology)
33 P. Carling (Sedimentology)
34 B.W. Flemming and M.T. Delafontaine (Geo-Marine Letters)
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42 K.R. Walker and D. Roeder (Appalachian Geodynamic Research: American Journal of Science)
43 A.H. Bouma, W.R. Normark, and N.E. Barnes (Submarine Fans and Related Turbidite Systems)
44 G.G. Zuffa (NATO Conference on "Provenance of Arenites")
G.C. Brown, D.S. Gorsline, and W.J. Schweller (Deep-Marine Sedimentation: Depositional Models and Case Histories in Hydrocarbon Exploration and Development)
45 K.L. Kleinspehn and C. Paola (New Perspectives in Basin Analysis)
46 E.M. Moores and F. Michael Wahl (The Art of Geology)
47 S.P. Hesselbo and D.N. Parkinson (Sequence Stratigraphy in British Geology)
48 R.D. Winn, and J.M. Armentrout (Turbidites and Associated Deep-Water Facies)
49 D.A.V. Stow and M. Mayall (Deep-water Sedimentary Systems)
50 J.H. Steele, K.K. Turekian, and S.A. Thorpe (Encyclopedia of Ocean Sciences, Second Edition)
51 M. Rebesco and A. Camerlenghi (Contourites)
52 A. Kumar and I. Nister (Paleotsunamis: Natural Hazards)
53 J. Cubitt (Handbook of Petroleum Exploration and Production series)
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Water Quality Index (WQI) to Evaluate Groundwater Quality in Chickmagaluru District, South Karnataka, India

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Abstract

Groundwater quality analysis is essentially prima facie in the present scenario. To evaluate groundwater quality 14 different physiochemical parameters were analyzed for groundwater samples in the study area. Water Quality Index (WQIs) is a composite indicator of water quality. The water quality index contains various parameters that can be quickly and easily communicated to its intended audience. WQI is one of the most effective techniques for determining the appropriateness of groundwater for drinking purposes. The extracted components indicate that geological, agricultural, rainfall, household wastewater, and industrial activities are causing the sources to exceed the permissible limit. The present study contributes in understanding the groundwater quality in the Chickmagaluru district. It also helps in the understanding hydrogeochemical process of groundwater and effective interpretation of groundwater.

Keywords: Groundwater quality, Water Quality Index, Water quality Parameter, Chikamagaluru.

INTRODUCTION

During the last few decades, conserving of water resources has been receiving more and more attention. With the population expansion, water consumption for different purposes such as agriculture, drinking, and industrial growth has increased many folds and investment in the water sphere has become unavoidable for its management. Several processes have impact on the quality of groundwater including anthopogenic activities and the natural ones. Groundwater composition is influenced by soil layers, precipitation and surface water chemistry, climate, topography, and human activities. Water quality evaluation for drinking water purposes includes determining the composition of groundwater as well as remedial procedures to restore water quality (Annapoorna and Janardhana 2015; Neisi et al. 2018). The water quality index (WQI) is a practical and relatively easy method for assessing the overall groundwater quality. It also represents the combined impact of the various water quality indicators.

The present study focusses on characterisation of groundwater quality by testing samples and comparing them with the guidelines stated by the Bureau of Indian Standards (BIS). The standard methods were used to determine parameters such as Electrical Conductivity (EC), pH, Total Dissolved Solids (TDS), Calcium (Ca_2), Magnesium (Mg_2), Chloride (Cl^-), Sulphate (SO_4^-), Nitrate (NO_3^-), Total Hardness (TH), Potassium(K), Bicarbonate (HCO_3), Sodium (Na) Fluorides (F^-), and Iron (Fe). The concentrations or relative abundances of major and minor constituents and patterns of variability in the various water samples were analyzed using different graphical and statistical techniques.

Study Area

The study area (Fig. 1) falls within the state of Karnataka. Chikmagalur district situated in the southwestern part of Karnataka state between 12° 54' 42" - 13° 53' 53" N and 75° 04' 46" - 76° 21' 50"E. The study area is 138.4 km from east to west is 138.4km and 88.5 kn from north-south. The study area is bounded by Tumkur district in the East, Hassan in the South, Dakshina Kannada in the west, Chitradurga in the Northeast, and Shimoga in the North. The overall geographical area of the district is 7201 km^2 consisting of seven taluks namely Chikmagalur, Kadur, Koppa, Mudigere, Narasimharajapura, Sringeri, and Tarikere. The district area is represented in topographical map numbers 48 O and 57 C.

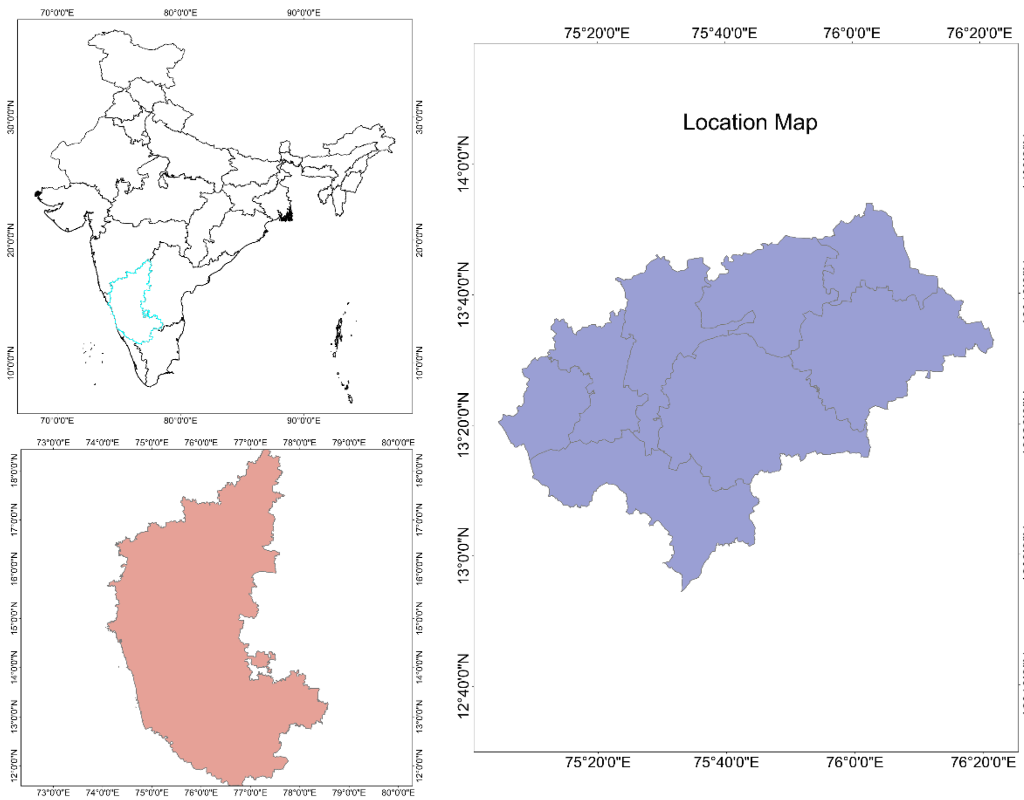


Fig. 1: Study area

Material and Methodology

The groundwater samples (Fig. 2) were collected from both dug/open and bore wells during pre-monsoon and post-monsoon in the year 2019. 95 representative groundwater samples were collected as per the standard protocol recommended by APHA (American Public Health Association) (Tab. 1). The samples were collected after 5 minutes of pumping well and placed in properly washed polythene containers at 4°C until the completion of the study. Each of the samples was analyzed for various physico-chemical parameters such as Electrical Conductivity (EC), pH, Total Dissolved Solids (TDS), Calcium (Ca_2), Magnesium (Mg_2), Chloride (Cl^-), Sulphate (SO_4^-), Nitrate (NO_3^-), Total Hardness (TH), Potassium(K), Bicarbonate (HCO_3), Sodium (Na) Fluorides (F^-), and Iron (Fe^-) (Tab. 2). pH and EC were measured in insitu and other parameters were analyzed in the laboratory using a spectrophotometer. The GPS readings were noted at each location to prepare various thematic maps using the ARC map.

Table 1: Drinking water standards used to calculate WQI

Parameter	Ca	Mg	Fe	F	SO_4	Cl	NO_3	TDS	EC	TH	pH	HCO_3	Na	K
	75	30	0.3	1	200	250	45	500	300	200	6.5 – 8.5	244	20	10

All parameters, except pH, are expressed in Mg/L

Groundwater Quality

pH: In pure form water has pH of 7, which indicates the water's hydrogen ion concentration. For drinking water, the range of pH should be in the range of 6.5-8.5 (BIS, 2012). Groundwater flow through carbonate-rich rocks like limestones and marbles, usually have a pH of greater than 7. The pH in the study area varies from 6.5 to 8.43 in the pre-monsoon and 6.5 to 8.35 after monsoon. All the samples in the study area fall within the allowable cap for both the pre-monsoon and post-monsoon samples (6.5 to 8.5).

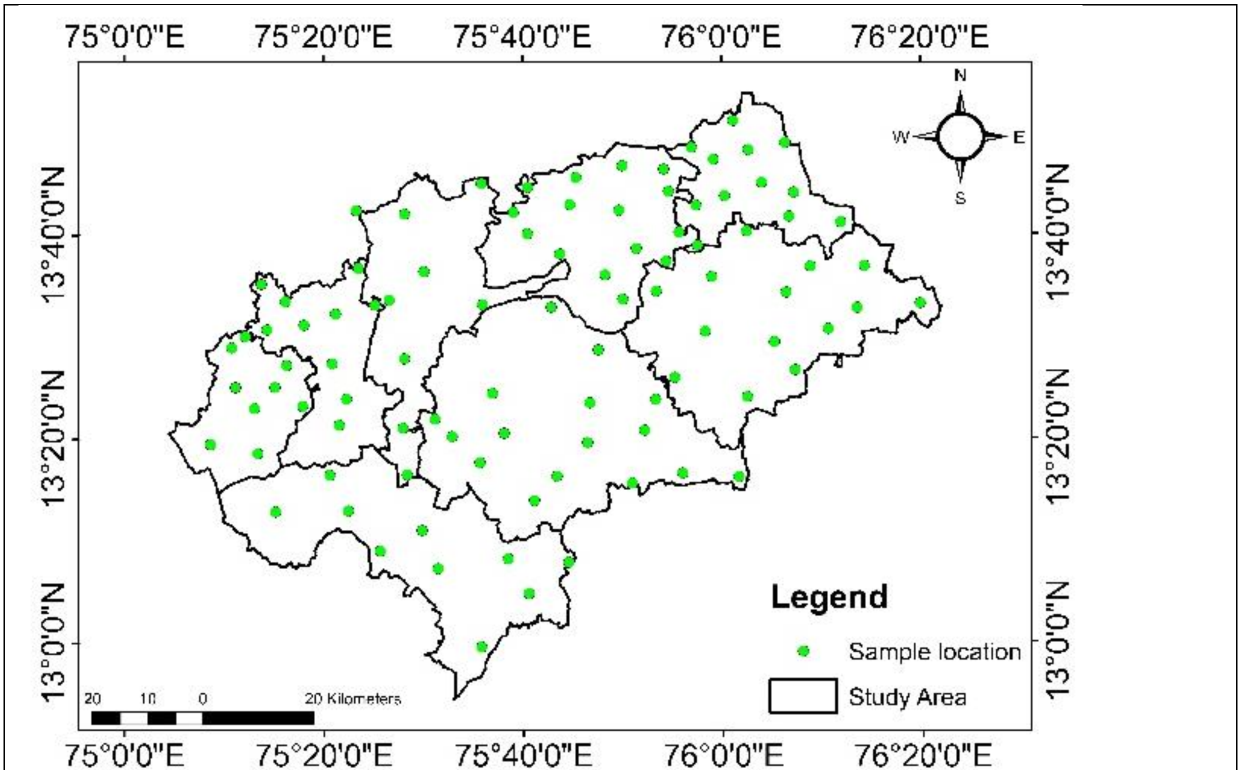


Fig. 2 Sample locations

EC: The quantity of the dissolved material in an aqueous solution is electrical conductivity (EC); the greater the dissolved material in a water sample, the higher the EC. The desirable EC cap for drinking is 300 µS/cm. The electrical conductivity in the present study ranges from 79 µS/cm to 2576 µS/cm in the pre-monsoon and 63 µS/cm to 2249 µS/cm in the post-monsoon samples. Around 41 percent of the samples in pre-monsoon and 47.3 % of the samples in post-monsoon fall under the acceptable limit (300 µS/cm).

Total Hardness: For its usage in the domestic domain, total hardness is a significant parameter of water. The hardness of water is a measure of the capacity of water to produce lather soap, hard water causes problems in the digestive system and the possibility of forming calcium oxalate crystals (Kidney stones) in the kidney. “It happens as a result of calcium and magnesium being present (Arumugam, 2010). Total hardness in the study area ranges from 36. 45 Mg/L to 1916 Mg/L in pre-monsoon and 23.22 Mg/L to 1672.5 Mg/L in the post monsoon samples. Around 53% samples in pre-monsoon and 66.3% samples in post-monsoon fall under the permissible limit of 300 Mg/L.

TDS: It is a consequential parameter for drinking water. Water containing high TDS is not suitable for drinking and it produces an unfavorable physiological reaction. It is made up mostly of inorganic salts, along with some small amounts of organic matter dissolved in water. The main compounds that are usually found in this compound are calcium, magnesium, sodium, and potassium, carbonate, bicarbonate, chloride, and sulfate cations. The optimum TDS for human drinking water, according to the BIS, is less than 500 Mg/L and the maximum permissible limit is 2000 Mg/L. In the study area, the TDS ranges from 68 Mg/L to 2215 Mg/L in the pre-monsoon and 48 Mg/L to 1975 Mg/L in the post-monsoon. Around 53.6% of samples in pre-monsoon and 66.3% samples in post-monsoon fall under the acceptable limit of 500 Mg/L.

Calcium: Calcium divalent cations are one of the important nutrients for living organisms. Calcium is found naturally in water. It will fade out from rocks such as limestone, marble, calcite, dolomite, gypsum, fluorite, and apatite. Calcium is a determining factor of water hardness because it can be found in water as Ca_2^+ ions. Depending on the type of rock, the quality of natural groundwater varies. In the present investigation, the calcium concentration in the study area ranges from 8 Mg/L to 378 Mg/L before monsoon and 5 Mg/L to 330 Mg/L after the monsoon. Around 48.4% of samples in pre-monsoon and 60% samples in post-monsoon fall under the acceptable limit of 75 Mg/L.

Magnesium: Magnesium is always associated with calcium in natural form, but its concentration is generally lower than calcium concentration. The higher magnesium content produces water hardness. Concentration >500 Mg/L imparts an unpleasant taste to water making it unportable. High concentration combined with sulfate acts as a laxative to human beings. In the present investigation, the Magnesium concentration in the study area ranges from 4 Mg/L to 241 Mg/L in pre-monsoon and 2 Mg/L to 221 Mg/L in post-monsoon. Around 43.15% of samples in pre-monsoon and 48.42% samples in post-monsoon fall under the acceptable limit of 30 Mg/L.

Nitrate: Nitrate is the most important nutrient in the ecosystem. Nitrates are of prime concern because when the concentration of methemoglobinemia exceeds 40 Mg/L. A high concentration of nitrates in groundwater may cause mortality in cattle, pigs, and calves. The concentration of Nitrate is 45 Mg/L, the limit imposed by BIS is exceeded, thus making this water unfit for portable. It is very difficult to point out the exact sources of nitrate contamination. One of the main causes of nitrate contamination is anthropogenic pollution. Nitrogen and nitrates from agricultural runoff due to the increased usage of chemical fertilizers. Nitrogen is also found in municipal waste and industrial wastewater, dumps, animal feedlots, septic tanks, and sewage disposal systems. Subsurface geology and the direction of groundwater flow also influence nitrate concentration. The concentration of nitrate in the sampling area ranges from 0.3 Mg/L and 147 Mg/L in pre-monsoon and 0.1 Mg/L to 126.8 Mg/L in post-monsoon. Around 95.78% of samples in pre-monsoon and 96.84% samples in post-monsoon fall under the acceptable limit.

Chloride: Chloride is found in all sorts of natural waters and gives saline flavor to water. High chloride contamination indicates contamination due to organic waste. Greater the chlorine content in water, the more dangerous it is to human health" (Anitha et al., 2011; Sadat-Noori et al., 2014). The concentration of chloride in the present study varies from 15 Mg/L to 610 Mg/L in the pre-monsoon period and 6 Mg/L to 378 Mg/L in the post-monsoon period. Around 85.26% of samples in pre-monsoon and 91.5% samples in post-monsoon fall under the acceptable limit of 250 Mg/L.

Sulfate: Sulfate leach out from rocks such as gypsum, iron sulphides, and other compounds. The sulfate ion is an important constituent of hardness with calcium and magnesium. It has an unpleasant taste at 300-400 Mg/L, is laxative at 1000 Mg/L, and interferes with the proper working digestion. The concentration of sulphate in the study area ranges from 3 Mg/L to 385 Mg/L in the pre-monsoon season and 2 Mg/L to 275 Mg/L in the post-monsoon season. Around 67.36% of samples in pre-monsoon and 87.36% samples in post-monsoon fall under the acceptable limit of 200 Mg/L.

Fluoride: "The main source of fluoride contamination in groundwater is geogenic. High concentration (>3.0 mg/l) of fluoride may cause skeletal fluorosis" (N. Janardhana Raju, 2009). Fluoride presents naturally in public water systems and by runoff from weathering of rocks and soils containing fluoride, leaching from rocks and soil into groundwater, and rainfall that brings the fluoride into the water system. The fluoride concentration in the study area varies from 0.02Mg/L to 1.65Mg/L for pre-monsoon reasons and 0.01Mg/L to 1.55Mg/L fora post-monsoon reason. Around 78.9% of samples in pre-monsoon and 86.3% samples in post-monsoon fall under the acceptable limit of 1 Mg/L.

Iron (Fe): The main source of iron contamination in groundwater is due to the leaching of iron from minerals and rocks, and rainfall that brings iron into the water system. The upper limit of iron is 0.3 Mg/L, if concentration exceeds this limit it results in a negative effect on the skin. In the study area, the iron concentration ranges from 0.014 mg/l to 5.64 Mg/L in pre-monsoon season and 0.003mg/l to 4.12mg/l in post-monsoon season amples. Around 77.8% of samples in pre-monsoon and 91.5% samples in post-monsoon fall under the acceptable limit of 0.3 Mg/L.

Sodium: Sodium is one of the most cation found naturally in water and is derived from weathering of rocks and minerals present in the locality. Domestic sewage and industrial wastes are abundant in sodium. Sodium concentration in the study area varied from 13 mg/l to 255 mg/l in pre-monsoon and 10mg/l to 212mg/l in post-monsoon samples. The acceptable maximum limit is 20 mg/l.

Potassium: Potassium is also a naturally occurring element but occurs at lower concentrations than sodium, calcium and magnesium. It has similar chemistry to sodium and remains in solution without forming any precipitate. As such, it is not very much significant from the health point of view. Sodium concentration in the study area varied from 2mg/l to 88mg/l in pre-monsoon and 2 mg/l to 63 mg/l in post-monsoon samples. Around 85.26% of samples in pre-monsoon and 91.5% samples in post-monsoon fall under the acceptable limit of 250 mg/l.

Table-2 Statistical analysis of analyzed physio-chemical groundwater quality parameter								
Parameter	Max	Min	Mean	Standard Deviation	Max	Min	Mean	Standard Deviation
	Pre-monsoon				Post-monsoon			
Ca	378.0	8	99.43	83.48	330	5	65.94	61.81
Mg	241.0	4	60.76	52.55	211	2	40.11	40.71
Cl	610	15	139.59	135.52	378	6	87.93	87.19
NO3	147	0.3	14.71	22.06	126.8	0.1	9.45	16.78
SO4	385	3	118.93	115.75	2	278	83.45	87.40
F	1.65	0.02	0.52	0.48	1.55	0.01	0.4	0.44
Fe	5.64	0.014	0.36	0.96	4.12	0.003	0.1981	0.62
TDS	2215	68	576	492	1975	48	411	382
EC	2576	79	745	624	2249	63	560	495
TH	1916	36.45	498.60	419.78	1672.5	23.22	329.9	314.80
HCO3	564.0	112	194.77	72.22	501	92	170.06	67.18
K	88.0	2	19.84	17.50	63	2	14.84	13.66
PH	8.43	6.5	7.08	0.5	8.35	6.5	0.4	7.04
Na	255.0	13	58.29	43.24	212	10	48.71	38.06

RESULTS AND DISCUSSION

Pearson's Correlation

All parameters are expressed in Mg/L, except pH and EC expressed in μS/cm

Table 2 shows the descriptive data for 95 groundwater samples. The detailed scrutiny of the correlation matrix is helpful for the interpretation of groundwater in the study area. The role of each parameter and its impact on the hydrochemistry process is depicted in the correlation matrix. (Helena et al., 2000; Khan, 2011). If the values of "r" are ''+ 1 or - 1" in the Pearson's correlation matrix (Table 3 & 4) they are considered as high correlation coefficient i.e., a functional dependence, between two variables. If the values are nearer to zero, it indicates no relationship between bivariate at a substantial level of $P < 0.05$ (Singh et al., 2011). If $r > 0.7$, and within 0.4 and 0.7, it can be considered that the parameters are strongly correlated and moderately correlated, respectively. A correlation matrix is utilised to comprehend any relationship between the empirically observed parameters and the factor loadings using PCA.

In the pre-monsoon samples, Ca^{2+} has a negative correlation with Fe^-, and a strong positive correlation with Na^+, K, Mg^{2+}, HCO_3^-, Cl^-, SO_4, NO_3^-, F^-, TDS, EC, pH, TH and moderate positive correlation with temperature. In the post-monsoon Ca^{2+} shows a strong positive correlation with Na^+, K, Mg^{2+}, HCO_3, Cl^-, SO_4, NO_3^-, F, TDS, EC, and TH and moderate positive correlation with Fe^-, pH and temperature. The pH displays a negative correlation with Fe^- and a positive correlation with all other parameters in pre-monsoon as well as post-monsoon. The Mg_2^+ has a positively strong correlation with Ca_2^+, Na^+, K, Cl^-, SO_4, NO_3^-, F^-, TDS, EC, pH, TH and moderately correlated with HCO_3^- and temperature except Fe^- which shows the negative correlation in the pre-monsoon and the post-monsoon samples Mg^{2+} has a positively strong correlation with Ca_2^+, Na^+, K, Cl^-, SO_4, NO_3^-, F^-, TDS, EC, and TH and moderately correlation with Fe^-, pH, and temperature. The significant association between $Mg^{2+}$and Cl-, Na^+ and Cl-, TDS and Cl- the studied area demonstrates the impact of agronomical activities. In the pre-monsoon EC has a strong positive association with Ca^{2+}, Mg^{2+}, Na^+, K, Cl^-, SO_4, NO_3^-, F^-, TDS, EC, and TH and moderately correlation with HCO_3^- and, T and Fe^- show a negative correlation. In the post-monsoon EC has a strong positive association with Ca^{2+}, Mg^{2+}, Na^+, K, Cl^-, SO_4, NO_3^-, HCO_3^-, Fe^- and TH and moderately positive correlation with F^-, pH, and T suggesting ions have the common source and are entangled in ion exchange reactions (Subbu Rao, 1996). TH is highly correlating with all the parameters except Fe^- in the pre-monsoon as well as the post-monsoon. TDS in the pre-monsoon samples is highly positive with Ca^{2+}, Mg^{2+}, Na^+, K, Cl^-, HCO_3^-, SO_4, NO_3^-, F^-, TDS, EC and TH and negative with Fe^-, when it comes to post-monsoon TDS shows a high positive correlation with Ca^{2+}, Mg^{2+}, Na^+, K, Cl^-, HCO_3^-, SO_4, NO_3^-, F^-, EC and TH and negative correlation with pH, and Fe^-. In general, the concentration of Cl^- is low in the crystalline subsurface (Karanth, 1987). The concentration of Cl^- is low in the post-monsoon as compare to the pre-monsoon samples due to rainfall.. The positive correlation between Na^+ and Cl^- is strong in the pre-monsoon, as well as the post-monsoon samples suggesting possible mizing of the two end-member composition groundwater.

The strong correlation between Mg^{2+} and Cl^-, Na^+ and Cl^-, TDS and Cl^- is related to agronomic activity in the study area. A scatter matrix plot and visual representations are used to interpret the correlation matrix. (Figs 3 & 4). Figure 3 & 4 are the replication of Tables 3 & 4 to understand the correlation easily. To check the adequacy of the data for statistical analysis, Kaiser–Meyer–Olkin (KMO) and Bartlett's tests were conducted; sampling adequacy rate is 0.852 in the pre-monsoon and 0.845 in the post-monsoon samples which show greater than the threshold values given by the test (0.5). KMO and Bartlett's tests assess the appropriateness of data for factor analysis, determining the sampling suitability for each variable in the model. KMO values 0.8 to 1, 0.5 to 0.8, and less than 0.5 are considered as adequate, moderately adequate, and unacceptable or not adequate, respectively.

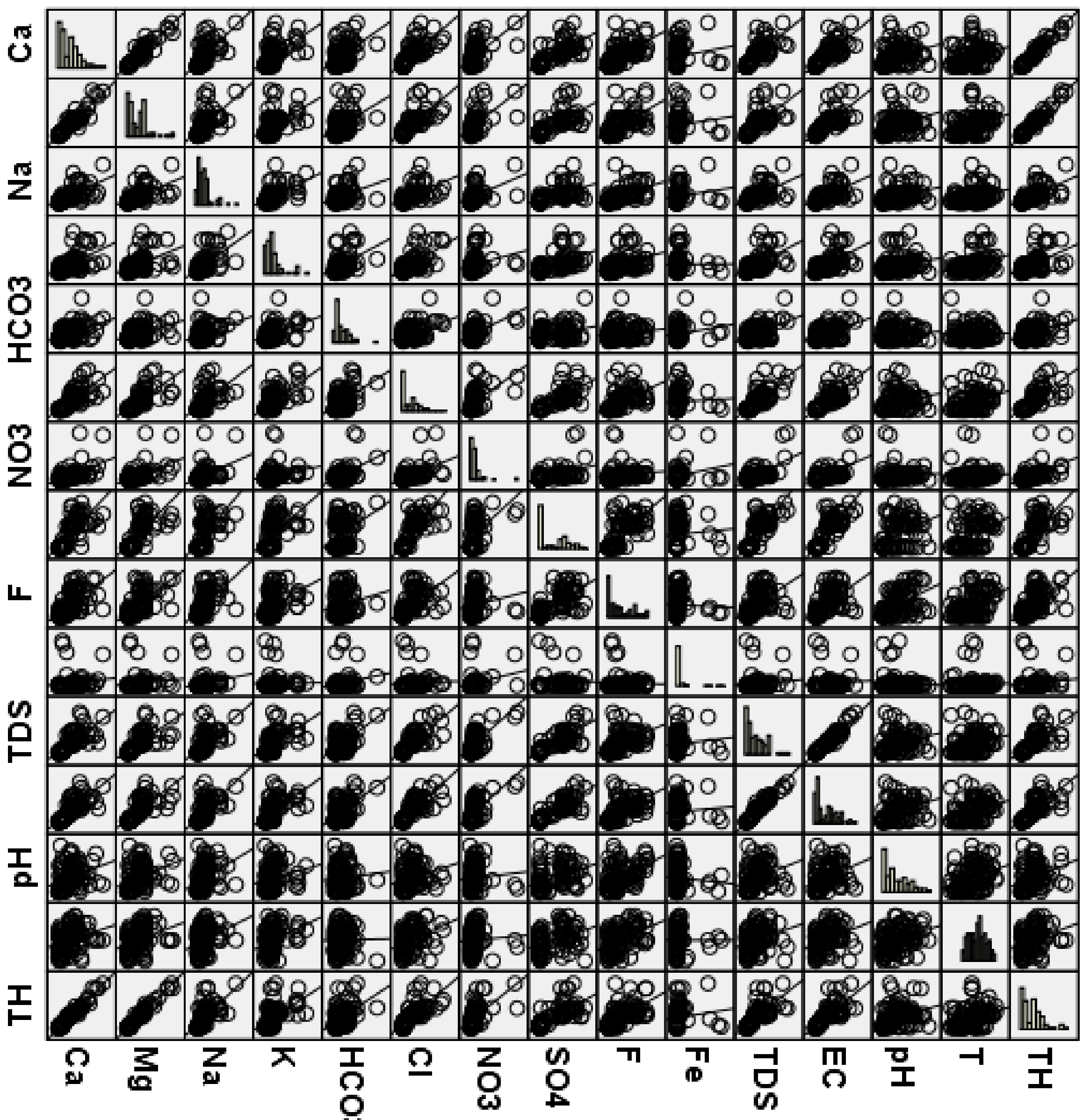


Fig. 3 Scatter matrix plot for pre-monsoon

	Ca	Mg	Na	K	HCO_3	Cl	NO_3	SO_4	F	Fe	TDS	Ec	pH	T	TH
Ca	1														
Mg	0.911	1													
Na	0.683	0.598	1												
K	0.545	0.48	0.564	1											
HCO3	0.433	0.387	0.348	0.471	1										
Cl	0.814	0.743	0.588	0.598	0.393	1									
NO3	0.604	0.542	0.406	0.24	0.481	0.607	1								
SO4	0.737	0.61	0.574	0.451	0.188	0.772	0.466	1							
F	0.588	0.522	0.549	0.35	0.151	0.597	0.164	0.723	1						
Fe	-0.059	-0.021	-0.015	-0.004	0.078	-0.038	-0.055	-0.066	-0.028	1					
TDS	0.827	0.702	0.653	0.461	0.418	0.757	0.756	0.783	0.552	-0.067	1				
Ec	0.844	0.746	0.686	0.51	0.393	0.793	0.69	0.825	0.652	-0.069	0.974	1			
pH	0.473	0.463	0.492	0.342	0.147	0.436	0.19	0.466	0.598	-0.026	0.465	0.529	1		
T	0.212	0.233	0.152	0.046	-0.006	0.132	0.003	0.209	0.286	0.068	0.135	0.18	0.157	1	
TH	0.974	0.978	0.654	0.523	0.418	0.795	0.587	0.686	0.565	-0.047	0.78	0.811	0.477	0.229	1

Table 3 Correlation coefficient matrix pre-monsoon

	Ca	Mg	Na	K	HCO_3	Cl	NO_3	SO_4	F	Fe	TDS	Ec	pH	T	TH
Ca	1														
Mg	0.952	1													
Na	0.607	0.67	1												
K	0.489	0.574	0.587	1											
HCO3	0.417	0.491	0.362	0.441	1										
Cl	0.767	0.793	0.577	0.65	0.484	1									
NO3	0.55	0.564	0.441	0.228	0.511	0.538	1								
SO4	0.733	0.762	0.585	0.541	0.347	0.815	0.469	1							
F	0.654	0.649	0.553	0.392	0.179	0.574	0.153	0.718	1						
Fe	0.124	0.143	0.176	0.011	0.187	0.05	0.228	0.059	-0.029	1					
TDS	0.722	0.779	0.63	0.583	0.544	0.814	0.671	0.838	0.539	0.094	1				
Ec	0.779	0.821	0.662	0.596	0.505	0.829	0.624	0.87	0.619	0.07	0.979	1			
pH	0.358	0.325	0.35	0.201	0.079	0.248	0.073	0.387	0.498	-0.068	0.313	0.37	1		
T	0.336	0.288	0.305	0.351	0.015	0.366	0.056	0.39	0.45	-0.002	0.287	0.35	0.348	1	
TH	0.987	0.986	0.647	0.538	0.458	0.789	0.566	0.756	0.658	0.124	0.759	0.81	0.344	0.317	1

Table 4 Correlation coefficient matrix post-monsoon. (Bold ones are r>0.4 showing the significance level

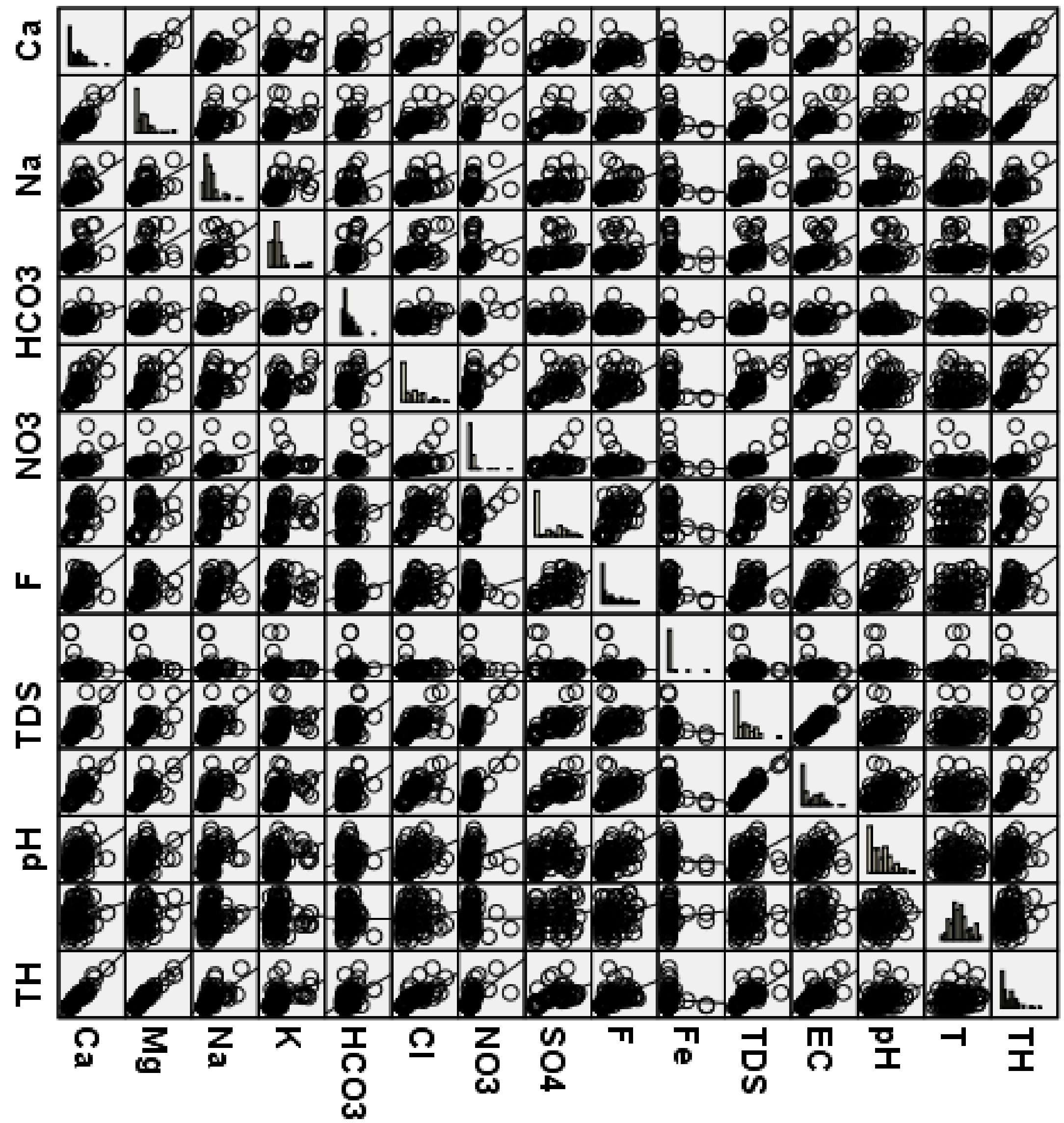


Fig. 4 Scatter matrix plot for post-monsoon

FACTOR ANALYSIS

The factor analysis is a useful technique, where a vast amount of data containing variables can be condensed down to a small number of variables. This methodology also identifies the relationship between the variables and their impact on the objects, i.e., the investigated samples. The PC, which is linear combination of the original variables that can represent the maximum of the overall variance, is a key component of this technique. The remaining parameters determine the greatest residual variability (Behera and Das, 2018). The extracted components are orthogonal to one another. The variances derived from the factors are called eigenvalues, and only factors with eigenvalues larger than 1 are chosen. Factor loadings represent the correlations between original variables and the factors extracted.

To simplify factor analysis data, Varimax with Kaiser normalisation rotation is utilised (Schot and Van der Wal, 1992; Jayakumar and Siraz, 1997; Adams et al., 2001; Aiuppa et al., 2003). The scree plot (fig. 5&6) two factors and three factors for te pre-monsoon and the post-monsoon samples respectively (Table 7 & 8) were used to describe 66.69% and 71.22% of total variances which are enough for obtaining correlation matrix (Cattell and Jaspers, 1967). With the help of these factors, total variance is described as the first component - 52.471% and asecond component – 66.698% in the pre-monsoon and component 1 – 43.989, component 2 – 63.817, and component 3 – 72.226 in the post-monsoon.

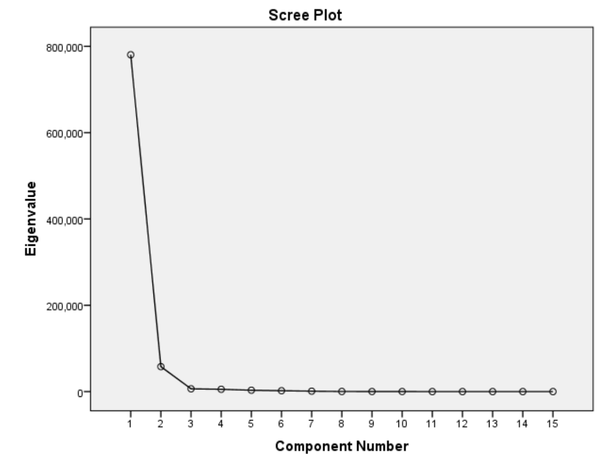


Fig.5 Scree plot graph for pre-monsoon

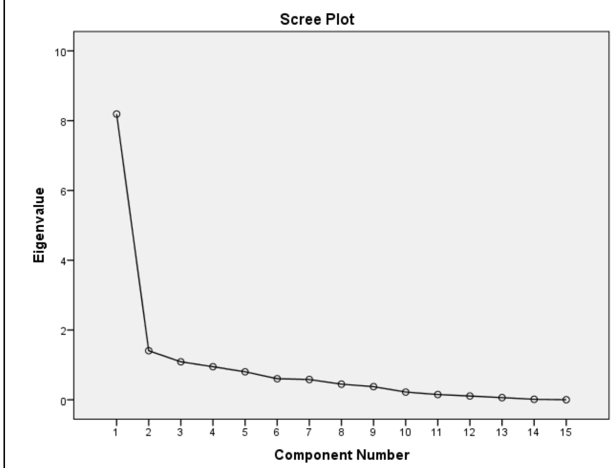


Fig.6 Scree plot graph for post-monsoon

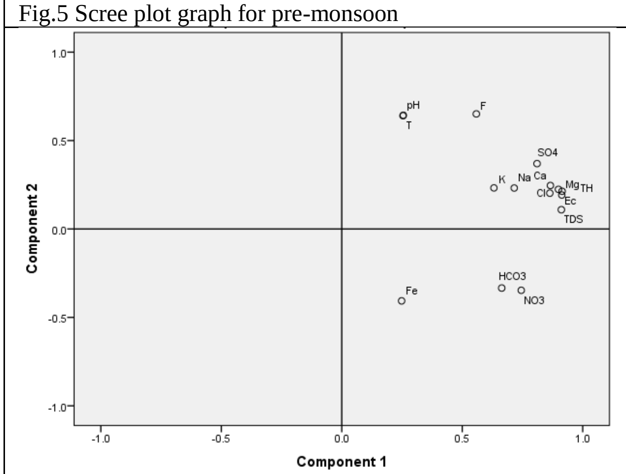


Fig. 7 Rotated components for pre-monsoon

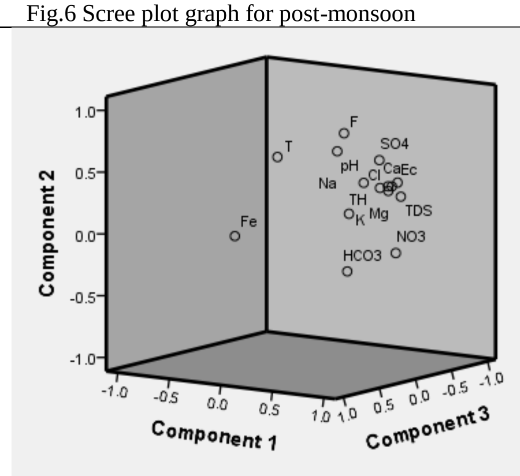


Fig. 8 Rotated components for post-monsoon

Variables with loadings greater than 0.3 are important for assessing the components and have been used to interpret the results (Mahloch, 1974). The absolute value of loading describes the variable's influence. A positive or negative sign indicates the direction of the influence. As a result, a huge negative number indicates that a variable has a significant and negative impact on the factor (Lawrence and Upchurch, 1982). In the pre-monsoon samples, we observed that in the component 1Mg, TDS, TH, and EC show very high loadings, but Ca, Na, K, HCO_3, Cl, NO_3, and SO_4 show moderate to high loadings. In the post-monsoon samples Ca, NO_3,TDS, EC and TH show moderate to high loadings. Ca, Mg, Cl, and SO_4 play important role in determining TDS, EC, and TH in the pre-monsoon as well as the post-monsoon. Component 1 is regulated by various hydro-geochemical processes like mineralization of the sampling location, soil conditions, anthropogenic activity, and rainfall intensity. However, the cation exchange mechanisms at the soil-water interface are controlled by Na and Mg (Guo and Wang, 2004).

Table 5 Total variance (pre-monsoon)			
Initial Eigenvalues			
Component	Total	% Of Variance	Cumulative %
1	8.378	55.854	55.854
2	1.627	10.844	66.698
3	.962	6.410	73.108
4	.842	5.616	78.724
5	.698	4.654	83.378
6	.641	4.270	87.648
7	.517	3.445	91.094
8	.468	3.121	94.215
9	.357	2.377	96.592
10	.189	1.262	97.854
11	.163	1.087	98.941
12	.110	.733	99.674
13	.036	.238	99.912
14	.012	.080	99.992
15	.001	.008	100.000
Extraction Sums of Squared Loadings			
Total	% Of Variance		Cumulative %
8.378	55.854		55.854
1.627	10.844		66.698
Rotation Sums of Squared Loadings			
Total	% Of Variance		Cumulative %
7.871	52.471		52.471
2.134	14.227		66.698

Table 6 Total variance (post-monsoon)			
Initial Eigenvalues			
Component	Total	% Of variance	Cumulative %
1	8.190	54.598	54.598
2	1.406	9.373	63.971
3	1.088	7.255	71.226
4	.949	6.324	77.550
5	.803	5.350	82.900
6	.604	4.024	86.924
7	.581	3.877	90.801
8	.448	2.985	93.786
9	.377	2.512	96.298
10	.222	1.477	97.775
11	.150	1.000	98.775
12	.107	.712	99.487
13	.062	.412	99.898
14	.013	.088	99.986
15	.002	.014	100.000
Extraction Sums of Squared Loadings			
Total	% Of Variance		Cumulative %
8.190	54.598		54.598
1.406	9.373		63.971
1.088	7.255		71.226
Rotation Sums of Squared Loadings			
Total	% Of Variance		Cumulative %
6.598	43.989		43.989
2.974	19.828		63.817
1.111	7.409		71.226

In the second component, we can see high loadings in F, pH, and temperature and, Fe shows negative interaction in the pre-monsoon as well as the post-monsoon sampless except Fe. When minerals including silicates, fluorite, fluorapatite, and volcanic ash are dissolved, the concentration of fluoride in groundwater rises (Hem, 1989). Fluorite is most commonly found in sedimentary, volcanic, and plutonic rocks. It can also be found in granite, gneiss, and pegmatite rocks (Rama Rao, 1982; Heinrich, 1948). Weathering of such rocks leaches out fluoride (Singh et al., 2011). Because of the high pH loading, we assume that the sources are likely organic or biogenic. Component 3 is only observed in the post-monsoon samples and most of the components are negatively correlated except Fe which is due to influencing components 1 & 2 present in factor 3.

The current assessment primarily assists in extracting information regarding ion sources and variables impacting groundwater quality (Islam et al., 2018). It can be summarized that four extracted PCs denote four dissimilar processes viz.:

(a) Geological processes such as weathering and dissolution of the minerals matter.
(b) Agricultural activities.
(c) Industrial effluent discharges.
(d) Rainfall intensity.
(e) Domestic waste waters.

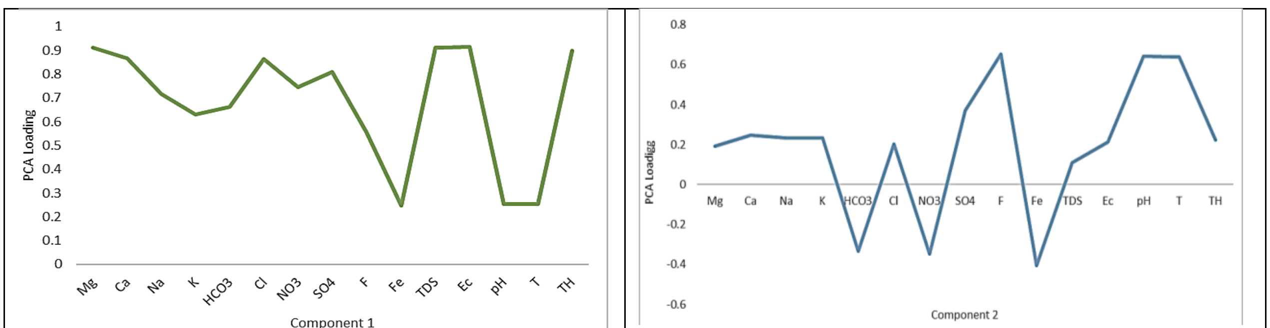
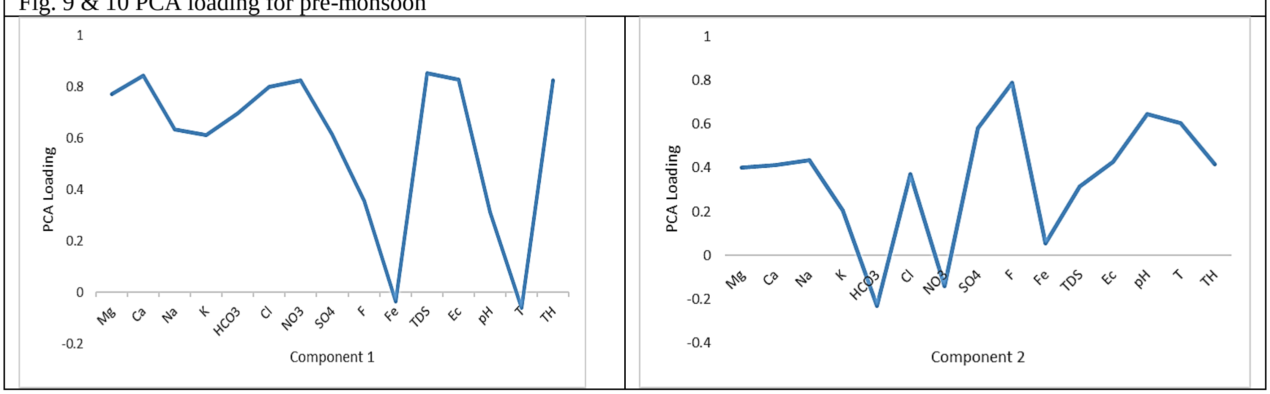


Fig. 9 & 10 PCA loading for pre-monsoon



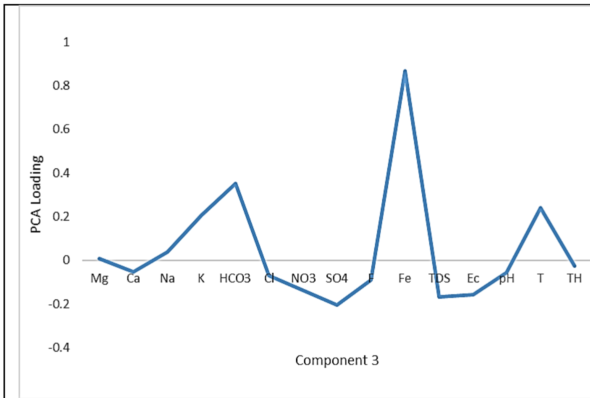


Fig. 11, 12 & 13 PCA loading for post-monsoon

Tab.7 Rotated Component Matrix

	Component	
	1	2
Mg	.913	.192
Ca	.866	.246
Na	.716	.232
K	.632	.232
HCO_3	.664	-.334
Cl	.863	.203
NO_3	.745	-.347
SO_4	.810	.370
F	.558	.651
Fe	.248	-.406
TDS	.911	.109
Ec	.914	.213
pH	.255	.643
T	.254	.640
TH	.899	.224

Tab. 8 Rotated Component Matrix

	Component		
	1	2	3
Mg	.772	.403	.007
Ca	.845	.414	-.052
Na	.636	.435	.039
K	.612	.207	.208
HCO_3	.696	-.230	.352
Cl	.799	.370	-.069
NO_3	.825	-.140	-.136
SO_4	.617	.581	-.206
F	.356	.789	-.089
Fe	-.035	.056	.867
TDS	.853	.316	-.167
Ec	.829	.428	-.156
pH	.313	.644	-.056
T	-.059	.603	.241
TH	.826	.416	-.027

There are different types rotation techniques available such as varimax, equamax, and quartimax, but varimax rotation is largely practiced, which includes an orthogonal rotation and it is complex to explain in the present study. The overall concept of this method was described by Kaiser (1958). Factor analysis extracts and produces new rotational factors (Tables 7 & 8) in which the meaning of each factor may be explained by the variables that have the greatest impact on it. The rotation mode analysis reveals a number of good characteristics that help to analyse the dataset more effectively. For all the samples, factor scores were generated, revealing the significance of a given component at that sample site. Extremely negative and positive PC scores indicate that the area is unaffected and largely influenced, respectively, by the variables influencing PC, whilst a result close to zero indicates that the area is affected to an average degree by the chemical process of that factor (Senthilkumar et al., 2008). This study inferred that the area is moderately affected by the chemical process as the scores are close to zero. Water Quality Index (WQI): For the calculation of the water quality index, 14 relevant parameters were chosen in the present study. The concentration of the WQI was measured using the drinking water quality criteria recommended by the world health organization (WHO), the Indian Standard Bureau (BIS) and the Indian Medical Research Council (ICMR). For the determination of the water's WQI, the weighted arithmetic index method (Brown et. al., 1972) was used.

The WQI was used to obtain a detailed image of overall groundwater quality. WQI is defined as a rating that represents the cumulative effect of various parameters of water quality on the overall water quality. Three steps were taken to compute the WQI. First, the weight (wi) was allocated to each of the 14 parameters i. e., Electrical Conductivity (EC), pH, Total Dissolved Solids (TDS), Calcium (Ca_2), Magnesium (Mg_2), Chloride (Cl^-), Sulphate (SO_4^-), Nitrate (NO_3^-), Total Hardness (TH), Potassium (K), Bicarbonate (HCO_3), Sodium (Na) Fluorides (F^-), and Iron (Fe) and according to its relative significance in the overall water quality for drinking purposes (Table 9).

Tab. 9 Weight (wi) and Relative weight (Wi) of parameter			
Parameter	Standard (Sn)	Weightage (wi)	Relative weight (Wi)
Ca	75	1	0.052631579
Mg	30	1	0.052631579
Cl	250	1	0.052631579
NO_3	45	2	0.105263158
SO_4	200	1	0.052631579
F	1	2	0.105263158
Fe	0.3	3	0.157894737
TDS	500	1	0.052631579
EC	300	1	0.052631579
TH	200	1	0.052631579
pH	6.5 – 8.5	1	0.052631579
HCO_3	244	1	0.052631579
Na	20	2	0.105263158
K	10	1	0.052631579
		19	$\sum Wi = 1$

Step 1

Nitrate was assigned a maximum weight of 5 because of its major importance in determining water quality; zinc was assigned a minimum weight of 1 because of its insignificant importance. Weights between 1 and 5 were assigned to other parameters, such as Electrical Conductivity (EC), pH, Total Dissolved Solids (TDS), Calcium (Ca_2), Magnesium (Mg_2), Chloride (Cl^-), Sulphate (SO_4^-), Nitrate (NO_3), Total Hardness (TH), Potassium (K), Bicarbonate (HCO_3), Sodium (Na) Fluorides (F^-), and Iron (Fe), based on their relative importance in the water quality assessment. The present investigation for F and Fe was given more weightage because of their impact more in the study area.

Secondly, the chemical parameter's relative weight (Wi) was computed using the following equation:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}$$

On summation of all selected parameters unit weight factor Wn = 1 (unit).

Step 2

Calculation of Quality rating (Qi) values by using formula.

$$Qi = \frac{Ci}{Si} \times 100$$

Where

Ci = Mean concentration of the n^{th} parameter.

Si = Standard desirable value of the n^{th} parameter.

Vo = Actual values of the parameter in the pure water (Generally, Vo = 0, for most of the parameters except pH and Turbidity)

$$QpH = \frac{\text{VpH} - 7}{8.5 - 7} \times 100$$

Step 3

Calculation of Sub-index (SIi) by using formula:

$$SIi = Wi \times Qi$$

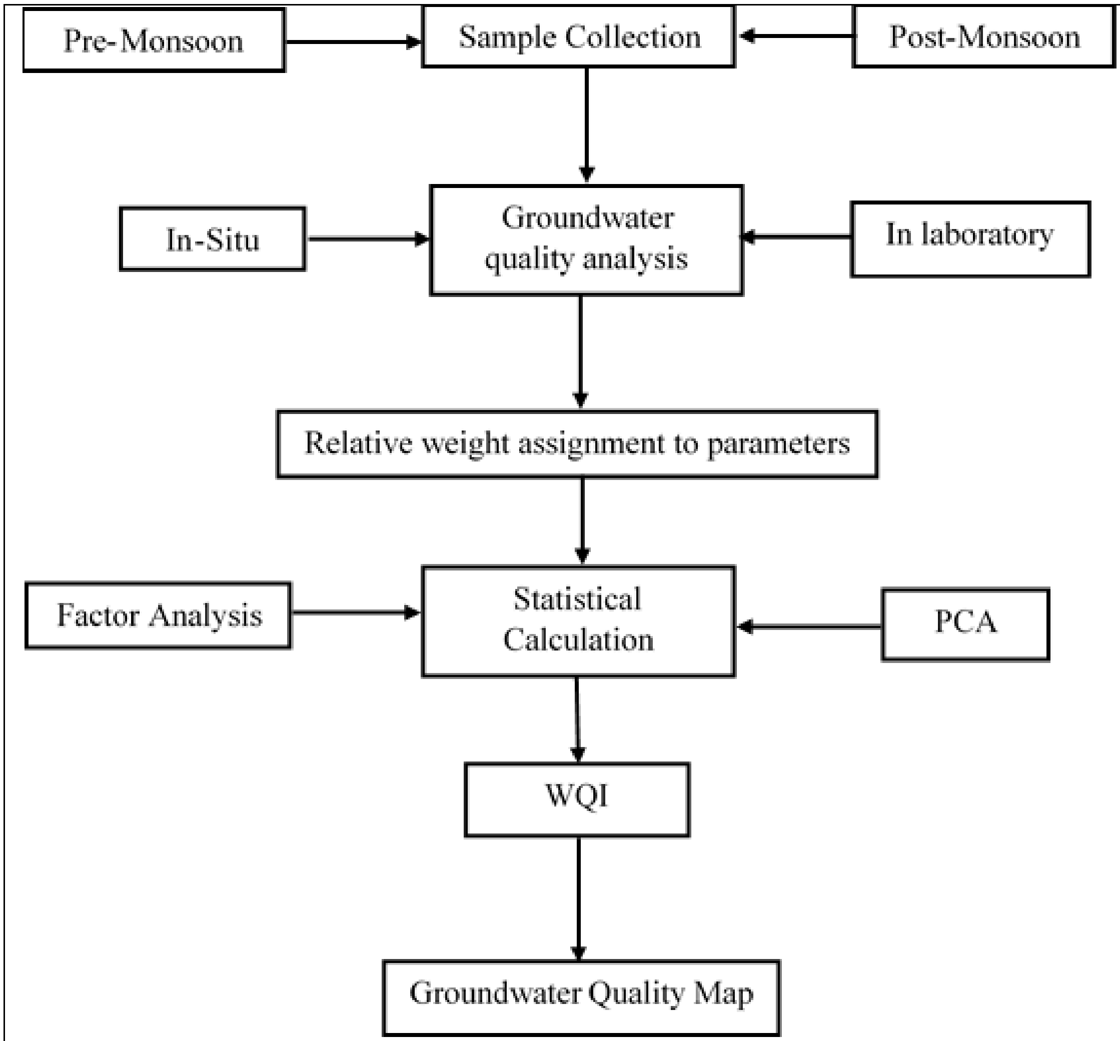


Fig. 16 Flow chart

Step 4

Combining step-2 and step-3. WQI is calculated as follows:

$$WQI = \sum SI\text{i-n}$$

Present study assessment of groundwater for drinking was carried using 14 relevant parameters, then using WQI water was classified. WQI is one of the best tools which work effectively in understanding groundwater quality (Mishra and Patel, 2001; Subba Rao, 1997). By comparing the WQI analytical results to the disclaimers established by the Indian Standards, the groundwater was evaluated for anthropogenic consumption (BIS 2012). The range of ionic concentration of groundwater in Table 2 and the standard of drinking water set by Indian standards is mentioned in Table 1. Classification of groundwater into five classes based on the WQI values (Table 11) and type of groundwater for each groundwater sample is given (Table 10).

Table 11 Classification of WQI

WQI Range	Class of water	No. of samples			
		Pre-monsoon	%	Post-monsoon	%
0-25	Excellent	35	36.84	56	58.94
26-50	Good	27	28.42	16	16.84
51-75	Poor	9	9.47	9	9.47
76-100	Very Poor	4	4.21	10	10.52
>100	Unfit	20	21.05	4	4.21

In the present analysis, the calculated values of WQI range from 5.42 to 357.51 in the pre-monsoon and 2.52 to 225.97 in the post-monsoon samples. Groundwater was classified into five categories from ‘‘excellent water’’ to ‘‘unfit water for drinking’’. The number of samples of each class and their percentage are given in tale. 11. Geographically study area can be classified as Malenadu and Maidana. Water quality during the pre-monsoon period in Malenadu is excellent to good but in Maidana water qualityis deteriorating, same consequences repeat in the post-monsoon period also but the concentration of minerals is low as compare to the pre-monsoon period. Due to leaching of minerals samples show a higher concentration of ions. The spatial variation in WQI in the pre-monsoon as well as post-monsoon samples is given in figures 15 & 16

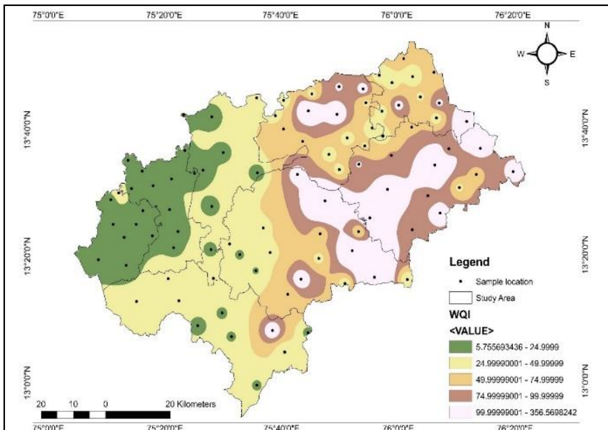


Fig. 15 Spatial distribution of WQI premonsoon

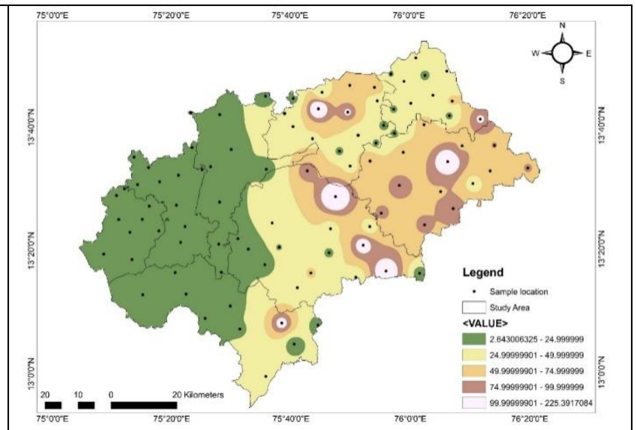


Fig. 16 Spatial distribution of WQI post-monsoon

CONCLUSION

To gain a quick overview of the data and understand the variation in the groundwater quality, descriptive statistics and various themes were used. To better infer the data, Pearson's correlation matrix was constructed using the scatter matrix graph. The correlation matrix is useful because it shows the relationship between variables and the function of each parameter. For groundwater quality, the correlation coefficient and factor analysis using PCA demonstrated that geological processes are important factors, such as weathering, industrial discharges, organic matter, and fertilizers from agricultural activities and dissolution of minerals which determine the quality of groundwater.

Water Quality Indices indicate the overall water quality status of groundwater in the study area. It is necessary to identif and maintain the quality of groundwater for sustainable growth. Allocate resources for drinking water depending on the quality of the groundwater. In the study area, the WQI changes over time indicating a decline in the quality of groundwater. The GIS application was used to create several digital theme maps, according to the analysis of the data generated at different phases of the work. The descriptive statistics and WQI suggest that priority should be given to water quality monitoring and its management in semi-arid areas like Kadur, Tarikere, and the parts of chikamagaluru taluks. Most of the population in the plain area depend on groundwater for drinking.

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Table 10 Water quality index values for groundwater samples.

Sl. No.	Location	Pre-monsoon		Post-monsoon		Sl. N0.	Location	Pre-monsoon		Post-monsoon	
		WQI Value	Remark	WQI Value	Remark			WQI Value	Remark	WQI Value	Remark
1	Jannapura	23.91	Excellent	10.70	Excellent	25	Kalasapura	306.09	Unfit	59.89	Poor
2	Gowthahalli	17.07	Excellent	11.96	Excellent	26	K B Hal	29.00	Good	13.10	Excellent
3	Hosakere	22.35	Excellent	27.16	Good	27	Mavinahalla	55.31	Poor	35.38	Good
4	Kottgehara	16.91	Excellent	38.50	Good	28	Sirivase	42.18	Good	35.46	Good
5	Durgadahalli	43.81	Good	11.79	Excellent	29	Aladagudde	138.5	Unfit	53.03	Poor
6	Mudigere	48.70	Good	19.96	Excellent	30	Lakya	984.41	Unfit	34.13	Good
7	Hornadu	29.04	Good	18.23	Excellent	31	Kichevi	28.95	Good	10.19	Excellent
8	Nidduvale	20.94	Excellent	13.25	Excellent	32	Chikkamagaluru	38.11	Good	18.13	Excellent
9	Innare	21.73	Excellent	22.48	Excellent	33	Magadi	32.03	Good	23.99	Excellent
10	Kuduremuka	131.5	Unfit	17.63	Excellent	34	Kabbinasethuve	52.31	Poor	41.41	Good
11	Balagere	12.02	Excellent	9.71	Excellent	35	Uddeboranahalli	45.15	Good	23.52	Excellent
12	Kerekatte	66.74	Poor	4.60	Excellent	36	Sangameshwarapetd evadana	20.41	Excellent	9.05	Excellent
13	Nemmaru	7.39	Excellent	3.69	Excellent	37	Avathi	39.85	Good	24.1	Excellent
14	Sringeri	9.15	Excellent	4.05	Excellent	38	HosapetTogarihankl u	357.51	Unfit	225.41	Unfit
15	Kavadi	19.36	Excellent	5.19	Excellent	39	Kesavinamane	184.13	Unfit	99.47	Very Poor
16	Begar	46.86	Good	2.74	Excellent	40	kanathi	21.81	Excellent	15.73	Excellent
17	Kigga	12.33	Excellent	11.59	Excellent	41	Mathigatta	90.61	Very Poor	73.64	Poor
18	Kuntur	13.18	Excellent	9.71	Excellent	42	Yagati	89.47	Very Poor	72.90	Poor
19	Asanabalu	13.16	Excellent	8.26	Excellent	43	Hochigalli	111.89	Unfit	75.68	Very Poor
20	Hariharapura	22.26	Excellent	12.02	Excellent	44	Antharagatta	107.75	Unfit	52.86	Poor
21	Kalkere	19.33	Excellent	9.43	Excellent	45	hogarehalli	105.03	Unfit	77.32	Very Poor
22	Jayapura	16.44	Excellent	10.09	Excellent	46	Uligere	62.55	Poor	52.61	Poor
23	Guddethotha	18.43	Excellent	10.27	Excellent	47	Sakkarayapattana	162.79	Unfit	84.07	Very Poor

24	Koppa	22.47	Excellent	8.13	Excellent	48	Singatigere	42.48	Good	33.50	Good
49	Kudregundi	17.69	Excellent	8.64	Excellent	77	Tarikere	162.46	Unfit	109.08	Unfit
50	Kammaradi	17.90	Excellent	5.43	Excellent	78	Saraswathipura	154.6	Unfit	96.70	Very Poor
51	Shanuvalli	17.44	Excellent	9.49	Excellent	79	Hadikere	103.88	Unfit	57.71	Poor
52	Siddaramata	21.47	Excellent	14.99	Excellent	80	Hunsanghatta	44.00	Good	33.79	Good
53	Bhandigadi	11.65	Excellent	2.52	Excellent	81	Mundre	46.81	Good	19.06	Excellent
54	Magudi	31.53	Good	6.81	Excellent	82	DoddaKunduru	69.27	Poor	35.82	Good
55	Balehonnur	19.19	Excellent	7.42	Excellent	83	Sevalal Nagar	28.25	Good	16.00	Excellent
56	Seethur	10.62	Excellent	4.46	Excellent	84	Sasuvehalli	26.63	Good	16.94	Excellent
57	N R Pura	14.57	Excellent	6.42	Excellent	85	attigatta	28.50	Good	22.16	Excellent
58	Muttinakoppa	10.25	Excellent	8.34	Excellent	86	Veerapura	25.03	Good	18.17	Excellent
59	Chikka Agrahara	17.03	Excellent	9.47	Excellent	87	Mugali	43.52	Good	36.67	Good
60	Varkate	5.42	Excellent	9.35	Excellent	88	Koratikere	21.45	Excellent	19.72	Excellent
61	Munduvalli	12.7	Excellent	8.97	Excellent	89	Mudigere	28.70	Good	17.81	Excellent
62	Byrapura	24.6	Excellent	14.07	Excellent	90	Yalambaise	248.73	Unfit	186.2	Unfit
63	Lakkavalli	35.6	Good	24.06	Excellent	91	Panchanahalli	106.57	Unfit	76.13	Very Poor
64	GanteKaneve	35.3	Good	23.92	Excellent	92	Jadakanakatte	113.63	Unfit	98.91	Very Poor
65	Cheeranahalli	52.58	Poor	40.94	Good	93	Hirenalluru	71.89	Poor	57.22	Poor
66	Beeranahalli	64.12	Poor	43.86	Good	94	Birur	76.17	Very Poor	64.74	Poor
67	Ajjampura	118.8	Unfit	39.49	Good	95	Nidagatta	91.62	Very Poor	80.78	Very Poor
68	Nandi	27.97	Good	23.25	Excellent	74	Chowlahiriyur	191.3	Unfit	106.2	Unfit
69	Shivapura	24.68	Excellent	17.41	Excellent	75	Guddadamallenalli	122.5	Unfit	75.79	Very Poor
70	Udevu	33.97	Good	39.45	Good	76	Sambainur	54.84	Poor	36.30	Good
71	Duglapura	224.4	Unfit	77.51	Very Poor						
72	Chikkanvangla	33.81	Good	34.53	Good						
73	Sokke	34.12	Good	19.58	Excellent						

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Provenance, tectonic setting and palaeoclimate of Proterozoic Jiran Sandstone, Southeastern Rajasthan, India: A petrographic approach

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Abstract

Proterozoic Jiran Sandstone rests unconformably on Binota Shale and Khori-Malan Conglomerate. The Jiran Sandstone is comprised mainly of fine to medium-grained, varicolored, thickly bedded sandstones, showing diverse primary sedimentary structures such as ripple marks, planar, and trough cross-bedding. Petrographically, Jiran Sandstone is of mainly quartzarenite which is composed of varieties of quartz with ultra-scarcity of feldspar, lithic fragments, micas, and heavy minerals. Quartz is more abundant mineral shown by X-ray Diffraction Analysis. The provenance, tectonic setting, and paleoclimatic condition of the Jiran sandstone were evaluated using integrated petrographic studies. Analysis pursuant, monocrystalline and polycrystalline quartz grains and heavy minerals are driven primarily from metamorphic and plutonic Precambrian basement source rocks of a craton interior setting with a minor quartzose recycled sedimentary source material. Intensive chemical weathering in warm and humid paleoclimate is indicated by lack of feldspar and rock fragments.

Keyword: Jiran sandstone, Petrography, X-ray Diffraction, Provenance, Tectonic setting

INTRODUCTION

Provenance, tectonic setting, weathering conditions, sediment transport processes, and depositional environment greatly influence the mineralogical composition of siliciclastic rocks (Armstrong-Altrin, 2015; Dickinson, 1988; Johnsson and Basu, 1993; Boggs, 2006; Critelli, 2018). Siliciclastic rock provenance analyses often aims to determine the composition and geological evolution of the sediment source area, as well as constrain the tectonic setting of the basin (Verma and Armstrong-Altrin, 2013 & 2016; Dickinson, 1985). Classification, tectonic setting, provenance, and paleoclimatic condition of Jiran Sandstone investigated by the study of quantitative mineralogical evolution of quartz, feldspar, rock fragments, and undulosity in detrital quartz. The frequency of several types of quartz grains was utilized to evaluate the source rock type (Basu et al., 1975; Tortosa et al., 1991), the framework mineralogical composition reflects the tectonic setting of sandstone (Crook, 1974; Dickinson and Suczek, 1979; Ingersoll and Suczek, 1979; Dickinson et al., 1983; Dickinson, 1985) and type of sandstone classified by Folk (1980) classification scheme. Suttner et al. (1981) model is used to explain the paleoclimatic conditions that occurred during the weathering of the source rock. Two analytical approaches for determining the mineralogical composition of sandstone have been investigated in this study: (i) Petrography (optical examination of thin sections), (ii) X-ray Diffraction (XRD). The principal objectives of this research are to determine the composition of the source area, the tectonic setting, and interpret paleoclimatic conditions during the deposition of the Jiran Sandstones of Southeastern Rajasthan.

Geologic Background of the Study Area

The Vindhyan Supergroup forms an unmetamorphosed succession in an intracratonic sedimentary basin exposed in the form of an arcuate belt that is locally affected by folding and faulting and is one of the best-preserved Meso-Neoproterozoic sequences in India (Singh et al., 2020). On the basis of its diverse tectonic settings, the Vindhyan Supergroup is divided into two major successions. The Lower Vindhyan deposited in an intracratonic rift basin (Bose et al., 1997) and Upper Vindhyan in an intracratonic sag basin (Sarkar et al., 2002). On the basis of lithology, carbonate dominant sedimentary rocks of Lower Vindhyan is overlain by siliciclastic dominant sedimentary rocks of Upper Vindhyan (Sen et al., 2014). Lower Vindhyan succession in Rajasthan constitutes the Satola, Sand, Lasrawan, and Khorip groups in ascending stratigraphic order can be correlated with the Semri Group of lower Vindhyan in Son valley (Auden, 1933; Malone, 2008). The Upper Vindhyan Supergroup comprises from base to top are Kaimur, Rewa, and Bhander groups (Gopalan et al., 2013). Unconformity was identified between the Semri and succeeding groups of Upper Vindhyans (Soni et al., 1987). The generalised stratigraphy of Vindhyan

Supergroup, southeastern Rajasthan is given in figure 1. The Vindhyan basin in Rajasthan is bordered on the northwest by the Delhi-Aravali orogenic belt and on the southeast by the Satpura orogenic belt. The Aravali and Satpura mobile belts are tectonic in nature, with intrinsic disturbances marked by the presence of large zones of displacement in the west, such as the Great Boundary Fault Zone (GBFZ), and the Central Indian Tectonic Zone (CITZ) in the south. The Great Boundary Fault is a significant lineament with a NE and SW trend that separates the Aravali-Delhi orogen from the Vindhyan basin (Khan, 2013). The Vindhyan Supergroup rests over Palaeoproterozoic Delhi-Aravali Supergroup and Archean Berach granite (Raza et al., 2012). The geological map of the Lower Vindhyan in Rajasthan is given in figure 2. Khorip Group of Lower Vindhyan consists of Khori-Malan Conglomerate (Fig. 3a) at the base, followed by Jiran Sandstone (Fig. 3b), Bari Shale (Fig. 3c), Nimbahera Limestone, and Suket Shale formations successively overlying Binota Shale of Lasrawan Group. The Jiran Sandstone unconformably overlies the Binota Shale and Khori-Malan Conglomerate, occurring as the long ridges and hillocks. The Jiran Sandstone is consisting mainly of sandstone with shale intercalation at some places (Fig. 3d). These sandstones mostly show gradational contact with underlying Binota Shale and overlying Bari Shale.

Sampling and Analytical Procedures

For the petrographic analysis total 24 fresh and unweathered samples were collected from the tectonically undisturbed outcrop of Jiran Sandstones. Thin sections were prepared and subjected to petrographic investigation under the petrological microscope. Thin sections were stained with sodium cobaltinitrite solution for K-feldspar identification during microscopic analysis. For Modal analysis, about 250-300 grain per thin section were counted by the point-counting method (Dickinson, 1985). Grain size counting was done using Gazzi Dickinson point counting method (Ingersoll et al., 1984). The definition of raw and recalculated parameters used in the investigation is presented in table-1 and relative proportions of quartz, feldspar, and rock fragments were determined. The counted grains were recalculated into percentage as summarized in table-2 and these tabular data were plotted in the diagrams suggested by Folk (1980), Suttner et al. (1981), and Dickinson et al. (1985) to interpret the type of sandstone, paleoclimate, provenance and tectonic setting of Jiran sandstone respectively. Sandstones were characterized by Folk (1980) classification.The source rock composition of Jiran Sandstone was determined by Basu et al. (1975) model.

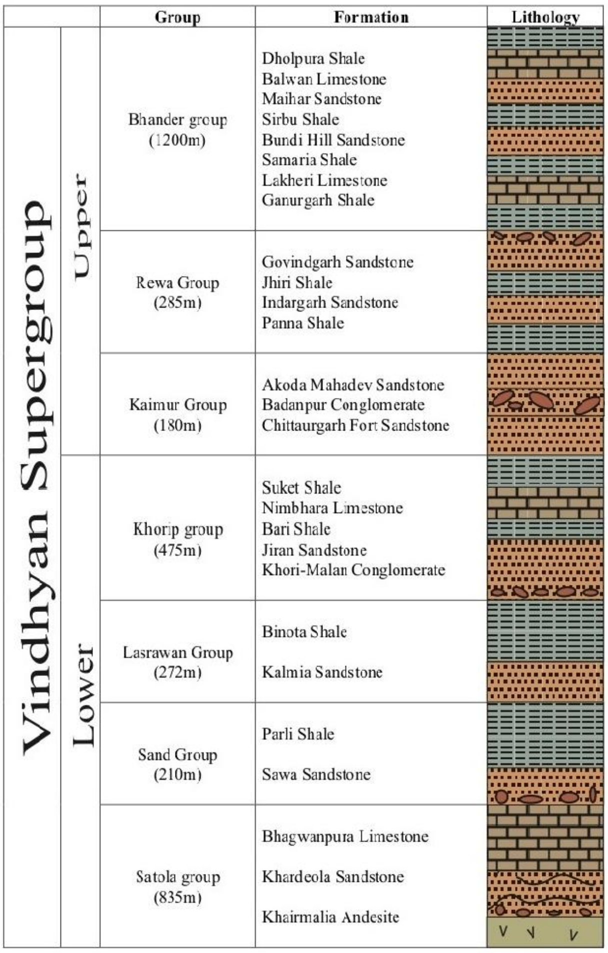

Fig. 1: Generalized stratigraphy of Vindhyan Supergroup, southeastern Rajasthan, modified after Malone et al. (2008) and Khan (2013).

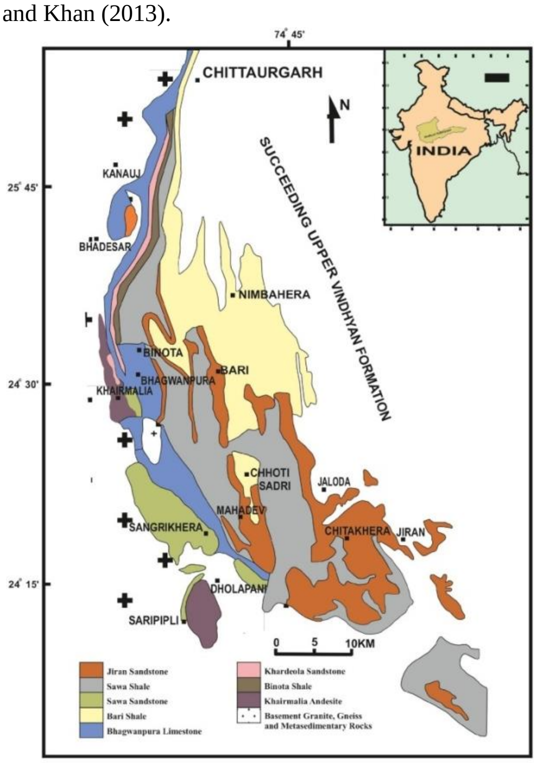

Fig.2: Geological map of Lower Vindhyan Basin (Along western margin), Southeastern Rajasthan.

Fig.3: Field Photographs of the study area, (a) Khori - Malan conglomerate, (b) Jiran Sandstone, (c) Bari Shale, (d) Intercalation of Jiran Sandstone and Bari Shale.

Table 1: Key for counted and recalculated petrographic framework grain parameters of sandstones, after Folk (1980), Dickinson and Suczek (1979), Suttner and Dutta (1986).

QFR	QtFL	QmFLt
Q = Total quartz grain (Qm+Qp), where Qm = Monocrystalline quartz Qp= Polycrystalline quartz F = Total feldspar (P+K), where P = Plagioclase, K = K-feldspar R = Total rock fragments including chert	Qt = Total quartz grain (Qm+Qp), where Qm = Monocrystalline quartz Qp = Polycrystalline quartz including chert F= Total feldspar (P+K), where P = Plagioclase, K = K-feldspar L= Total lithic fragments	Qm = Monocrystalline quartz F = Total feldspar (P+K), where P = Plagioclase, K = K-feldspar Lt = Total lithic fragments + Polycrystalline quartz

After useful thin section screening, five representative samples were selected for X-ray diffraction analysis. Bulk powder samples of Jiran Sandstones were quantitatively analyzed by X-ray diffractometer (XRD in Lab, Department of Physics, AMU, Aligarh) for their mineral composition. The samples were scanned in 2θ range of 5°- 40° with X-rays using Cu (λ=1.540598) target source for crystalline phase identification. Obtained "Intensity vs. 2 θ" data were plotted and identified minerals peaks.

RESULTS

Petrographic study and X-ray Diffraction of sandstone

Jiran Sandstones are pinkish white to dirty white quartzarenite, the significant proportion of detrital grains of the sandstone are showing subangular to sub-rounded, moderately to well sorted with fine to medium grain size. The detrital grains of sandstone are composed mainly of varieties of quartz (97.02 %) with ultra-scarcity of feldspar (0.3 %), lithic fragments (1.74 %), micas (0.35 %), and heavy minerals (0.32 %). All of the sandstone samples data shown in the QFR triangle diagram indicate close distribution in the quartzarenite field, indicating that sandstone is mostly quartzarenite with little variance in mineralogy (Fig. 4a). Quartz is the most dominant detrital grain in sandstone. Among dominant quartz grain, monocrystalline quartz is dominant over polycrystalline quartz (Fig. 5a).

Table 2: Recalculated percentages of detrital grain modes of Jiran Sandstone, Southeastern Rajasthan.

Sample	QFR			QtFL			QmFLt		
	Q	F	R	Qt	F	L	Qm	F	Lt
JJST – 1	100.00	0.00	0.00	100.00	0.00	0.00	98.33	98.33	98.33
JJST – 2	97.48	0.25	2.27	98.75	0.25	1.00	96.16	96.16	96.16
JJST – 3	99.69	0.00	0.31	100.00	0.00	0.00	96.07	96.07	96.07
JJST – 4	99.26	0.20	0.54	99.26	0.20	0.54	98.73	98.73	98.73
JJST – 5	99.70	0.00	0.30	99.70	0.00	0.30	89.42	89.42	89.42
JJST – 6	99.05	0.32	0.63	99.39	0.32	0.28	97.47	97.47	97.47
JJST – 7	99.80	0.00	0.20	99.80	0.00	0.20	97.98	97.98	97.98
JJST – 8	97.10	0.45	2.44	97.97	0.46	1.57	95.67	95.67	95.67
CJST – 1	91.22	1.21	7.57	97.01	1.28	1.71	91.22	91.22	91.22
CJST – 2	97.40	0.00	2.60	98.44	0.00	1.56	95.50	95.50	95.50
CJST – 3	98.52	0.00	1.48	98.52	0.00	1.48	94.50	94.50	94.50
CJST – 4	99.74	0.00	0.26	99.74	0.00	0.26	97.30	97.30	97.30
CJST – 5	98.85	0.56	0.58	99.43	0.57	0.00	96.98	96.98	96.98
CJST – 6	97.58	0.49	1.93	97.58	0.49	1.93	94.18	94.18	94.18
CJST – 7	100.00	0.00	0.00	100.00	0.00	0.00	95.83	95.83	95.83
CJST – 8	99.15	0.44	0.40	99.37	0.45	0.18	96.78	96.78	96.78
BJST – 1	99.19	0.32	0.49	99.47	0.32	0.20	95.78	95.78	95.78
BJST – 2	95.95	0.61	3.43	98.01	0.63	1.37	95.82	95.82	95.82
BJST – 3	96.83	0.36	2.81	97.65	0.37	1.98	95.13	95.13	95.13
BJST – 4	95.08	0.66	4.25	98.56	0.69	0.75	95.07	95.07	95.07
BJST – 5	98.33	0.32	1.34	99.67	0.33	0.00	98.59	98.59	98.59
BJST – 6	95.08	0.42	4.50	95.63	0.43	3.95	93.80	93.80	93.80
BJST – 7	97.94	0.60	1.46	98.99	0.61	0.40	95.12	95.12	95.12
BJST – 8	97.59	0.00	2.41	98.38	0.00	1.62	95.84	95.84	95.84

Monocrystalline quartz has undulose as well as nonundulose variety and polycrystalline quartz grains are mainly composed of randomly oriented crystallites with straight to undulose extinction. Some of the monocrystalline quartz grains show the inclusions of heavy minerals (Fig. 5b). Some of the quartz grains show silica overgrowth and most of the quartz grains show triple junction, dominant long, concavo-convex contacts are common (Fig. 5c). The framework grains of sandstone are cemented by mainly silica, ferruginous (Fig. 5d) cement, and matrix (Fig. 5e). Feldspar grains population is rarely present in thin sections; microcline is the common variety of k-feldspar dominates over plagioclase. Rock fragments are absent in many thin sections, identified rock fragments mainly are of volcanic (Fig. 5f), chert (Fig. 6a), shale, and metamorphic (phyllite, schist) rocks (Fig. 6b). Sparkling color of muscovite (Fig. 6c) and heavy minerals mainly rounded zircon (Fig. 6d), tourmaline (Fig. 6e), and rutile (Fig. 6f) are present in sandstones.

Using bulk X-ray diffraction spectrum analysis, mineralogical investigations of Jiran Sandstone revealed a high intensity and dominating quartz (Fig. 7). As a result, the principal binding materials and dominant framework grains are silica.

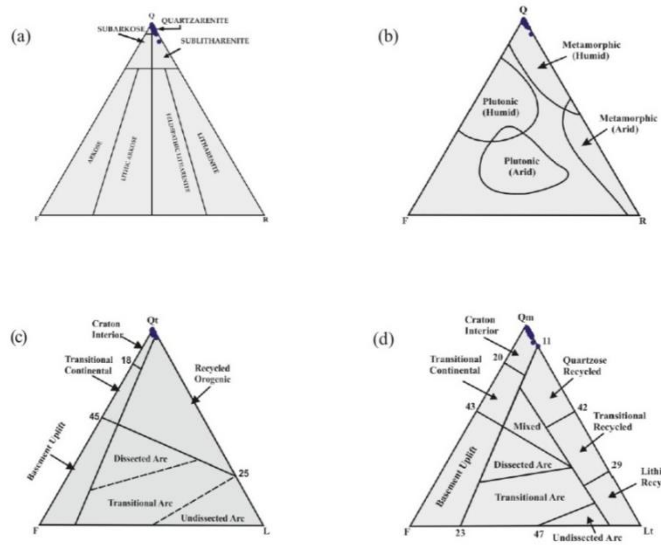

Fig. 4: Ternary plots of Jiran Sandstone, (a) QFR diagram, after Folk (1980), (b) QFR diagram after Suttner et al. (1981), (c & d) QtFL & QmFLt diagrams, after Dickinson et al. (1985).

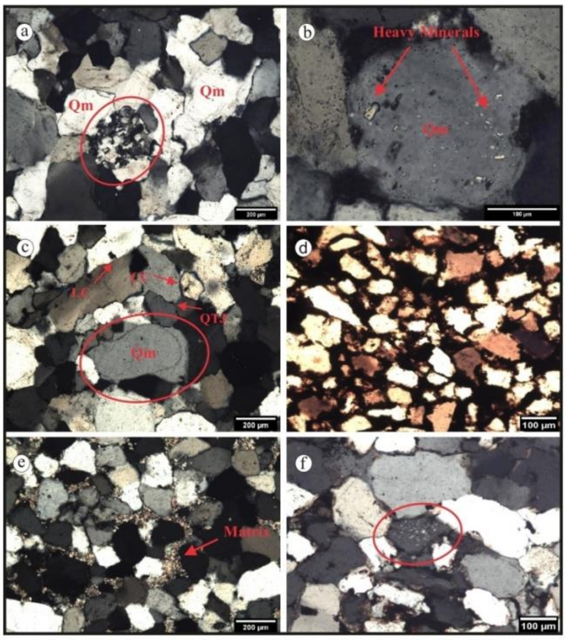

Fig. 5: Photomicrographs of Jiran Sandstones, (a) Medium size polycrystalline quartz grain, (b) Heavy mineral inclusions in monocrystalline quartz grain, (c) Grain of monocrystalline quartz with silica overgrowth and arrows show quartz grain triple junction (QTJ), Long Contact (LC), Concavo-Convex Contact (CC), (d) Ferruginous cement, (e) Matrix, (f) Volcanic Rock Fragment.

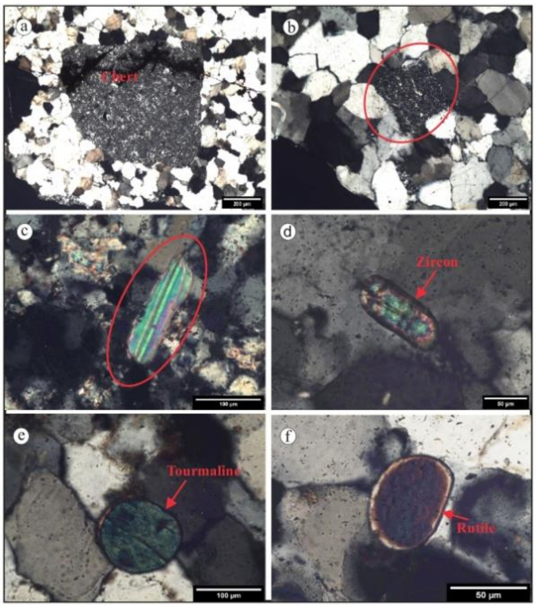

Fig. 6: Photomicrographs of Jiran Sandstones, (a) Chert, (b) Metamorphic Rock Fragment, (c) Sparkling color of muscovite flake between quartz grains, (d) Rounded zoned zircon grain, (e) Rounded greenish tourmaline, (f) Rounded rutile.

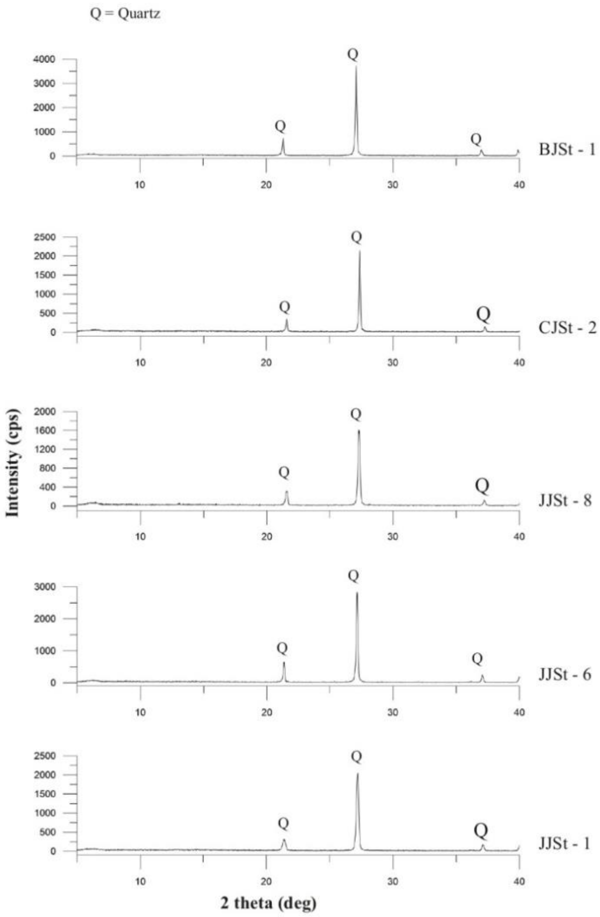

Fig. 7: X-ray diffraction pattern of Jiran Sandstone shows peaks of Quartz (Q).

DISCUSSION

Provenance and Palaeoclimatic conditions

Various petrographic techniques, such as the study of polycrystallinity and undulosity of quartz grain (Basu et al., 1975; Young, 1976), types of feldspar (Pittman, 1970), and type of heavy minerals (Morton, 1985) have been used to establish the provenance of Jiran Sandstone. Due to the ultra-deficiency of feldspars and rock fragments in the samples, provenance was mainly determined by quartz type and the examination of heavy minerals. In the sandstone sample, dominant medium to strong undulose monocrystalline quartz grains indicates a metamorphic origin, whereas mildly undulose to non-undulose quartz grains indicate a plutonic origin (Basu, 1975; Potter, 1978a). According to Basu et al. (1975), Diamond diagrams of polycrystalline quartz vs. non-undulatory and undulatory monocrystalline quartz reveal a dominant metamorphic with plutonic origin (Fig. 8).The heavy minerals observed, mostly zircon, tourmaline, and rutile, indicate an alkaline plutonic rock source (Preston et al., 2002; Wanas and Abdel-Maguid, 2006), with some quantity of garnet suggesting a metamorphic source rock (Morton, 1985; Morton et al., 1992), and moderately rounded to rounded zircon grains indicating reworked sedimentary sources (Chaudhuri et al., 2018). Zircon and opaque mineral inclusions in certain monocrystalline quartz grains suggest plutonic origin (Krynine,1940). As a result of the availability of heavy mineral types, the Jiran Sandstone is originated from metamorphic, igneous, and sedimentary rock sources.

The variation in the framework mineralogy or compositional maturity of sandstone is influenced by the climate. Climate is thought to be the most important element influencing maturity (Young et al., 1976; Suttner et al., 1981; Franzinelli and Potter, 1983; Ghosh and Kumar, 2000). The lack of feldspar and rock fragments suggests that source rocks were subjected to extensive weathering over a long period in a warm, humid climate (Pettijohn et al., 1987; Amireh, 1991) and also indicating that sandstones were originated from low relief interior part of the craton (Burnett and Quirk, 2001; Patra et al., 2014). Jiran Sandstone is plotted in a metamorphic source with a humid climatic field in the QFR ternary diagram (Suttner et al., 1981) (Fig. 4b). In warm and humid climatic conditions, feldspar and other unstable components are destroyed during weathering of igneous and metamorphic source rock. Phyllite rock fragments indicate low to medium metamorphic rocks in the source, whereas shale and chert fragments indicate derivation from the sedimentary source rock. Shale and phyllite are unstable rock fragments that are usually disintegrated in humid climates; hence their retention implies a very slow source material transportation rate and/or a low subsidence rate in a passive tectonic setting. NE-SE paleocurrent data shows provenance lies in NW to SW direction (Prasad, 1984). Paleocurrent of Vindhyans of Rajasthan suggests Palaeoproterozoic Delhi-Aravali Supergroup including Berach granite rocks are the most probable source of this sandstone.

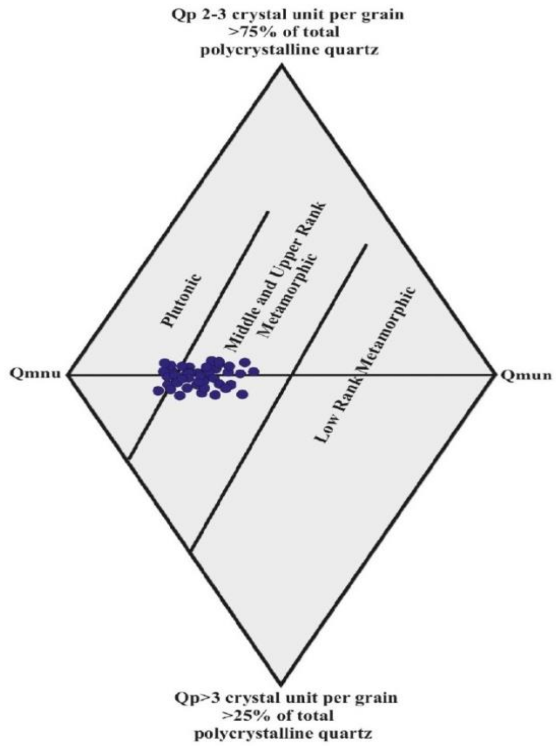

Fig. 8: Diamond diagram plot of Jiran Sandstone, a plot between polycrystalline quartz vs. non-undulatory and undulatory monocrystalline quartz. Qmnu: Low undulosity monocrystalline quartz grains; Qmun; High undulosity monocrystalline quartz grains; Qp 2-3: Coarse-grained polycrystalline quartz grains; Qp>3: Fine-grained polycrystalline quartz grain. Jiran Sandstone is compared with the provenance field, after Basu et al. (1975).

Tectonic setting

The principal premise behind the provenance analysis of sandstone is to consider that different tectonic setting contains characteristic of the rock type which, when eroded, produce sandstone with specific composition (Dickinson, 1985). The framework mineralogy is used to establish the tectonic setting of sandstone (Crook, 1974), characterised sandstone composition based on primary provenance types such as craton interior, basement uplifts, recycled orogens, and magmatic arcs (Dickinson and Suczek, 1979; Dickinson et al., 1983; Dickinson, 1985; Verma and Shukla, 2015). Detrital components displayed on QFR ternary diagram with significant provenance types such as craton interior, basement uplift, recycled orogeny, and magmatic arc are used to define the tectonic setting of Jiran Sandstone (Dickinson and Suczek, 1979; Dickinson et al., 1983; Dickinson, 1985). The data from the modal analysis of the Jiran Sandstone plotted in the ternary Qt-F-L and Qm-F-Lt diagrams (Dickinson et al., 1983), the examined samples fall in the craton interior and partially in recycled orogenic fields (Fig. 4c and 4d), illustrates that the Jiran sandstones are mainly mature sandstone originate from craton and medium to high rank metamorphosed supra crustal rock release quartzose debris of continental affiliation into the basin with supplemented by recycled sediment which associate with passive marginal basin.

CONCLUSIONS

The petrographic study reveals that the Proterozoic Jiran sandstone in the south-east Rajasthan is mainly quartzarenite, predominantly comprised of quartz, ultra-scarcity of feldspar, and rock fragments with various types of cementing materials are mainly silica and iron. Fine to medium detrital grains of sandstone are showing moderately to moderately well sorted, sub-angular to sub-ounded nature.

The presence of dominant long and concavo-convex contact between quartz grains, quartz overgrowth, and quartz triple junction suggests that Jiran sandstones has suffered mechanical compaction due to the pressure of overlying strata.

Petrographic attributes, mainly framework mineralogy-quartz type and heavy minerals suggest the Jiran sandstones are originated from medium to high-rank metamorphic, plutonic, and recycles sedimentary sources. Qt-F-L and Qm-F-Lt ternary diagrams suggest these sandstones were derived mainly from craton interior with comparatively low contribution from quartzose recycled orogeny.

Palaeocurrents of the sandstones supported the Precambrian basement rock of the pre-Aravalli and Berach granite as the most probable source of this sandstone.

According to the XRD analysis, the sandstone samples show almost identical minerals wirh mostly quartz peaks.

Acknowledgments

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Nature and Provenance of Heavy Mineral Distribution at Krishna River Delta, East Coast of India

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Abstract
The present study deals with four sedimentary cores viz. Turumella (120m), Inturu (160m), Ponnapalli (110m) and Nizampatnam (150m) which were recovered from the Krishna delta. Total heavy minerals wt% varies from 0.32 to 7.00 (av. 2.44%) in the study area. The major heavy minerals were noticed in four studied cores i.e. opaques (Ilmenite + magnetite), pyriboles (pyroxenes + amphiboles), garnet, zircon, monazite, rutile and other heavy minerals (epidote, kyanite, tourmaline, etc.). Heavy mineral substance in Krishna river sediments forced by basement rocks, drainage basin and weathering conditions of the river environment. The occurrence of different lithological units in the drainage basins is contributing sediments, mainly opaques (Ilmenite + magnetite) and pyriboles (Amphibole + pyroxenes) from Deccan traps as well as Archean provenance which covered more than 55% of drainage basin. The red garnets (almandine), prismatic sillimanites and rounded zircons are derived from khondalites (metapeletic rocks) and pink garnets, elongated zircons and ortho- pyroxenes are derived from charnockites of Eastern Ghat Granulite Belt (EGGB). The fresh appearance of heavy minerals indicates short residence time in depositional environment without any chemical dissolution effect. The rounded and sub rounded grains of magnetite and ilmenite indicate long distance of transportation and/or reworked nature. The sub angular grains of magnetite and ilmenite indicate that they might have been derived from nearby sources, i.e. mainly an Eastern Ghat Group of rocks. The prismatic characteristic of the sillimanite mineral grains also suggests that their derivation is from khondalitic rocks. Opaques are from Deccan traps as well as Archean provenance. Garnets, sillimanites and zircons are derived from khondalites (metapeletic rocks) and charnockites of Eastern Ghat Granulite Belt.

Key words: Heavy minerals, Deccan traps, Eastern Ghat Granulite Belt and Archean rocks.

INTRODUCTION

Heavy mineral analysis is one of the most sensitive and effective tools for provenance discrimination and can determine the source terrain and depositional environment of sediments (Morton, 1985; Morton and Hallsworth, 1994, 1999; Kwon et al., 1999; Mange and Wright, 2007; Akaram et al., 2015; Liu et al., 2015 and Meng et al., 2016). Source-rock composition, climate, relief, slope, vegetation and dynamics of the fluvial environment play an important role in controlling the composition of fluvial sand (Blatt, 1967; Suttner et al., 1981; Johnson et al., 1991). Although most sands in the geologic record at one time passed through a fluvial system, little research has been directed at evaluating controls on sand composition in river systems.

In India, detailed studies on heavy mineral variations have been restricted to some major river systems which include Godavari (Naidu, 1966), Krishna (Swamy, 1970; Krishna Rao and Swamy, 1991 and Sreenivasa Rao et al., 1995), Mahanadi (Satyanarayana, 1973), Vasishta-Godavari (Dora, 1978) and Cauvery (Seralathan, 1979). Unlike river systems, a considerable amount of information exists on the heavy mineral occurrences of the beach environments. Reddy et al. (2012) carried out a distribution study of heavy minerals in Nizampatnam-Lankavanidibba coastal sands, Andhra Pradesh, East coast of India. Nayak (2021) identified changing tropical estuarine sedimentary environments with time and metals contamination in the West Coast of India.

The objective of the present investigation is a) to study the heavy mineral distribution in different cored samples of the Krishna River delta b) to identify provenance of the heavy minerals. The details presented above clearly illustrate that though a number of studies have been carried out primarily based on surface features and samples from various subenvironemnts on different aspects of Krishna Delta. There is a distinct gap in knowledge on sub-surface studies of Krishna Delta. Hence, in order to bridge this gap in scientific information, the present study incorporates cored subsurface information to study the evolution of Krishna Delta.

STUDY AREA

The study area covers western part of a lower delta of Krishna River adjacent to Nizampatnam Bay. The cored holes fall in the area bounded in between E 80° 37' 40" and 80° 42' 03" and N 15° 54' 04" and 16° 06' 12' ' (Fig.1).

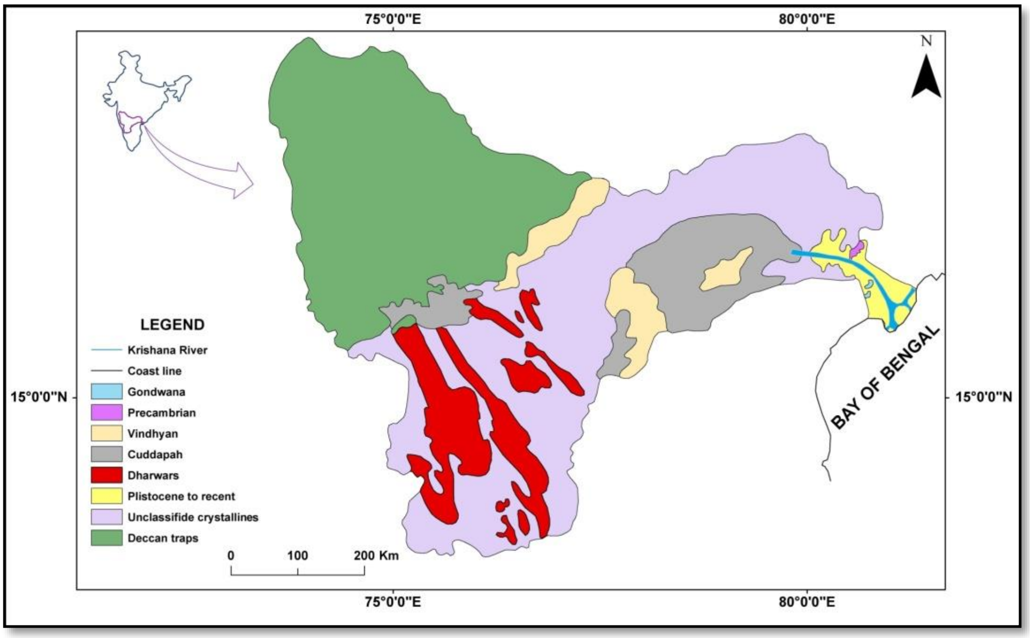

Fig. 1 Location map of the study area

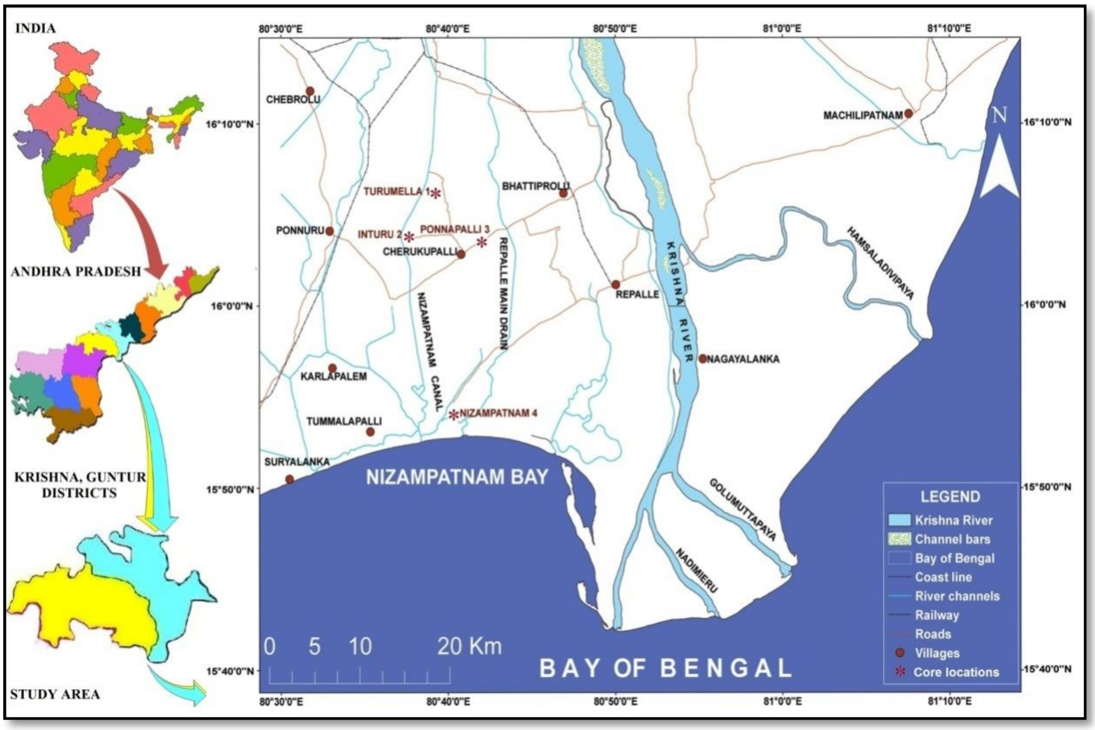

Fig. 2 Geology of the Drainage basin of Krishna River (Source: Geological Survey of India)

Geology of the Krishna River Basin

The geological formations in the Krishna River basin mainly comprise of Deccan Traps (50%), unclassified crystalline rocks of Archaeans and Precambrian sediments of Cuddapah, Vindhyan and Kurnool Super groups and Khondalites of the Eastern Ghats (Fig. 2). They exhibit uniformity in the mineralogical character and chemical composition. The normal compact dolertic to basaltic (Thoeliite) type occurs over large areas in the upper basin. The unclassified crystallines are comprised of the Dharwarian sediments and various gneisses and granites, including charnockites. These rocks together cover the upper half of the drainage basin. The Cuddapah and Kurnool sediments consist of quartzites, limestones, shales, slates and sandstones. The Khondalites are quartz, feldspar, garnet, sillimanite gneisses with occasional presence of graphite. These rocks intruded by charnockites and pegmatites resulting in the development of a complex group of interaction rocks such as garnetiferous granulites, garnetiferous hypersthene gneisses and banded gneisses etc. Alluvial sediments of Pleistocene to recent age occur over the delta.

Material and Methods

The four sedimentary cores, viz. Turumella (120m), Inturu (160m), Ponnapalli (110m) and Nizampatam (150m) were recovered from the Krishna delta coast ~ 5 km inland from the shoreline. The bore hole samples were obtained using a rotary rig up to bedrock by the Geological Survey of India, Southern Region, Hyderabad. Drilled cores were preserved at the Delta Studies Institute, Andhra University, Visakhapatnam. Total sixty three sediment samples were subjected to heavy mineral analysis. The sand fractions were repeatedly washed with distilled water to remove salts and added stannous chloride for the removal of iron coatings. Bulk samples were separated using bromoform (sp.gr.2.89) following the procedure outlined by Krumbein and Pettijohn (1938). The heavy and light fractions were weighed and their weight percentages were calculated. Heavy minerals from bulk samples were mounted on glass slides with Canada balsam. About 300-400 grains in each slide were identified and counted using the line method (Galehouse, 1971).

DOWN CORE VARIATION OF HEAVY MINERAL ASSEMBLAGES

Turumella Core

Eighteen sand samples from various depths of Turumella core were subjected to heavy mineral analysis and results i.e. the down core variations of total heavy mineral (wt %) and individual heavy minerals (wt %) content in Turumella core sediments are given in Table 1. The heavy mineral assemblage in Turumella core sediments is opaques (Ilmenite+ magnetite), garnet, sillimanite, pyroxenes, monazite, amphiboles, zircon, and rutile in the decreasing order of abundance (Fig. 3). The total heavy minerals (THM) percentage ranges from 0.38 to 4.20 % (av. 2.59%). The maximum total heavy mineral content 4.20% occurred at a depth of 102 -103m followed by 3.92 % (105-108m), 3.90 % (67.30-70.50m), 3.80 % (119-120m) and 3.70 % (44.10-44.20m and 96-99m). The minimum heavy mineral content 0.38% occurred at a depth of 90-93m, followed by 0.80% (59.65-61.45m) (Table.1).

In Turumella core sediments the average total heavy mineral content is 2.59%, in which 37% is ilmenite, 21% magnetite, 9% garnet, 7% sillimanite, 5% pyroxene, 5% zircon, 5% monazite, 4% amphiboles, 4% other heavy minerals and 3% rutile (Fig. 4 a).

Inturu Core

Thirteen sand samples from various depths of Inturu core were subjected to heavy mineral analysis and results i.e. the down core variations of total heavy mineral (wt%) and individual heavy mineral (wt%) content in Inturu core sediments are given in Table 1. The heavy mineral assemblage in Inturu core sediments is opaques (Ilmenite + magnetite), garnet, sillimanite, pyroxenes, monazite, amphiboles, zircon, and rutile in order of decreasing abundance (Fig. 5). The total heavy mineral (wt %) varies from 1.83 to 7.00% (av. 3.61%). In Inturu core

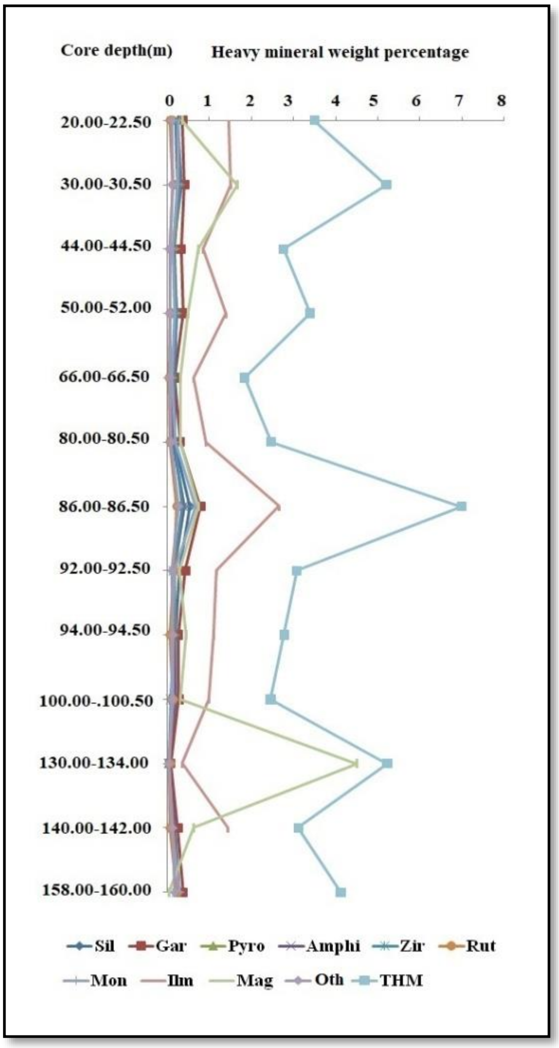

Fig. 3 Down core variation of an individual heavy mineral in Turumella sediments

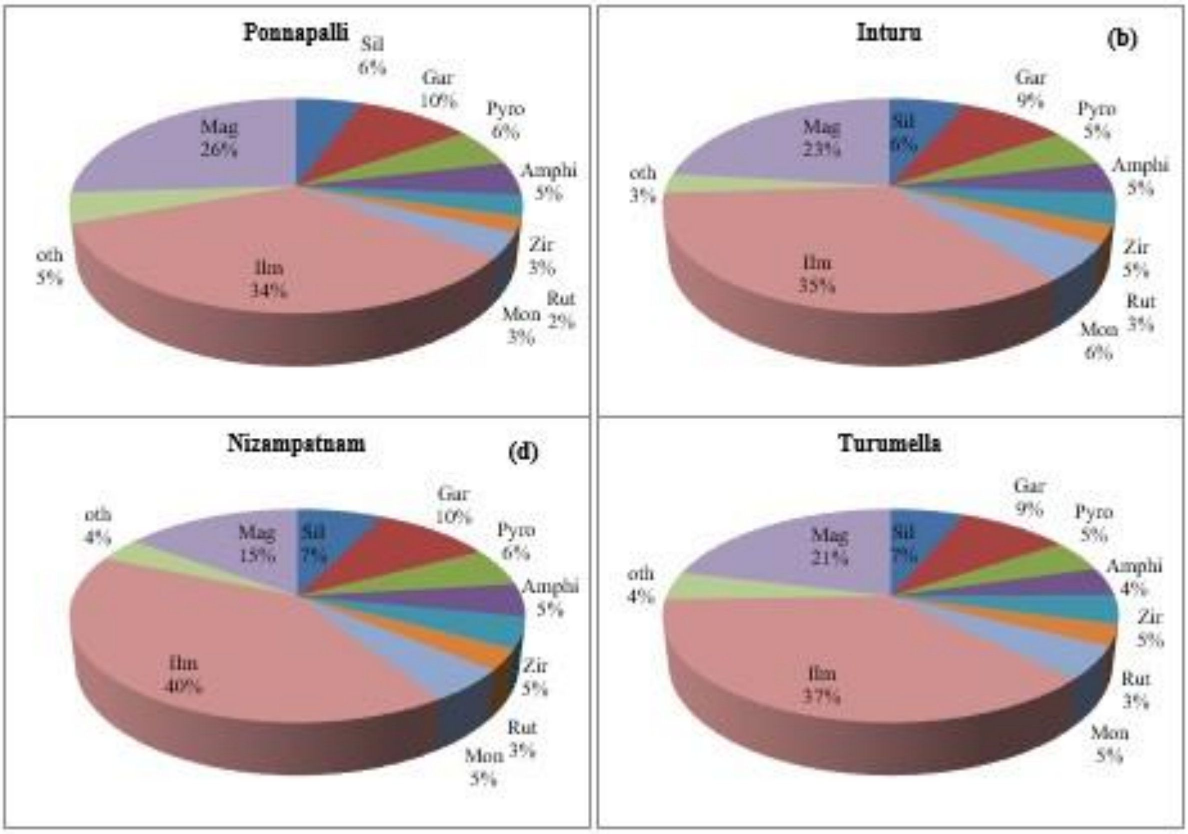

Fig. 4 Distribution Pattern of Individual Heavy Minerals in a) Turumella b) Inturu c) Ponnapalli and d) Nizampatnam core sediments

sediments the maximum total heavy mineral 7% occurred at a depth of 86.00-86.50m, followed by 5.23% (130-134m), 5.20% (30.00-30.50m) and 4.23% (160-162m). The minimum total heavy mineral content 1.83% occurred at a depth of 66.00-66.50m, followed by 2.45% (100.00-100.50m), 2.46% (80.00-80.50m), 2.76% (44.00-44.50m) and 2.77% (94.00-94.50m) (Table.1). In Inturu core, average total heavy mineral (THM) weight percentage is 3.61%, in which 35% ilmenite, 23% magnetite, 9% garnet, 6% sillimanite and monazite each, 5% pyroxenes, amphiboles and zircon each, 3% rutile and 3% other heavy minerals (Fig. 4 b).

Ponnapalli core

Twenty sand samples from various depths of Ponnapalli core were subjected to heavy mineral analysis and results i.e. the down core variations of total heavy minerals (wt %) and individual heavy minerals (wt %)

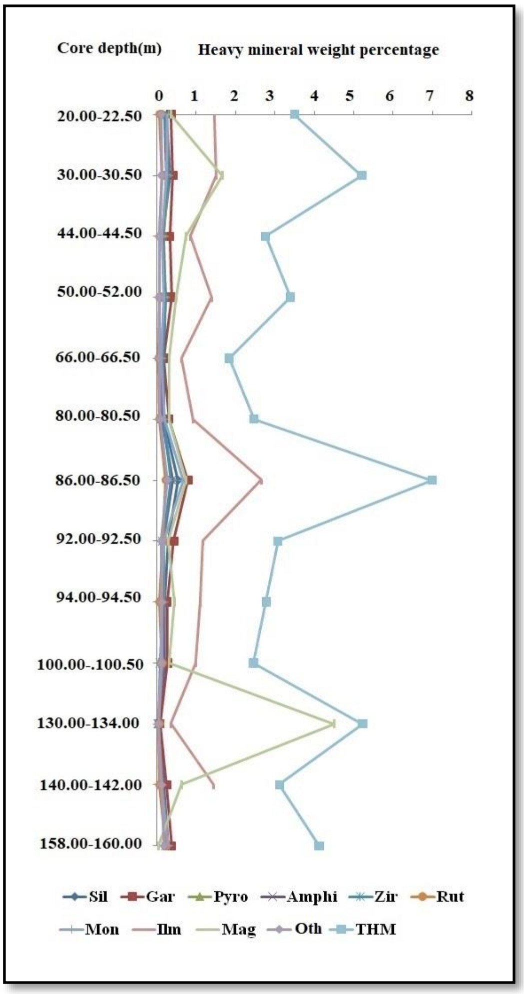

Fig. 5 Down core variation of an individual heavy minerals in Inturu sediments

Table 1: Distribution of total and individual heavy minerals (wt%) in core sediments

Sample No	Depth(m)	Sill	Gar	Pyro	Amphi	Zir	Rut	Mon	Ilm	Mag	Oth	THM%
Turumella core												
T-13	24.20-24.25	0.08	0.33	0.08	0.09	0.07	0.02	0.09	0.47	0.74	0.07	2.04
T-15	30.30-30.35	0.13	0.34	0.12	0.09	0.11	0.05	0.09	0.57	0.78	0.13	2.42
T-18	35.90-36.00	0.09	0.20	0.12	0.09	0.08	0.04	0.08	0.52	0.62	0.08	1.90
T-20	44.10-44.20	0.23	0.37	0.23	0.20	0.21	0.06	0.18	1.39	0.66	0.18	3.70
T-22	48.00-48.10	0.14	0.20	0.10	0.09	0.11	0.03	0.09	0.49	0.34	0.06	1.64
T-24	52.60-52.70	0.07	0.12	0.06	0.05	0.07	0.02	0.08	0.38	0.20	0.04	1.10
T-26	56.00-56.75	0.17	0.25	0.13	0.12	0.11	0.07	0.21	0.84	0.19	0.08	2.17
T-28	59.65-61.45	0.06	0.09	0.04	0.03	0.03	0.03	0.04	0.25	0.20	0.02	0.80
T-30	63.00-64.50	0.12	0.15	0.11	0.08	0.09	0.04	0.06	0.66	0.31	0.08	1.71
T-32	67.30-70.50	0.30	0.42	0.23	0.23	0.13	0.19	0.17	1.58	0.46	0.19	3.90
T-34	73.50-76.50	0.26	0.33	0.18	0.15	0.13	0.19	0.17	1.10	0.56	0.13	3.20
T-36	82.00-82.50	0.22	0.29	0.16	0.13	0.13	0.08	0.14	1.13	0.42	0.14	2.84
T-38	90.00-93.00	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.10	0.18	0.01	0.38
T-40	96.00-99.00	0.25	0.33	0.14	0.11	0.13	0.16	0.23	1.45	0.70	0.20	3.70
T-42	102.00-103.00	0.21	0.24	0.14	0.13	0.18	0.13	0.18	1.65	1.20	0.15	4.20
T-44	105.00-108.00	0.19	0.22	0.14	0.14	0.14	0.12	0.18	1.52	1.12	0.15	3.92
T-46	114.00-117.00	0.19	0.24	0.12	0.11	0.16	0.11	0.16	1.38	0.60	0.13	3.20
T-48	119.00-120.00	0.23	0.20	0.17	0.17	0.18	0.14	0.15	1.82	0.60	0.15	3.80
Min.		0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.10	0.01	0.18	0.38
Max.		0.30	0.42	0.23	0.23	0.21	0.19	0.23	1.82	0.20	1.20	4.20
Av.		0.16	0.24	0.13	0.11	0.11	0.08	0.13	0.96	0.11	0.55	2.59
Inturu core												
I-11	20.00-22.50	0.25	0.35	0.24	0.18	0.20	0.07	0.27	1.46	0.36	0.11	3.50
I-14	30.00-30.50	0.33	0.40	0.30	0.24	0.28	0.14	0.24	1.49	1.67	0.11	5.20
I-20	44.00-44.50	0.14	0.32	0.19	0.14	0.13	0.06	0.13	0.85	0.74	0.05	2.76
I-23	50.00-52.00	0.23	0.37	0.23	0.20	0.21	0.06	0.18	1.38	0.49	0.05	3.39

Table 1 Continued..

I-29	66.00-66.50	0.17	0.17	0.12	0.11	0.13	0.04	0.11	0.62	0.30	0.05	1.83
I-35	80.00-80.50	0.17	0.30	0.15	0.13	0.16	0.05	0.20	0.91	0.31	0.08	2.46
I-38	86.00-86.50	0.54	0.79	0.41	0.39	0.35	0.21	0.66	2.65	0.74	0.27	7.00
I-41	92.00-92.50	0.29	0.43	0.19	0.15	0.13	0.15	0.17	1.16	0.29	0.10	3.07
I-42	94.00-94.50	0.20	0.25	0.18	0.14	0.15	0.07	0.10	1.10	0.45	0.13	2.77
I-45	100.00-100.50	0.19	0.27	0.14	0.14	0.08	0.12	0.11	0.99	0.30	0.12	2.45
I-56	130.00-134.00	0.06	0.08	0.04	0.03	0.03	0.05	0.04	0.35	4.52	0.03	5.23
I-58	140.00-142.00	0.18	0.24	0.13	0.11	0.10	0.06	0.12	1.43	0.62	0.12	3.11
I-63	160.00-162.00	0.28	0.37	0.28	0.27	0.20	0.21	0.29	1.99	0.04	0.18	4.12
Min.		0.06	0.08	0.04	0.03	0.03	0.04	0.04	0.35	0.04	0.03	1.83
Max.		0.54	0.79	0.41	0.39	0.35	0.21	0.66	2.65	4.52	0.27	7.00
Av.		0.23	0.33	0.20	0.17	0.17	0.10	0.20	1.26	0.83	0.11	3.61
Ponnapalli core												
P-1	0.00-0.50	0.02	0.05	0.04	0.02	0.02	0.01	0.01	0.08	0.10	0.03	0.38
P4	6.00-6.25	0.12	0.16	0.08	0.09	0.05	0.02	0.05	0.55	0.40	0.09	1.60
P-6	10.00-10.50	0.09	0.11	0.09	0.04	0.02	0.03	0.03	0.42	0.40	0.07	1.30
P-8	14.00-14.50	0.12	0.14	0.12	0.11	0.06	0.04	0.04	0.58	0.60	0.10	1.90
P-12	22.00-22.10	0.06	0.09	0.07	0.05	0.03	0.03	0.03	0.45	0.42	0.05	1.30
P-16	30.00-30.25	0.07	0.10	0.04	0.06	0.03	0.02	0.02	0.29	0.42	0.06	1.12
P-20	38.00-38.10	0.11	0.15	0.08	0.07	0.04	0.02	0.05	0.42	0.44	0.11	1.48
P-22	42.00-42.50	0.13	0.14	0.09	0.07	0.03	0.02	0.05	0.63	0.46	0.09	1.70
P-26	50.00-50.25	0.15	0.25	0.12	0.10	0.05	0.04	0.07	1.01	0.50	0.12	2.40
P-28	54.00-54.25	0.12	0.34	0.10	0.16	0.07	0.04	0.11	0.62	0.30	0.13	2.00
P-32	62.00-62.50	0.08	0.15	0.10	0.13	0.08	0.07	0.14	0.63	0.30	0.12	1.80
P-34	66.00-66.50	0.07	0.19	0.10	0.11	0.07	0.04	0.07	0.36	0.30	0.10	1.40
P-36	70.00-70.25	0.08	0.23	0.10	0.11	0.07	0.09	0.08	0.69	0.26	0.08	1.80
P-40	78.00-78.10	0.20	0.27	0.30	0.23	0.06	0.05	0.09	0.70	0.42	0.09	2.40
P-42	82.00-82.15	0.16	0.20	0.18	0.14	0.06	0.04	0.06	0.78	0.30	0.09	2.00
P-43	84.00-84.25	0.27	0.33	0.31	0.19	0.14	0.09	0.14	1.50	0.74	0.14	3.84
P-44	94.00-95.00	0.17	0.58	0.17	0.17	0.14	0.09	0.16	1.67	3.32	0.17	6.64

Table 1 Continued..

P-46	98.00-99.00	0.20	0.36	0.19	0.15	0.12	0.09	0.09	1.27	0.56	0.16	3.20
P-47	100.00-100.50	0.12	0.25	0.11	0.10	0.10	0.08	0.08	0.98	0.50	0.10	2.40
P-50	106.00-110.00	0.13	0.24	0.13	0.11	0.14	0.10	0.14	1.29	0.60	0.12	3.00
Min.		0.02	0.05	0.04	0.02	0.02	0.01	0.01	0.08	0.03	0.10	0.38
Max.		0.27	0.58	0.31	0.23	0.14	0.10	0.16	1.67	0.17	3.32	6.64
Av.		0.12	0.22	0.13	0.11	0.07	0.05	0.08	0.75	0.10	0.57	2.18
Nizampatnam core												
N-1	0.00-0.50	0.03	0.04	0.02	0.03	0.02	0.01	0.03	0.15	0.05	0.01	0.38
N-5	8.00-8.40	0.02	0.02	0.02	0.01	0.02	0.01	0.01	0.08	0.12	0.01	0.32
N-21	40.00-40.10	0.07	0.15	0.09	0.07	0.06	0.03	0.06	0.40	0.14	0.02	1.09
N-23	46.00-46.10	0.07	0.10	0.07	0.06	0.06	0.02	0.05	0.40	0.14	0.01	0.97
N-25	48.00-48.10	0.16	0.15	0.11	0.10	0.12	0.04	0.10	0.55	0.06	0.05	1.43
N-37	72.00-72.10	0.04	0.07	0.03	0.03	0.04	0.01	0.04	0.20	0.10	0.02	0.57
N-42	82.00-83.20	0.05	0.08	0.04	0.04	0.04	0.02	0.07	0.27	0.09	0.03	0.72
N-47	92.00-92.20	0.08	0.11	0.05	0.04	0.03	0.04	0.04	0.30	0.09	0.03	0.81
N-65	132.00-133.00	0.19	0.23	0.16	0.13	0.13	0.06	0.09	0.99	0.74	0.11	2.84
N-66	135.00-138.00	0.15	0.21	0.11	0.11	0.06	0.09	0.09	0.78	0.16	0.10	1.86
N-68	142.00-143.00	0.20	0.24	0.13	0.11	0.09	0.14	0.12	1.08	0.23	0.09	2.44
N-71	148.00-150.00	0.20	0.27	0.15	0.12	0.12	0.07	0.13	1.60	0.60	0.13	3.38
Min.		0.02	0.02	0.02	0.01	0.02	0.01	0.01	0.08	0.01	0.05	0.32
Max.		0.20	0.27	0.16	0.13	0.13	0.14	0.13	1.60	0.13	0.74	3.38
Av.		0.10	0.14	0.08	0.07	0.07	0.04	0.07	0.57	0.05	0.21	1.40

Sil-Sillimanite, Gar-Garnet, Pyro-Pyroxene, Amphi-Amphiboles, Zir-Zircon, Rut-Rutile, Mon-Monazite, Ilm-Ilmenite, Mag-Magnetite, Oth-Other Heavy minerals and THM-Total Heavy minerals

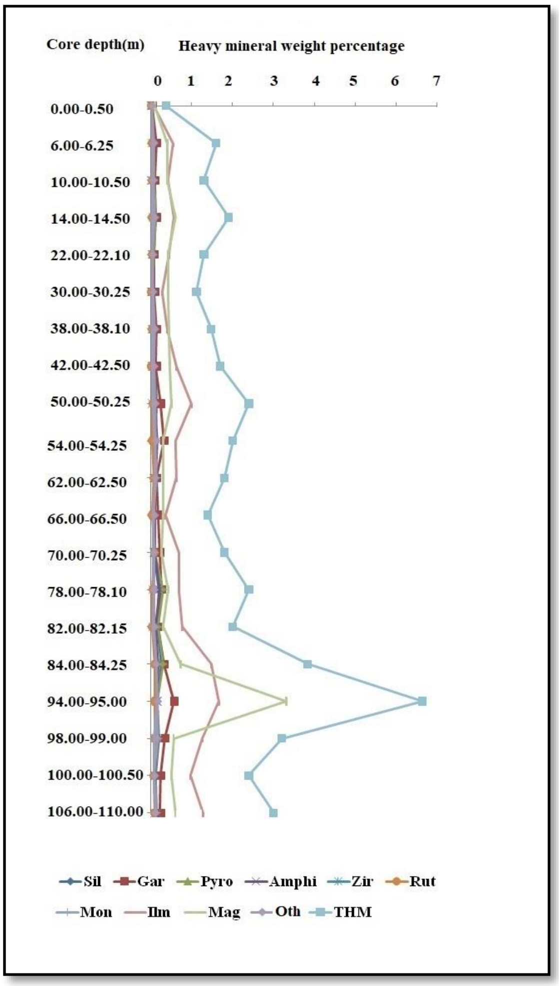

Fig. 6 Down core variation of an individual heavy minerals in

Fig. 7 Down core variation of an individual heavy minerals in Nizampatnam sediments in Ponnapalli sediments

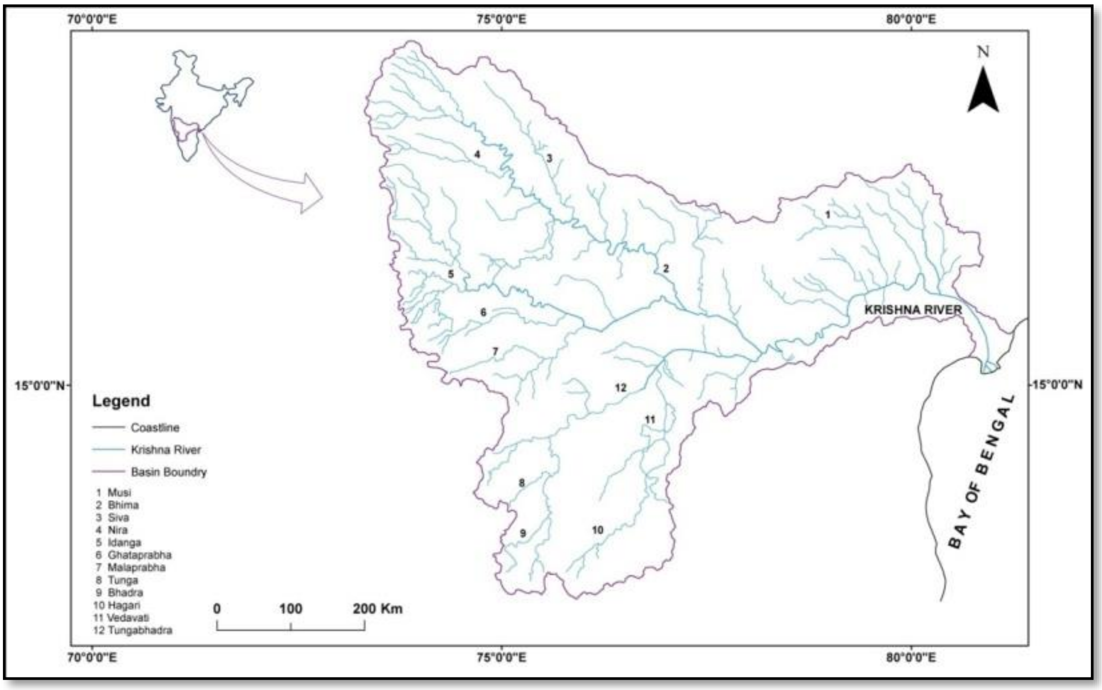

Fig. 8 Drainage map of the Krishna River basin (Source: Central Ground Water Board)

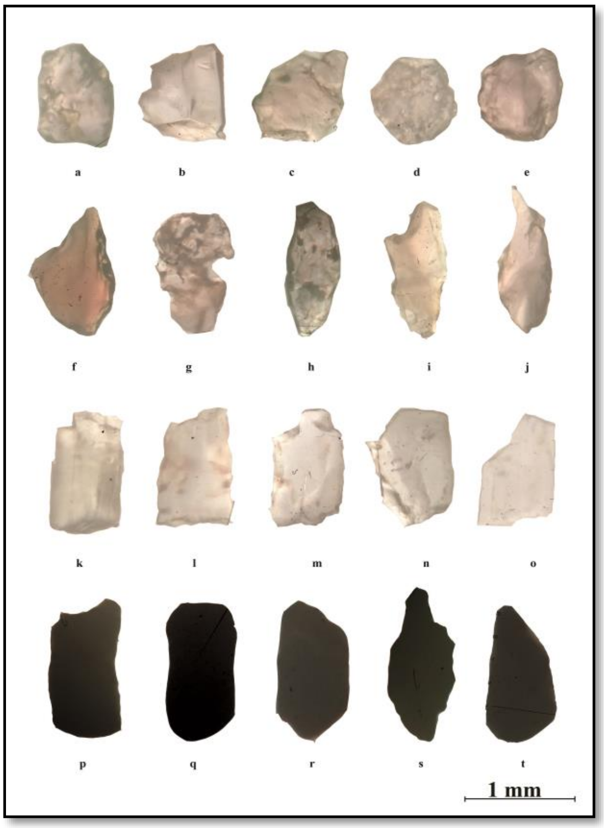

Plate 1 Microphotographs of garnets (a-j), sillimanites (k-o) and opaques (p-t) in study area

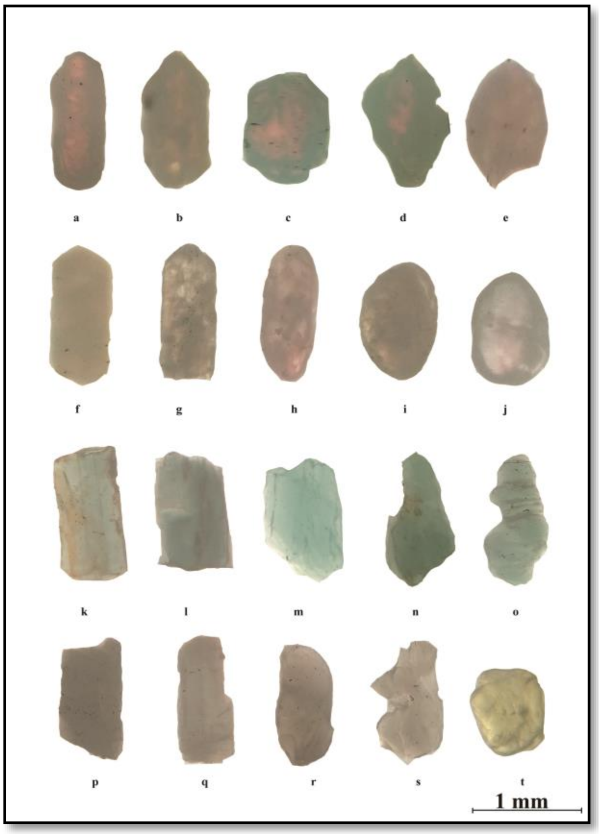

Plate 2 Microphotographs of rutile (a-e), zircon (f-j), pyroxenes (k-o), amphiboles (p-s) and monazite (t) in study area

content in Ponnapalli core sediments are given in Table 1. The heavy mineral assemblage in Ponnapalli core sediments is opaques (Ilmenite + magnetite), garnet, sillimanite, pyroxenes, monazite, amphiboles, zircon, and rutile in order of decreasing abundance (Fig .6). The total heavy mineral (wt%) ranges from 0.38 to 6.84% (av. 2.18%). The maximum heavy mineral content 6.64% occurred at a depth of (94.00-95.00m) followed by 3.84% (84.00-84.25m), 3.20% (98.00-99.00m) and 3.00% (106.00-110.00m). The minimum content of heavy mineral is 0.38% occurred at a depth of 0.00-0.50m followed by 1.12% (30.00-30.25m), 1.30% (10.00-10.50m, 22.00-22.10m) and 1.48% (38.00-38.10m). In Ponnapalli core sediments, an average total heavy mineral (THM) weight percentage is 2.18%, in which 34% ilmenite, 26% magnetite, 10% garnet, 6% sillimanite, 6% pyroxenes, 5% amphiboles and other heavy minerals each, 3% zircon and monazite each and 2% rutile (Fig. 4 c).

Nizampatnam Core

Twelve sand samples from various depths of Nizampatnam core were subjected to heavy mineral analysis and results i.e. the down core variations of total heavy minerals (wt %) and individual heavy minerals (wt %) content in Nizampatnam core sediments are given in Table 1. The heavy mineral assemblage in Nizampatnam core sediments is opaques (Ilmenite + magnetite), garnet, sillimanite, pyroxenes, monazite, amphiboles, zircon, and rutile in the order of decreasing abundance (Fig. 7). The total heavy minerals (wt %) content ranges from 0.32 to 3.38% (av. 1.40%). The maximum heavy mineral content 3.38% occurred at a depth of 148-150m and 2.84% (132-133m). The minimum heavy mineral content 0.32% occurred at a depth of 8.00-8.40m followed by 0.38% (0.00-0.50m), 0.57% (72.00-72.10m), 0.72% (82.00-83.20m), 0.81% (92.00-92.20m) and 0.97% (46.00-46.10m).

In Nizampatnam core sediments, an average total heavy mineral (THM) weight percentage is 1.40%, in which 40% ilmenite, 15% magnetite, 10% garnet, 7% sillimanite, 6% pyroxenes, 5% amphiboles, zircon and monazite each, 4% other heavy minerals and 3% rutile (Fig. 4 d).

DISTRIBUTION PATTERN OF INDIVIDUAL HEAVY MINERALS IN DIFFERENT CORE SEDIMENTS

The main heavy minerals of the Krishna River sands consist of opaques (Ilmenite + magnetite), garnets and sillimanites. The lesser content of heavy minerals are pyroxenes, amphiboles, zircon, rutile and monazite (Plates 1 and 2).

Garnets

The concentration of garnets in Turumella core sediment ranges from 0.02 to 0.42% with an average of 0.24%. In Inturu core sediments, the concentration of garnet ranges from 0.08 to 0.79% with an average of 0.33%. In Ponnapalli core sediments, the concentration of garnet ranges from 0.05 to 0.58% with an average of 0.22%. In Nizampatnam core sediments, the concentration of garnet ranges from 0.02 to 0.27% with an average of 0.14%. The average concentration of garnets in decreasing order of abundance, among the four cores are Inturu (0.33%), Turumella (0.24%), Ponnapalli (0.22%) and Nizampatnam (0.14%).

Sillimanite

The concentration of sillimanite in Turumella core ranges from 0.02 to 0.30% with an average of 0.16%. In Inturu core sediments, the concentration of sillimanite ranges from 0.06 to 0.54% with an average of 0.23%. In Ponnapalli core sediments, the concentration of sillimanite ranges from 0.02 to 0.27% with an average of 0.12%. In Nizampatnam core sediments, the concentration of sillimanite ranges from 0.02 to 0.20% with an average of 0.10%. The average concentration of sillimanite in decreasing order of abundance, among the four cores are Inturu (0.23%), Turumella (0.16%), Ponnapalli (0.12%) and Nizampatnam (0.10%).

Opaques

The concentration of opaques (Ilmenite + magnetite) in Turumella core ranges from 0.28 to 2.85% with an average of 1.51%. In Inturu core sediments, the concentration ranges from 0.92 to 4.87% with an average of 2.09%. In Ponnapalli core sediments, the concentration ranges from 0.18 to 4.99% with an average of 1.31%. In Nizampatnam core sediments, the concentration ranges from 0.19 to 2.20% with an average of 0.78%. The average concentration of opaques (Ilmenite + magnetite) in decreasing order of abundance, among the four cores Inturu (2.09%), Turumella (1.51%), Ponnapalli (1.31%) and Nizampatnam (0.78%.).

Pyroxenes

The concentration of pyroxenes in Turumella core varies from 0.01 to 0.23% with an average 0.13%. In Inturu core sediments, the concentration of pyroxene ranges from 0.04 to 0.41% with an average 0.20%. In Ponnapalli core sediments, the concentration of pyroxene varies from 0.04 to 0.31% with an average 0.13%. In Nizampatnam core sediments, the concentration of pyroxene ranges from 0.02 to 0.16% with an average 0.08%. The average concentration of pyroxenes in decreasing order of abundance, among the four cores Inturu (0.20%), Turumella (0.13%), Ponnapalli (0.13%) and Nizampatnam (0.08%.).

Amphiboles

The concentration of amphiboles in Turumella core varies from 0.01 to 0.23% with an average 0.11%. In Inturu core sediments, the concentration of amphiboles ranges from 0.03 to 0.39% with an average 0.17%. In Ponnapalli core sediments, the concentration of amphibole varies from 0.02 to 0.23% with an average 0.11%. In Nizampatnam core sediments, the concentration of amphibole ranges from 0.01 to 0.13% with an average 0.07%. The average concentration of amphiboles in decreasing order of abundance, among the four cores Inturu (0.17%), Turumella (0.11%), Ponnapalli (0.11%) and Nizampatnam (0.07%.).

Zircons

The concentration of zircons in Turumella core varies from 0.01 to 0.21% with an average 0.11%. In Inturu core sediments, the concentration of zircon ranges from 0.03 to 0.35% with an average 0.17%. In Ponnapalli core sediments, the concentration of zircon varies from 0.02 to 0.14% with an average 0.07%. In Nizampatnam core sediments, the concentration of zircon ranges from 0.02 to 0.13% with an average 0.07%. The average concentration of zircons in decreasing order of abundance, among the four cores Inturu (0.17%), Turumella (0.11%), Ponnapalli (0.07%) and Nizampatnam (0.07%.).

Rutile

The concentration of rutile in Turumella core varies from 0.01 to 0.19% with an average 0.08%. In Inturu core sediments, the concentration of rutile ranges from 0.04 to 0.21% with an average 0.10%. In Ponnapalli core sediments, the concentration of rutile varies from 0.01 to 0.10% with an average 0.05%. In Nizampatnam core sediments, the concentration of rutile ranges from 0.01 to 0.14% with an average 0.04%. The average concentration of rutile in decreasing order of abundance, among the four cores Inturu (0.10%), Turumella (0.08%), Ponnapalli (0.05%) and Nizampatnam (0.04%.).

Monazite

The concentration of monazite in Turumella core varies from 0.01 to 0.23% with an average of 0.13%. In Inturu core sediments, the concentration of monazite ranges from 0.04 to 0.66% with an average 0.20%. In Ponnapalli core sediments, the concentration of monazite varies from 0.01 to 0.16% with an average 0.08%. In Nizampatnam core sediments, the concentration of monazite ranges from 0.01 to 0.13% with an average 0.07%. The average concentration of monazite in decreasing order of abundance among the four cores is Inturu (0.20%), Turumella (0.13%), Ponnapalli (0.08%) and Nizampatnam (0.07%).

DISCUSSION

The core sediments of the Krishna delta under this study same heavy mineral assemblages i.e. opaques (Ilmenite + magnetite), pyriboles (pyroxenes + amphiboles), garnet, zircon, monazite, rutile and other heavy minerals (epidote, kyanite, tourmaline, etc.). The average heavy minerals wt% in the core sediments of Turumella, Inturu, Ponnapalli and Nizampatnam are 2.59%, 3.60%, 2.40% and 1.40% respectively, there is no systematic variation either increase or decrease of heavy minerals content from top to bottom of studied cores.

The variation of heavy mineral content in river sediments is controlled by (a) source rocks, (b) weathering conditions, (c) which part of the drainage basin area exposed to erosion (river erosion) linked with the rainfall, (precipitation) (d) energy of the river environment.

Present day Krishna River basin has 12 tributaries (Fig. 8), each carries the sediment load and joins in the main river channel. Depending on the rainfall and source rocks of sub basins, the nature of sediment depends similarly in the geological past also the Krishna River had a number of tributaries controlled by sediment load.

Most of the sediment in the studied cores are of polymodal nature, it indicates that the sediments were derived from many sources. The occurrence of different lithological units in the drainage basins is contributing sediments, mainly opaques (Ilmenite + magnetite) and pyriboles (Amphibole + pyroxenes) are from Deccan traps as well as Archean provenance which covered more than 55% of drainage basin. The red garnets (almandine), prismatic sillimanites and rounded zircons are derived from khondalites (metapeletic rocks) and pink garnets, elongated zircons and ortho- pyroxenes derived from charnockites of Eastern Ghat Granulite Belt (EGGB). Similar observations were made in sub environments of Godavari delta (Sambasiva Rao, 1979) and in Pudimadaka - Pentakota coastal sediments along the east coast of India (Rajasekhar Reddy et al., 1998). The fresh appearance of heavy minerals indicates that short residence time in depositional environment without any chemical dissolution effect.

The rounded and sub rounded grains of magnetite and ilmenite indicate long distance of transportation and/or reworked nature. The sub angular grains of magnetite and ilmenite were indicating that they might have been derived from nearby sources, i.e. mainly an Eastern Ghat Group of rocks. The prismatic characteristic of the sillimanite mineral grains also suggests that these were derived from khondalitic rocks. The heavy mineral assemblages of present day Krishna River sediments (Krishna Rao and Swamy, 1991) and studied cores are same.

CONCLUSIONS

1. Total heavy minerals wt% varies from 0.32 to 7.00 (av. 2.44%) in the study area. The heavy mineral concentration is higher in Inturu (3.61%), followed by Turumella (2.59%), Ponnapalli (2.18%) and Nizampatnam (1.40%).
2. The opaques (Ilmenite + magnetite) and pyriboles (Amphiboles + pyroxenes) are dominant in the present study; these are from Deccan traps as well as Archean provenance.
3. Garnets, sillimanites and zircons are derived from khondalites (metapeletic rocks) and charnockites of Eastern Ghat Granulite Belt.
4. Presence of rounded zircons and rutiles in some samples indicate that, they are sourced from reworked sediments. In some places anhedral rutiles are also present. They are probably derived from the adjoining acid igneous and metamorphic rocks. Presence of monazites indicates that they have been derived either from the Eastern Ghat Group of rocks or from reworked sediments of Western Ghat rocks or from both.
5. The fresh appearance of heavy minerals indicates that short residence time in depositional environment without any chemical dissolution effect.

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Abundance of Sulphur in Paleogene coals of North-East India and Its Paleo-environmental Implications

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Abstract :
The present paper entails the occurrence and distribution of different forms of sulphur in Paleogene coals of north-eastern India. All the coal seams present in the north-eastern region of India are characterized by the presence of high sulphur with total sulphur content ranging from 3 to 7%. Among all the forms of sulphur recognised, organic sulphur is dominant. The total sulphur content originated in the Platform area for Eocene coal under stable shelf condition vary from 4.20 % to 6.01 % for Jaintia Hills, from 2.78 % to 4.01 % for Khasi Hills and from 1.90 % to 3.00 % for Garo Hills, whereas Oligocene coal evolved under the foredeep basin have total sulphur ranging in from 2.90 % and 6.60 %. In the Eocene coals, there is a distinct lateral and vertical variation of sulphur i.e., sulphur content increases from the bottom to the top seam and also from western side of Meghalaya to the eastern side. This lateral variation of sulphur was because of the more marine nature of the Eastern Meghalaya than the Western Meghalaya. Both Eocene and Oligocene coals have been derived from seawater as evidenced by the presence of pyritic form of sulphur. Study of forms of sulphur also suggests that the deposition of the coals in a different part of the region was influenced by roof strata, peat-forming plant communities, tectonic uplifting, and marine or freshwater incursion.

Keywords: High sulphur; Paleogene coal; North-East India; foredeep basin; platform area;

Introduction

In the Paleogene coals of India, the occurrence of sulphur attracted the attention of early workers (LaTouche, 1882; Ghosh, 1964; Ahmed, 1971). The large deposits of the Paleogene coals are mainly distributed in the states of Assam, Arunachal Pradesh, Nagaland and Meghalaya. Considering the Gondwana coals of India the Paleogene coals contribute only a meagre portion of the total Indian coal inventory (Indian Bureau of Mines, 2018). But the Paleogene coal deposits are of good quality having characteristically low ash content and medium caking property. The only drawback of this coal is the presence of a high amount of sulphur (inorganic constituent) which render it unsuitable for commercial utilization. However, energy demand has increased recently, which focused attention on the utilization of high sulphur coals.

Sulphur is an undesirable but economically important constituent of all coals. The amount of sulphur in coal ranges from traces to as high as 10% or more. The maximum permissible amount of sulfur existing in fuels demonstrates a descending trend on a global scale that raises the importance of accurately measuring the total amount of sulfur in coals and its desulphurization steps, if required (Borah et al., 2001; Mukherjee and Borthakur, 2001; Hashan, 2016; Singh et al., 2018). Inorganic, as well as organic forms of sulphur, remain present in coal. Combustion of sulfur-containing fossil fuels, especially coal/lignite and oil, by boilers and industry emits over 90% of atmospheric SO2. At high temperature, the organic sulfur compounds of coal degrade to elemental sulfur or inorganic sulfur species, such as hydrogen sulfide, and further converts to SO2. This SO2 get oxidized to sulfur trioxide (SO3), which combines with water vapour to produce ultrafine (<0.1 μm diameter) sulfuric acid particles (Schlesinger, 2010). Sulphur in coals of north-eastern region of India occurs as 1) pyritic sulphur 2) sulphate sulphur and 3) organic sulphur. Pyritic and sulphate sulphur together is commonly referred to as inorganic sulphur. Iron sulphide (FeS2), the primary inorganic form of sulphur, occurs in two crystalline forms, pyritic (cubic) and marcasite (orthorhombic). The major classes of organic sulphur include thiols, disulfides, organic sulfides, polysulfides, thiophene derivatives and sulfonates (Tissot and Welte, 1985)

The sulphur content of coal seams is an important factor in resource development and utilization. The studies have shown that the coals with marine roof rocks have higher sulphur contents than those with fresh or brackish water roof rocks (Diessel, 1992; Chou, 1997).

The coal deposits of north-east India dealing mainly with sulphur have been studied from time to time, but the earlier studies lack systematic sampling and regional approach.

Mention may be made of the work of (Ahmed and Bora, 1981; Chandra et al., 1983; Ahmed and Rahim, 1996; Nath, 2016).

The present study is mainly focused on the determination and detailed description of the amount and occurrence of different forms of sulphur (total, pyritic, sulphate and organic) in the coals of north-east India. Lateral as well as the vertical distribution of the sulphur forms has also been discussed with emphasis on the paleoenvironmental aspects of these coals.

Geological setting

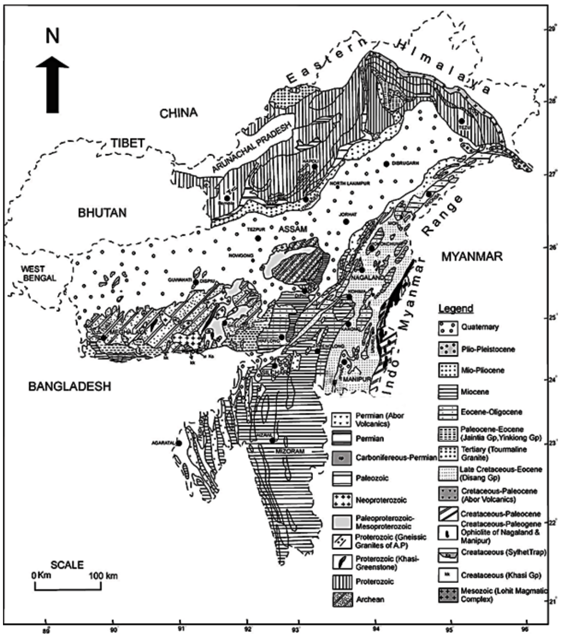

Figure 1 Geological map of North-Eastern India (after Singh et al., 2017)

In north-east India, coal deposits mainly occur in the states of Assam, Arunachal Pradesh, Nagaland and Meghalaya (Figure 1) confined to the Oligocene and Eocene arenaceous formations. The coal deposits of these areas are understood to have been formed in two distinct tecto-sedimentary settings. The coal deposits of Assam (Makum and Dilli- Jeypore), Arunachal Pradesh (Namchik-Namphuk coalfield) and Nagaland (Borjan coalfield) have probably originated in a foreland basin (Singh et al., 2013), whereas the coalfields of Garo, Khasi, and Jaintia Hills of Meghalaya represent the development of coal facies over platform areas (Singh and Singh, 2000). In the Garo, Khasi and Jaintia Hills of Meghalaya the coal seams occur in the Lakadontg Sandstone Formation of Jaintia Group (Table 1) and are sandwiched between the overlying Umlatholoh Limestone and underlying Lakadong Limestone. The result of intermittent marine transgression and regression during the Eocene period has resultd in the deposition of these formations (Raja Rao, 1981).

Drifting of the Indian plate during the Cretaceous period towards the north and north-east and finally, its collision with the Burmese plate (Asian plate), which proceeded with the subduction of Indian plate margin in the foredeep are believed to be the result of such activity. The development of the foredeep (trench/ technogenic) is because of subduction, which provided the site for deposition of Tertiary sequences of stupendous thickness (~15,600 m). In the Early Eocene period the sedimentation began with the deposition of Disang Group followed by Barail Group of Oligocene age (Table 2). In the Tikak Parbat Formation of Barail Group, the coal seams of the fore deeps occur (Figure 1). Alternate bands of sandstone, shale and carbonaceous shale is the lithology of the Barail Group. The Tikak Parbat Formation of Barail Group is disturbed more tectonically than the underlying Borgagolai Formation (alternating sandstone and shale with carbonaceous shale and thin lamination of coal) and Naogaon Formation (splintery, grey or brownish coloured, iron-stained shales with occasionally interbedded with thin bands of fine-grained sandstone and sandy shale) (Ahmed, 1996).

Methods of Study

Coal samples [pillar/channel/run-of-mine (ROM)] were collected from different collieries of the coalfields of Assam (Dilli-Jeypore), Arunachal Pradesh (Namchik-Namphuk coalfield), Nagaland (Borjan and Moulong-Kimong) and Meghalaya (Garo, Khasi and Jaintia Hills) covering whole Paleogene coals of north-east India. To cover the entire north eastern coals sulphur studies done by different workers have also been taken into account. The data of sulphur for West Daranggiri coalfield was collected from Phukan (2002), for Makum coalfield the data was collected from (Gogoi et al., 2010) and for Tiru coalfield the data was taken from (Singh et al., 2012).

The lithology of the seam, roof and floor strata, intervening dirt band and partings were also studied while collecting the samples from the collieries.

The samples were prepared to pass a 72 mesh (212 µm) sieve. The total sulphur was determined by digesting the coal with Eschka mixture containing 2 parts of MgO (Magnesium Oxide) and 1 part of Na2CO3 (Sodium Carbonate).

The sulphur was extracted by using (barium chloride) to precipitate BaSO4 (Barium Sulphate) from the solution. The total sulphur was then determined by the gravimetric method. The sulphate sulphur concentration was determined by treating the coal samples with dilute HCl and the concentration of the combined pyrite and sulphate sulphur fraction was determined by treating the coal with dilute nitric acid. The organic sulphur was calculated by subtracting total sulphur from pyritic and sulphate sulphur.

Results and Discussion

The results of various forms of sulphur of Paleogene coals of north-eastern regions of India are furnished in Tables 3, 4, 5, 6, 7 and 8. These coals have high sulphur content, which varies from 7.03% to 1.62% (with an average of 2.98%). Coal with less than 1% sulphur is placed under low-

Table:1 Geological succession of the coalfields of platform areas (modified after Raja Rao, 1981).

Age	Formation and Member	Thickness	Rock Types
Upper Eocene	Kopili		Ferruginous sandstone, grey siltstone and shale
Middle Eocene	Sylhet Limestone: Prang Limestone/ Siju Limestone	60 to 150 m	Bluish massive to thinly bedded limestone with marlyinterband
Lower Eocene	Nurpuh Sandstone	15 to 26 m	Coarse to medium-grained ferruginous sandstones with bands of sandy limestone
Lower Eocene	Umlatdoh limestone	70 m to 110 m	Grey to pinkish grey limestone, sandy limestone and calcareous sandstone
Lower Eocene to Palaeocene	Lakadong sandstone	35 m to 250 m	Predominantly buff coloured medium grained arkosic sandstone with thin grey and carbonaceous shale and coal seams
Lower Eocene to Palaeocene	Lakadong limestone	25 m to 60 m	Grey to brownish grey limestone,siliceous limestone
Lower Eocene to Palaeocene	Therria sandstone	20 m to 80 m	Buff coloured medium to coarse-grainedarkosic sandstone with thin bands of pyrite-rich silty sandstone
Upper Cretaceous (Danian)	Langpar	10 m to 50 m	Buff coloured calcareous ferruginous sandstones, earthy limestones etc.
Upper Cretaceous (Maestrichtian)	Mahadek	160 m to 335 m	Massive coarse-grained glauconitic sandstones containing dark grey shales and calcareous horizons
Jurassic to lower Cretaceous	Sylhet Trap	250 m to 400 m	Aa and pahoehoe type basalts

Table 2: Geological succession of the coalfields of Schuppen zone (modified after Raja Rao, 1981).

Age	Group &Formation	Thickness	Rock Types
Pliocene	Dihing Group	1800 m.	Mostly pebbly sandstone with thin greyish clay beds
……………………………..Unconformity………………………………………..			
Mio-Pliocene	Namsang Formation	800 m.	Fine to coarse-grained sandstone with bands of clay
……………………………..Unconformity………………………………………..			
Miocene	Tipam Group (i) Girujan Clay (ii)Tipam Sandstone	1800 m 2300 m.	Mottled clay with greyish soft sandstone Ferruginous, fine to coarse-grained micaceous to felspathic sandstone
……………………………..Unconformity………………………………………..			
Oligocene	Barail Group (i)Tikak Parbat Formation (ii)Baragolai Formation (iii)Naogaon Formation	600 m. 3500 m. 2200 m.	Greyish to yellowish white sandstone, sandy shale, coal seams Greyish to bluish grey or yellowish red mudstone, shale, sandstone, carbonaceous shale and thin coal seam Compact, fine-grained, dark grey sandstone with bands of splintery shale.
Eocene	Disang Group	3000 m.	Splintery dark grey shales and thin sandstone interband

Table 3: Distribution of different forms of sulphur in Eocene Coalfields of Jaintia Hills, Meghalaya.

Coalfield	Seam characteristics			Sample characteristics		Total Sulphur			Sulphate Sulphur			Pyritic Sulphur			Organic Sulphur		
	No’s	Total Tickness (m)	Name	Type	Total No’s	Max	Min	Av.	Max.	Min	Av.	Max	Min	Av.	Max	Min	Av.
Bapung Coalfield	3	0.31-1.05	T	Channel	24	7.03	5.23	6.01	0.78	0.60	0.65	1.21	0.52	0.81	5.04	4.11	4.65
			M			6.23	5.01	5.27	0.65	0.52	0.54	0.84	0.28	0.47	4.74	4.21	4.31
			B			5.02	4.09	4.52	0.55	0.48	0.49	0.65	0.14	0.35	3.82	3.47	3.58
Jarain Coalfield	2	0.3-1.0	T	Channel	18	6.06	4.12	5.01	0.75	0.51	0.59	1.01	0.92	0.94	4.30	2.69	3.41

			B			5.95	4.01	4.25	0.66	0.45	0.51	0.90	0.72	0.79	4.39	2.84	3.57
Sutunga Coalfield	2	0.1-1.07	T	Channel	15	5.92	4.52	4.03	0.71	0.49	0.57	1.02	0.89	0.93	4.19	3.14	3.53
			B			4.89	3.92	3.57	0.64	0.31	0.44	0.97	0.65	0.78	3.28	2.96	3.01
Lakadong	1	0.3-2.1		ROM	15	5.03	3.97	4.20	0.69	0.21	0.41	1.05	0.64	0.70	3.29	3.12	3.17

Table 4: Distribution of different forms of sulphur in Eocene Coalfields of Khasi Hills, Meghalaya.

Coalfield	**Seam characteristics**			**Sample characteristics**		**Total Sulphur**			**Sulphate Sulphur**			**Pyritic Sulphur**			**Organic Sulphur**		
	No's	**Total Tickness (m)**	**Name**	**Type**	**Total No's**	**Max**	**Min**	**Av.**	**Max**	**Min**	**Av.**	**Max.**	**Min.**	**Av.**	**Max.**	**Min.**	**Av.**
Langrin Coalfield	6	1.5-2	T	Channel	20	3.82	2.40	3.01	0.58	0.42	0.44	0.78	0.52	0.58	2.46	1.38	1.99
			M			4.51	3.22	3.81	0.65	0.49	0.52	0.82	0.61	0.68	3.04	2.12	2.61
			B			4.61	4.10	4.13	0.69	0.54	0.57	0.89	0.71	0.78	3.03	2.85	2.89
Laitryngew Coalfield	2	0.2-1.9	T	Channel	15	5.01	3.86	4.01	0.89	0.41	0.61	0.94	0.65	0.68	3.18	2.80	2.92
			B			4.60	3.12	3.13	0.94	0.51	0.63	0.84	0.69	0.72	2.82	1.92	2.01
Mawbehlakhar Coalfield	3	0.10-0.50	T	Channel	15	4.60	1.79	3.01	0.10	0.05	0.66	0.75	0.34	0.48	3.75	1.40	1.87
			M			4.39	1.74	2.99	0.08	0.03	0.04	0.67	0.29	0.45	3.64	1.42	2.50
			B			4.40	1.62	2.98	0.09	0.02	0.03	0.40	0.29	0.31	3.91	1.31	2.64
Mawlong-Shella Coalfield	1	0.3-1.5	T	ROM	10	4.01	3.01	3.47	0.52	0.32	0.38	0.66	0.41	0.47	2.83	2.28	2.62
			B			3.00	2.75	2.78	0.24	0.11	0.15	0.25	0.09	0.15	2.51	2.01	2.31

Table 5: Distribution of different forms of sulphur in Eocene Coalfields of Garo Hills, Meghalaya.

Coalfield	**Seam characteristics**			**Sample characteristics**		**Total Sulphur**			**Sulphate Sulphur**			**Pyritic Sulphur**			**Organic Sulphur**		
	No's	**Total Tickness (m)**	**Name**	**Type**	**Total No's**	**Max**	**Min**	**Av.**	**Max.**	**Min**	**Av.**	**Max.**	**Min.**	**Av.**	**Max.**	**Min.**	**Av.**
West Darranggiri*	3	0.3-2.7	T	Pillar	28	5.20	2.50	3.00	0.40	0.10	0.10	1.90	0.60	0.80	3.20	1.70	2.10
			M			3.00	2.30	2.90	0.30	trace	0.20	0.80	0.10	0.60	2.30	1.80	2.10
			B			2.60	2.10	2.30	0.10	0.20	0.10	0.90	trace	0.40	2.20	1.50	1.80
Siju Coalfield	3	0.15-1.1	T	Channel	10	3.00	2.50	2.60	0.40	0.20	0.30	1.80	0.80	1.20	1.50	0.80	1.10
			M			2.80	2.20	2.30	0.30	0.10	0.20	0.90	0.60	0.60	1.60	1.50	1.50
			B			2.10	1.80	1.90	0.20	trace	trace	0.70	0.50	0.60	1.20	1.10	1.10

**Data collected from Phukan, (2002).*

Table 6: Distribution of different forms of sulphur in Oligocene Coals of Assam.

Coalfield	**Seam Characteristics**			**Sample Characteristics**		**Total Sulphur**			**Sulphate Sulphur**			**Pyritic Sulphur**			**Organic Sulphur**		
	No's	**Total Tickness (m)**	**Name**	**Type**	**Total No's**	**Max.**	**Min.**	**Av.**	**Max.**	**Min.**	**Av.**	**Max.**	**Min.**	**Av.**	**Max.**	**Min.**	**Av.**
Makum*	5	1.2-33		Channel	49	6.28	2.20	4.43	0.90	0.08	0.40	1.88	0.15	1.01	5.65	1.60	3.38
						6.88	3.09	3.98	0.95	0.04	0.64	1.90	0.45	1.11	5.76	1.80	3.18
						4.82	3.19	4.01	0.40	0.19	0.25	1.20	0.60	0.88	3.78	2.00	2.68
Jajpur Coalfield	7	1.3-2.7		ROM	15	5.83	2.80	4.08	0.87	0.15	0.45	1.18	0.75	0.86	3.78	1.90	2.77
Dilli Coalfield	8	3.0-6		ROM	15	6.20	3.20	4.30	0.75	0.11	0.37	1.43	0.78	0.98	4.02	2.31	2.95

**Data collected from Gogoi et al. (2010).*

Table 7: Distribution of different forms of sulphur in Oligocene Coals of Nagaland.

Coalfield	**Seam Characteristics**			**Sample Characteristics**		**Total Sulphur**			**Sulphate Sulphur**			**Pyritic Sulphur**			**Organic Sulphur**		
	No's	**Total Tickness (m)**	**Name**	**Type**	**Total No's**	**Max.**	**Min.**	**Av.**	**Max.**	**Min.**	**Av.**	**Max.**	**Min.**	**Av.**	**Max.**	**Min.**	**Av.**

Borjan Coalfield	2	2.0-7.0	T	Channel	15	5.52	4.42	4.75	0.73	0.33	0.43	1.01	0.99	0.99	3.78	3.10	3.33
			B			4.42	3.75	3.95	0.63	0.24	0.38	0.98	0.89	0.91	2.81	2.62	2.66
MoulongKimong	1	<1		ROM	10	3.51	2.89	2.98	0.64	0.53	0.51	0.94	0.61	0.71	1.93	1.84	1.76
Tiru Coalfield*	1	<2		Pillar Sampling	9	11.00	6.00	6.66									

**Data collected from Singh et al. (2012).*

Table 8: Distribution of different forms of sulphur in Oligocene Coals of Arunachal Pradesh.

Coalfield	**Seam Characteristics**			**Sample Characteristics**		**Total Sulphur**			**Sulphate Sulphur**			**Pyritic Sulphur**			**Organic Sulphur**		
	No's	**Total Tickness (m)**	**Name**	**Type**	**Total No's**	**Max.**	**Min.**	**Av.**	**Max.**	**Min.**	**Av.**	**Max.**	**Min.**	**Av.**	**Max.**	**Min.**	**Av.**
Namchik-Namphuk	8	1-17.4	S-8 (Top)	Channel	10	5.80	4.20	4.80	0.94	0.85	0.86	1.50	0.94	1.12	3.36	2.41	2.82
			S-3			4.30	3.50	3.70	0.74	0.55	0.62	1.11	0.89	0.98	2.45	2.06	2.10
			S-1 (Bottom)			3.10	2.80	2.90	0.75	0.41	0.51	1.04	0.85	0.92	1.31	1.54	1.47

Table 9: Coalfields of platform areas (Raja Rao, 1981).

Areas/State	**Coalfields**
Jaintia Hills	Bapung
	Malwar
	Lumshnong
	Mutang
	Lakadong
	Sutunga
	Jarain
Khasi Hills	Laitryngew
	Mawsynram Area
	LumDidom Hill
	PynurslaPlateau
	Maw-Beh-Larkar Area
	Umrileng Area
	Langrin
	Mawlong-Shella
Garo Hills	West Daranggiri
	East Daranggiri
	Balphakram-Pendengru Area
	Siju
	Baljong, Dogrengg and Hansapal
	Rongrenggiri

Table 10: Coalfields in the zone of Schuppen (Raja Rao, 1981; Indian Bureau of Mines 2018).

State	**Coalfields**
Assam	Makum
	Dilli-Jeypore
	Mikir Hills
Arunachal Pradesh	Namchik-Namphuk
Nagaland	Borjan
	Jhanzi-Disai Valley
	Tuen Sang
	Tiru Valley
	Monlong-kimong

sulphur coals. Coal with 1% to <3% sulphur is medium sulphur coal and coal with ≥ 3% sulphur is considered high sulphur coal (Chou, 1997).For the coalfields of north-east India, all the coals contain sulphur more than 3% (except, few samples) and therefore are placed under high sulphur coal category. Due to the complex nature of organic sulphur, its desulphurization is difficult while chemical desulphurization processes helps in reduction of aliphatic sulphur structure but to achieve a high desulphurization rate biological techniques are useful (Calkins, 1994). These coals have high organic sulphur as compared to inorganic sulphur.

Coalfield of Platform basins

The coalfields of platform areas are shown in Table 9 (Raja Rao, 1981) however mining activity is confined to the areas listed in Table 3, 4 and 5.

The total sulphur content of Eocene coals (Meghalaya) varies from 1.62 to 7.03% (Tables 3, 4, 5). In the Jaintia Hills (Table 3) the total sulphur content ranges from 3.57 to 7.03%, i.e. all the samples show values above 3% and the coals are classified as high sulphur coals. The sulphate sulphur of the coal is 0.21 to 0.78%. The pyritic sulphur varies from 0.14 to 1.21%. The organic sulphur varies from 2.69 to 5.04%.

In the Khasi Hills (Table 4), the total sulphur varies from 1.62 to 5.01%. Although all the samples show sulphur content above 3% except 3 samples of Mawhehlakhan area, where the value is slightly above 1. The sulphate sulphur varies from 0.11 to 0.94%, pyritic sulphur- 0.09 to 0.94% and organic sulphur- 1.31 to 3.91%.

In the Garo Hills (Table 5), only 2 working coalfields are exposed. The total sulphur content of Garo Hills coals varies from 1.8 to 5.2% having sulphate sulphur from trace to 0.4%, pyritic sulphur trace to 1.9% and organic sulphur from 0.8 to 3.2%.

The sulphur percentage of the bottom seam is less than 3 and is placed in the medium sulphur category. All other coals are classified as high sulphur coal and only a few samples have characteristics of medium sulphur coal.

From the sulphur study of coals of Jaintia, Khasi, and Garo Hills, it is revealed that there is a lateral and vertical variation of total sulphur concentration which increases from the bottom seam to the top seam (Tables 3, 4, 5) having highest amount in Jaintia Hills followed by Garo Hills and Khasi Hills. The seams at the top have a higher content of sulphur than that of the seam at the bottom. The Bapung and Jaintia coalfields of Jaintia Hills are located in the eastern part of Meghalaya whereas West Daranggiri and Siju coalfields of Garo Hills are located in the western part of Meghalaya.

Stratigraphically Bapung coalfield belongs to the Lakadong Sandstone member of Shella Formation of Jaintia Group of Lower to Middle Eocene age and is the oldest in Meghalaya whereas West Daranggiri and Siju coalfields belong to the Tura Formation of Lower Eocene age (Table 1).

Pyritic sulphur content is found to increase from west to the eastern part of Meghalaya, which is mainly due to the prevalent marine conditions at the time of the deposition in the eastern part of the basin (Mishra and Ghosh, 1996). Coals of Meghalaya are characteristically higher in sulphate sulphur content. High sulphate sulphur content in coals of Meghalaya generally occur with thin overburden, which suggests that the high sulphate sulphur may be due to the weathered nature of coal (Chandra et al., 1983).

The regional lateral variation of coals of Meghalaya is strictly a palaeoenvironmental effect. In other words, the increase in sulphur content from western to eastern part is due to the more marine nature of the peat-forming swamps of Khasi and Jaintia Hills as compared to that of Garo Hills (Chandra et al., 1983).

The coalfields of foreland basins

The coalfields of foreland basins are placed in Table 10 (Raja Rao, 1981). These fields are confined to the states of Assam, Arunachal Pradesh and Nagaland.

The principal coalfield of Oligocene coal is the Makum coalfield of Assam, having main collieries, Tipong, Ledo, Borgolai, Tirap and Namdong. There are 5 seams of 60 ft., 20 ft., 8 ft., 5 ft. thick, and a new seam present in the area. The sulphur content varies as follows- total sulphur- 2.20 to 6.88% (average 4.43%), sulphate sulphur 0.04 to 0.95% (average 0.64%), pyritic sulphur 0.15 to 1.90% (average 1.01 to 1.1) and organic sulphur 1.60 to 5.76% (average 3.38 to 3.18%). In general, sulphate sulphur is lesser than other forms of sulphur. There is no uniformity in variation of sulphur in the seam both in the lateral and vertical direction.

From the other coalfield of Assam in Jeypore and Dilli coalfield run-of-mine samples were collected and analyzed which contain total sulphur from 2.8 to 6.2%, sulphate

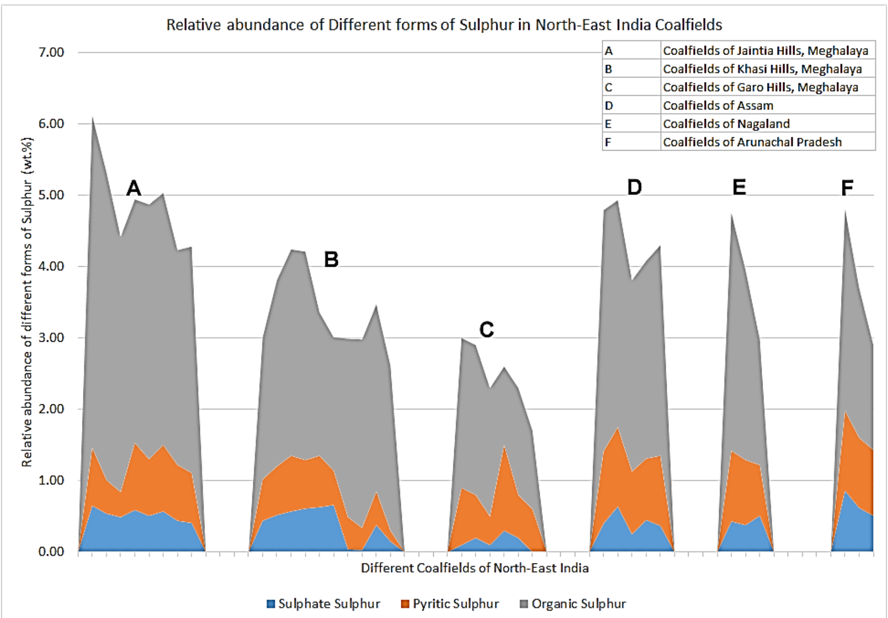

Figure 2: The relative abundance of different forms of sulphur in different coalfields of North-East India.

sulphur from 0.7 to 4.3%, pyritic sulphur from 0.75 to 1.43% and organic sulphur from 1.9 to 4.02%. Namchik-Namphuk coalfield of Arunachal Pradesh also contains sulphur in high amount with total sulphur varying from 2.8 to 3.8% (Table 8). Sulphate sulphur ranges from 0.41 to 0.94%, pyritic sulphur 0.85 to 1.50% and organic sulphur 1.54 to 3.36%.

The sulphur content of Nagaland coalfield (Table 7) is also high. For, Borjan Coalfield the total sulphur content ranges from 3.75- 5.52% with sulphate sulphur in the range of 0.24 to 0.73%, pyritic sulphur 0.89 to 1.01%, and organic sulphur- 2.62- 3.78%.

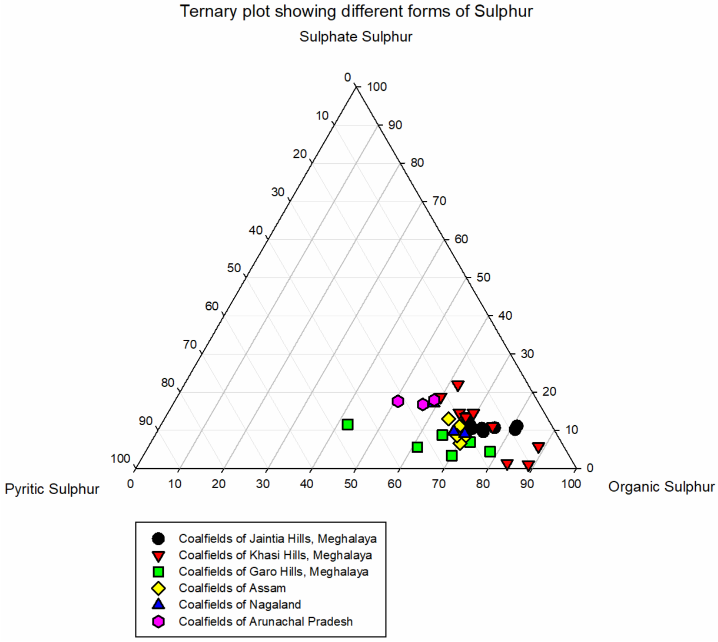

Figure 3: Ternary plot showing different forms of sulphur in different coalfields of North-East India.

For, Moulong Kimang coalfield, the total sulphur varies from 2.89 and 3.01% with sulphate sulphur from 0.53 to 0.64%, pyritic sulphur 0.61 to 0.94% and organic sulphur- 1.84 to 1.93%.

In the case of Tiru coalfield, the total sulphur varies from 6-11% (Singh et al., 2012), which is quite high of all the coalfields of north-eastern region, which may be classed as super high organic sulphur (SHOS) coals as a special class of coal that is remarkably enriched in organic sulphur, usually in the range of 4 to 11% (Chou, 2012).

Sulphur is generally rich in marine influenced coals as observed by Teichmuller (1962). This observation is further supported by Price and Shieh (1979), Sinninghe Damste and De Leeuw (1990) and Chou (1990), where they showed that coals usually more than 1% sulphur comes from the seawater. A similar situation prevails in case of Oligocene coals of northeast India, which have a relatively high sulphur content. A relative abundance of different forms of sulphur in coals of the study area is presented in Figure 2.

Sources of Sulphur

In coal, sulphur (S) primarily originate from sea water, fresh water, vegetation and extraneous mineral matter. During (syngenetic) or after (epigenetic) coal formation secondary sulphur can be introduced by ground water, which is probably remobilizing sulphur that originated in sea water or as loosely held organic matter in the vegetation (Ryan and Ledda, 1997). They observed that fresh water does not contribute any sulphur in coal as they contain 0 to 10 ppm sulphur. However, their observation infer that in coal about 0.5% sulphur was probably derived from sea water which contains average 0.265% SO4 or 885 ppm S (SO4 contain 33.4% S). This is substantiated further by Casagrande (1987) that the marine-influenced peats generally have a higher sulphur content. Similar conditions prevailed in northeastern coals where sulphur content is more than 3% (except a few samples) and higher sulphur content is probably derived from seawater.Liang (2013) also found that the marine biota release organic sulfur compounds, such as dimethyl sulfide (DMS), to the marine boundary layer. Organic sulfur may be a residue of sulfur in proteins of the peat-forming plant communities or may be bounded with organic substances by bacterial activity whereas pyritic sulphur and sulphate sulphur formed due to chemical reactions involving iron, sulphur and other chemicals present in swamp water (Dai et al., 2002). A triangular plot showing the distribution of different forms of sulphur in Paleogene coals are presented in Figure 3. The figure clearly shows the dominance of organic form of sulphur in all the coalfields.

Paleoenvironment

The abundance of sulphur in coal is pointed towards a sedimentary environment of coal-bearing strata. White et al. (1913) from the study of Illinois basin, USA suggests that the high sulphur content of coal was related to the marine and brackish environment of coal deposits. Williams and Keith (1963) while studying the sulphur distribution in the lower Kittanning area concluded that sulphate ions from seawater played an important role in the sulphur enrichment of coal. H2S is formed by reduction of sulphate and pyrite is produced by subsequent reaction with ferrous iron (Kaplan et al., 1963; Rickard, 1975; Goldhaber and Kaplan, 1980; Olson et al., 1985; Raiswell and Berner, 1985; Morse and Berner, 1995).

The coal deposits of the northeast region formed under the marine conditions as evidenced

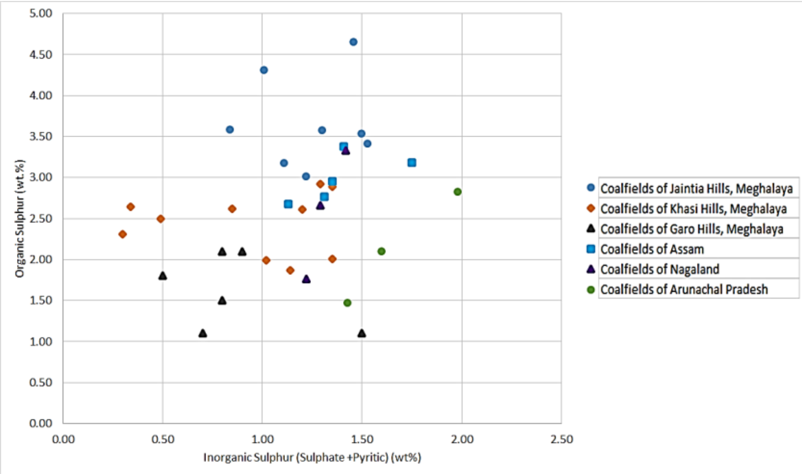

Figure 4A: Cross plot between organic and inorganic forms of sulphur for different coalfields of North-East India.

by the high content of sulphur (3-7%). Both Eocene and Paleocene coals were developed under the marine conditions of sedimentation. The Eocene coals of Meghalaya were probably deposited during the Eocene time under stable shelf conditions. The Oligocene coal of foredeep basins evolved as a consequence of subduction of Indian plate margins with that of the Burmese plate so there was miogeosyncline of flysh and molasses type of sediments (Raja Rao, 1981). Dasgupta and Biswas (2000) have shown that brackish water condition prevailed during Barail Formation. Peat is either connected to Brackish water (Bustin and Lowe, 1987; Casagrande 1987) or it is overlain by marine sediments as revealed by the high sulphur amount. Further studies supported that on modern peats under the marine influence which has shown enrichment of sulphur due to sulphate reducing bacteria which results into precipitation of pyrite in peat (Phillips et al., 1994). Pyrite in the form of iron sulphides is found in coal as the dominant sulphide. Euhedral and massive pyrite also marcasite generally form during early syngenetic processes in uncompressed peat whereas early to late syngenetic processes are responsible for the formation of cell-filling pyrite in cell cavities of macerals. Pyrite formed in the cleats of coal indicate its origin by late syngenetic or epigenetic processes whereas dendritic pyrite forms at the later stages of coal formation (Grady, 1977).

Pyrite in coal typically forms from H_2S and Fe in solution. The process involves bacterial reduction of SO_4 to H_2S at pH values of 7 to 4.5 followed by the combining of H_2S, elemental sulphur and ferrous iron oxide (FeO) to form pyrite and water. This is the only way pyrite can form in peat and low-rank coals. Consequently the presence of bacteria and required pH range are very important controls on pyrite formation in coals. The SO_4 may come from sea or vegetation, but either of these sources provides iron, which is usually in plentiful supply and comes from other sources (Nayak, 2013). It is probably derived from the breakdown of clay minerals and is possibly carried in solution as stabilized organic colloids (Chou, 2012). In coal with a high amount of total sulphur, the more proportion comes from seawater (Chou. 1990). A cross plot between organic and inorganic forms of sulphur is presented in Figure 4, which clearly shows the separate clusters formed by coalfields of different regions of northeast India. This indicates that all these coals are having high sulphur,whose variation is mainly controlled by tectonic uplifting, peat-forming plant communities, roof strata, and marine or freshwater incursion.

Conclusion

On the basis of a detailed study of the distribution of sulphur of NE region of India following conclusion can be drawn:

The coals of Meghalaya were deposited in platform areas under stable condition duringthe Eocene Period,whereas Oligocene coals of Assam, Arunachal Pradesh, and Nagaland developed in foredeep basins of the Barail Group of Tikak Parbat Formation. The coals are rich in S content which ranges from 3-7%. All the forms of S recognised, organic sulphur is the dominant one.

There is a vertical and lateral variation of sulphur in Eocene coals of Meghalaya which is absent in Oligocene coals of Assam, Arunachal Pradesh and Nagaland. The sulphur content of platform basins increases towards the top seam from bottom one. More so sulphur content increases from the western part of Meghalaya to the Eastern part.

The main sources sulphur of both the Paleogene coals are the sea water as there was a marine incursion during that period as evidenced by the pyrite content of sulphur (0.20 to 1.42%). Pyrites were typically formed from bacterial reduction of SO_4 to H_2S at pH values of 7 to 4.5.

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Petrographic Characterization and evolution of Eocene Coal from Bapung coalfield, East Jaintia Hills, Meghalaya, North-East India

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Abstract

The Bapung coalfield in the East Jaintia Hills of Meghalaya belongs to the Shella Formation of Jaintia Group and is of Eocene age. Thinly bedded seams of about 1 m thick are vastly exposed in the Bapung area. The present study includes petrographic and geochemical characterization of these coals. This study reveals that the Bapung coals are sub-bituminous 'A' to high volatice bituminous 'C' in rank. These coals are perhydrous in nature with moderately high volatile matter content. The sulphur content is high in these coals having pyrite as the most abundant mineral. Vitrinite is the dominant maceral group constituting nearly 76.5-82.6% of the entire group macerals, while inertinite occurs in subordinate amount and liptinite concentration is insignificant. Facies-critical models used to decipher the paleodepositional environment suggest that anoxic moor condition dominantly prevailed in the paleomire and there was association of peat with brackish water condition which allowed the sulphate reducing bacteria to thrive.

Keywords: Bapung coal, Meghalaya, coal Petrography, geochemistry, depositional environment.

INTRODUCTION

The coal resources of India occur in two main stratigraphic horizons - the Gondwana coals of Permian age and the Tertiary coal resources of Paleogene. Gondwana coals account for over 99% of India's output while the Tertiary coal contributes the rest. The Tertiary coal deposits in the northeastern region of India mainly occur in the States of Assam, Arunachal Pradesh, Meghalaya and Nagaland. The coal-bearing sequences of Meghalaya are deposited over a platform basin having a stable self-conditions especially along the peripheral margins of the Shillong Plateau. Raja Rao (1981) reported three groups of coalfields in Meghalaya located in the Garo Hills, Khasi Hills and Jaintia Hills.

It was Medlicott (1868) who first reported the occurrence of coal in Meghalaya and the subsequent researches were carried out by Bose (1904), Evans (1932), Fox (1934), Gosh (1940 & 1964), Goswami and Das (1965), Chakraborty and Bhattacharyya (1969), Raja Rao (1981), Ahmed and Bharati (1985), Goswamy (1985), Singh (1989), Chandra and Behera (1992), Ahmed and Rahim (1996), and Rajarathnam et al. (1996). Recently, the coalfields of northeastern India have been petrologically studied by several workers and significant contributions have been made by Mishra (1992); Mishra and Ghosh (1996); Singh and Singh (2000 & 2001); Singh et al. (2012c, 2013a). Present study focusses on coals of Bapung coalfield (Fig. 1) which is a minor but important coalfield of Jaintia Hills, Meghalaya. The coal seams occur in the Shells Formation of Eocene age and belong to Jaintia Group. The objective of the present study is to provide comprehensive information of the composition and evolution of Bapung coals from Jaintia Hills of Meghalaya using coal petrography and geochemistry.

Geological Setting

The coal sequences in the Tertiary Assam-Arakan tectono-sedimentary basin occur in two distinct geotectonic provinces: (i) the coal deposits of Garo and Khasi Hills of Meghalaya and Karbi Anglong of Assam deposited over the stable platform areas peripheral to the shield; (ii) the deposits of Upper Assam, Nagaland and Eastern Arunachal Pradesh formed in the peri-cratonic down wraps in a Schuppen zone. Thus, the coal bearing sequences of Jaintia Hills of Meghalaya evolved over platform areas under stable self-conditions. In Meghalaya the sediments associated with coal measures range in age from Upper Cretaceous to Eocene exhibiting lateral and vertical variation in lithofacies. Sedimentation began during the

Upper Cretaceous time when marine transgression took place in the area towards north and inundated the southern block of the Shillong plateau. Though the sedimentation continued throughout the Tertiary period but the sedimentation during the Cretaceous period had a restricted areal extent. The eastern sector is characterized by thick lava flows during Sylhet Trap volcanism of Jurassic period. After cessesion of volcanic activity there was accumulation of thick pile of sediments which progressively decreased towards the Garo hills. It is believed that the sea inundated the present day Jaintia Hills during Eocene period. Probably the Jaintia hills in the east remained a landmass till early Eocene and experienced down sinking during the deposition of the coal-bearing sandstones of Eocene age. Medlicott (1869) was first to provide the stratigraphy of Meghalaya and introduced the names Mahadek, Langpar, Cherra bands and Nummulitic series within Cretaceous-Eocene sediments exposed along the South Shillong Plateau. Subsequently, Evans (1932) provided a comprehensive stratigraphy of the Assam-Arakan Basin and established stratigraphic framework of South Shillong Plateau along with Naga Hills, Barail Range and Surma Valley. While working on the geology of the western part of Garo Hills, Fox (in Heron, 1937) discussed its stratigraphic relationship with the strata exposed in the eastern part of the Shillong Plateau and Ghosh (1940) established the stratigraphic relationship of the lower Tertiary sediments in the Cherrapunji area. The Sylhet Stage of Evans (1932) was subdivided by Wilson and Metre (1953) who introduced several substages with local names. Mathur and Evans (1964), however, felt that 'Series', 'Stages' and' Substages' appear to be equivalent to 'Group', 'Formation' and 'Member' respectively and therefore proposed another scheme of classification for both the shelf and the geosynclinal part of the Assam-Arakan basin. Chandra et al. (1959) and Chakraborty et al. (1974) mapped the South Shillong Plateau for Oil and Natural Gas Corporation (ONGC). The generalized stratigraphic succession of Meghalaya with subdivision and lithology (after Deshpande et al., 1993) are given in Table 1.

Table 1: Stratigraphic Sequence of Meghalaya (after Deshpande et al., 1993)

		Garo Hills		**Khasi and Jaintia Hills**	
Age	**Group**	**Formation**	**Member**	**Formation**	**Member**
Recent		Alluvium			
Pliocene to Pleistocene	Dihing Group	Dihing Formation			
	Dupitila Group	Dupitila Formation		Dupitila Formation	
Miocene to Pliocene	Tipam Group			Tipam Formation	
	Surma Group	Undifferentiated		Bokabil Formation Upper Bhuban Formation Middle Bhuban Formation Lower Bhuban Formation	
Oligocene	Barali Group	Undifferentiated		Renji Formation Jenam Formation Laisong Formation	
Eocene	Jaintia Group	Kopili Formation		Kopili Formation	
		Sylhet Formation		Sylhet Formation	Prang Limestone
		Tura Formation			Nurpuh Limestone
					Umlatdoh Limestone
					Lungshnong Limestone
					Lakadong Limestone
					Lakadong Sandstone
				Therria Formation	Upper Sandstone
					Lower Sandstone
Palaeocene	Khasi Group			Langpar Formation	

Cretaceous		Mahadek Formation	Mahadek Formation
Upper Jurassic to Lower Cretaceous	Sylhet Trap		Sylhet Trap
Precambrian Metamorphic Basement			

Structure and Tectonics

The Shillong Plateau has a horst type structure which got uplifted during the Lower Cretaceous period. Its tectonic evolution is closely related to the outpouring of lava flows (Sylhet Trap) during Upper Jurassic-Lower Cretaceous period. The deposition of coal bearing sequences began in the southern periphery of the plateau during the Palaeocene period under the stable shelf conditions. The coal sequences are sub-horizontal in attitude but further south, near Bangladesh border; the beds are thrown into a major monoclonal flexture, with major dislocation known as Dawki Fault. From Haflong, it runs westwards, towards the boundary of the Surma Valley near Dawki and it is a continuation of the Disang thrust. Evans and Mathur (1964) consider this fault as a tear fault. The movement along this fault is nearly 250 km which separates Sylhet Trap from the Rajmahal Trap of Bihar. Chakraborty (1972) believes that it is a system of up thrust with a differential vertical movement of the basement rocks. The thrust has an east-west trend with northward steep dip which brings gneisses structurally over the Tura sediments. The northern boundary of the Shillong plateau has a thick cover of Brahmaputra alluvium while the eastern margin is characterized by N-S trending graben (Kopili Lineament) which separates it from Karbi Anglong Plateau, and its western boundary is marked by the Bengal Basin separating it from the Chotanagpur Plateau of Bihar.

Materials & Methods

Channel coal samples were collected from all the working/exposed coal seams from Bapung area (Fig. 2). The samples of coal collected were air dried to remove the free moisture. After drying, the required amount of the sample was taken from each sample by coning and quartering method. The portion selected was crushed and passed through 72 mesh (211 micron) sieve for proximate analysis. Polished blocks were prepared from the channel samples selecting hand lumps of coal. In order to prepare polish blocks to study the coal under reflected light, two alternate faces (vertical and horizontal) are selected. The faces were then ground by increasing fine grades of carborundum powder up to 600-grade on a revolving disc in wet condition. The blocks were then polished on a plane glass using alumina suspension. The block was washed with water to remove impurities. The washed surfaces were polished by using energy papers from 004-001 grades. Final polishing was made in a sylvet cloth fitted on a revolving disc. The maceral analysis was carried out on polished blocks under reflected light with oil-immersion lens using a Leitz Microscope. Coal petrography was carriesd out as per ICCP recommendations (1971, 1975, 1998 & 2001). The procedure recommended by Bureau of Indian Standard (BIS 2003, 1974 & 1975) was followed for proximate and ultimate analyses. The vitrinite reflectance measurements were carried out in the KDMI institute, Dehradun using Leitz MPV-2 microscope under oil immersion lens.

RESULTS AND DISCUSSION

Megascopic Characteristics

The Bapung coal is dark grey to black in colour. The coal is hard and compact, but some portion of the seam is soft and friable. The coals break with cubical fracture, but the hard ones break with sub-conchoidal to conchoidal fracture. The coal depicts a dull to glossy lustre and at places thin pyrite bands are also observed. When exposed to sun, most of the coal disintegrates and crumbles into small chips, indicating a high percent of volatile matter in them.

Chemical Attributes

The proximate and ultimate analyses data are summarized in Tables 2 and 3 respectively. The Bapung coals are chemically characterized by a low ash yield (1.1% to 4.2%), low moisture (1.5% to 2.1%) and high volatile matter (40.02% to 45.25%). The ultimate analysis shows that these coals have carbon contents ranging from 74.30% to 79.65% while hydrogen content is moderately high with more than 5wt% in all the samples. The sulphur content is also high and ranges from 3.58% to 5.03%. H/C and O/C atomic ratios have been calculated. The H/C varies frpm 0.84 and 0.94 (mean 0.90) while O/C ranges from 0.07 to 0.13 (mean 0.10). Generally marine influenced coals are rich in sulphur, hydrogen and nitrogen contents and also have a characteristically high volatile matter than other coals (Teichmüller, 1962). This generalization was further substantiated by Price and Shieh (1979) and Chou (1990) who confirmed that this increased proportion of sulfur (usually>1%) comes from seawater. Under such a situation, the hydrogen and nitrogen are retained in the humic materials and finally appear as perhydrous vitrinite (Taylor et al., 1998). This condition could also have been with Bapung coals which have relatively high sulphur and volatile matter contents (Fig. 3) and shows perhydrous nature. Bapung coal in the Van Krevelen diagram (Fig.4) indicates that the coal was derived essentially from continental plants, whose microbial degradation in the basin of deposition was limited due to high sedimentation and rapid burial.

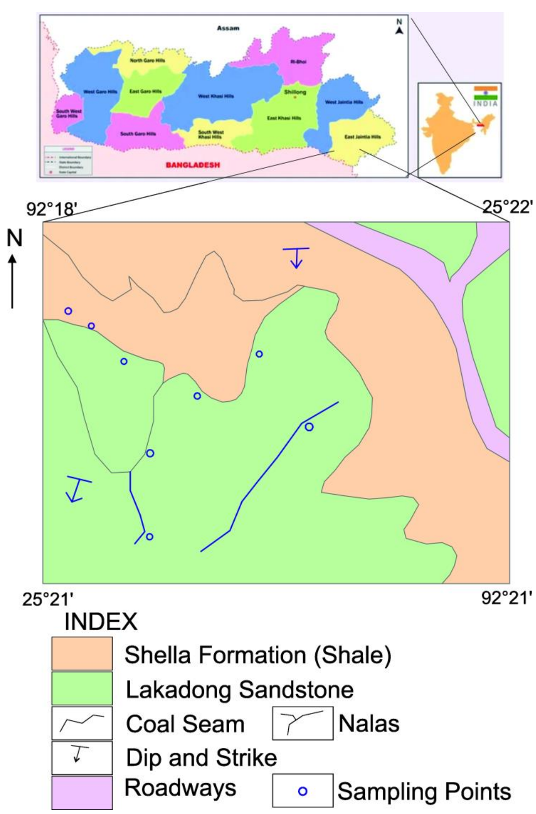

Fig. 1: Location and geological map of Bapung coalfield

Petrographic Composition

The maceral composition of Bapung coals is summarized in Table 4. The representative macerals microphotographs in studied samples are illustrated in Figure 5. The Bapung coals of Meghalaya, in general, are poor in liptinite and inertinite while vitrinite is the most abundant maceral. The vitrinite content ranges from 76.50% to 82.62% (mmf basis). It is dominated by telovitrinite which is mainly represented by collotelinite. It is light grey in colour and shows low to moderate reflectance and occurs as groundmass and coal bands. Liptinite ranges from 1.25% to 3.25% (mmf basis) and it is represented mainly by sporinite and resinite. Sporinite occurs as thread like bodies within vitrinite and it has a low reflectivity than vitrinite. Resinites occur as rounded to oval shaped bodies, in these coals, mostly as inclusions in vitrinite and are almost opaque in reflected light. It includes the plant resin and wax occurring as rodlets in vitrinitic groundmass. Inertinite also occurs in low amounts (8.6% to 18.0%, mmf basis) and it is mainly represented by fusinite, semifusinite, macrinite, inertodetrinite and funginite. Fusinite is characterized by the presence of well-preserved cell structure and higher reflectance. In some cases, cell structure is crushed producing 'Bogen structure'. Semifusinite is characterized by cell structures less preserved than fusinite and higher reflectivity than the vitrinite. Macrinite occurs as fine particulate matter in the form of lenses. It shows white colour and high reflectance. Inertodetrinite is seen with the cracks and cavities. Funginite occurs as single and multi-chambered body having circular to oval shapes.

Fig. 2: Bapung coal seam during sampling

It represents fungal remains and has variable size, and is characterized by high reflectance.

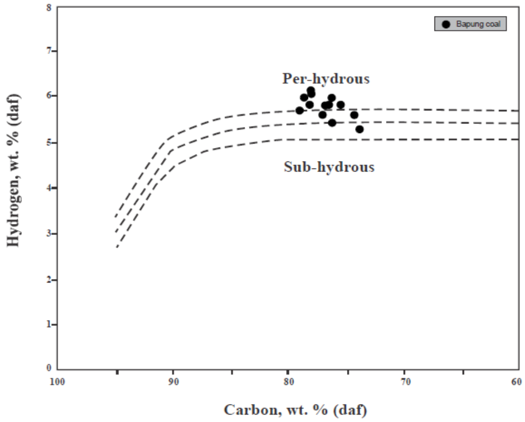

Fig. 3: Simplified Seylers chart with the 'bright coal band' indicated by dashed lines. The sulphur rich Bapungcoals of Meghalaya are at the upper limit of the bright coalband and also in the area of per-hydrous coals.

Mineral matter ranges from 3.1% to 6.3% and is represented mainly by pyrite. It occurs as disseminated grains and specks within vitrinite and as framboidal pyrite bodies. These framboids occur as single or clustered bodies or in the cavities. Argillaceous minerals and carbonates are next in abundance (Table 4).

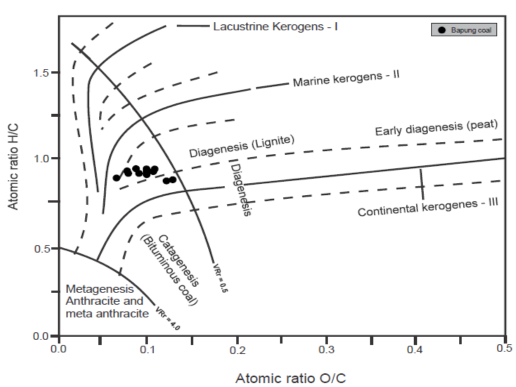

Fig. 4: Position of Bapung coal, Meghalaya in Van Krevelen diagram of H/C versus O/C atomic ratios (after Van Krevelen, 1961)

Reflectance and Thermal Maturation

The thermal maturity of organic matter is related to its chemical changes. A number of parameters are available to assess the maturity like volatile matter, vitrinite reflectance and T_{max} but in the present investigation, vitrinite reflectance was used to know the thermal maturity of Bapung coals. The vitrinite random reflectance (Rr) ranges from 0.57% to 0.67% (avg. 0.62%). The details of reflectance measurements are summarized in Table 4. As per ISO-11760 (2005), Bapung coals are 'medium rank C'/ 'bituminous C' in rank.

Table 2: Results of proximate analysis of Bapung coal in air dried basis (in weight per cent)

Sample No.	Moisture	Ash	Volatile matter	Fixed carbon
1	1.8	1.5	42.15	54.55
2	2.0	1.6	40.25	56.15
3	1.9	2.8	41.20	54.10
4	2.0	1.6	42.30	54.10
5	1.7	2.7	44.70	50.90
6	1.8	2.4	44.25	51.55
7	1.6	1.5	43.70	53.20
8	1.8	2.4	40.10	55.70
9	1.5	2.2	42.75	53.55
10	1.7	4.2	44.10	50.00
11	2.0	2.4	40.25	55.35
12	1.9	3.4	42.35	52.35
13	1.6	1.1	44.20	53.10
14	1.5	1.6	42.23	54.67
15	1.7	1.5	40.02	56.78
16	1.5	1.7	40.02	56.78
17	1.7	2.2	42.32	53.78
18	1.6	2.1	42.02	54.28
19	1.7	2.5	43.67	52.13
20	2.1	2.7	45.25	49.95
21	1.8	2.5	43.07	52.63
22	1.6	3.7	44.25	50.45
23	1.9	3.1	42.02	52.98
24	1.5	3.2	42.87	52.43
Average	1.7	2.4	42.50	53.39
Maximum	2.1	4.2	45.25	56.78
Minimum	1.5	1.1	40.02	49.95

Evolution of Bapung Coal

Teichmüller (1962) believed that the coals formed under marine conditions are generally rich in sulphur, hydrogen and nitrogen contents and are also characterized by relatively high volatile matter. This fact has also been substantiated by Price and Shieh (1979) and Chou (1990) who demonstrated that increasing sulfur proportion (usually> l%) of such coals comes from sea water. Taylor et al. (1998) have shown that hydrogen and nitrogen are retained in the humic materials and are reflected consequently as perhydrous vitrinite. Similar conditions were also recorded in the nearby coal seams of Nagaland (Singh et al., 2012) and could also be applicable with coals which have relatively high sulphur content and volatile matter as in Bapung coals. Bapung coal in the Van Krevelen diagram (Fig. 4) indicates that the coal was derived mainly from continental plants, whose microbial degradation in the basin of deposition was controlled by sedimentation and rapid burial. However, the marine influence cannot be ruled out as few plots also show some deviation from pure continental route (Fig.4).

Table 3: Elemental composition of coal in dry mineral matter free basis

Sample No.	Carbon (wt. %)	Hydrogen (wt. %)	Nitrogen (wt. %)	Total sulphur	Oxygen (wt. %)	H/C	O/C
1	77.06	5.83	2.66	4.11	10.34	0.08	0.14
2	74.30	5.32	2.82	4.25	13.31	0.07	0.19
3	79.15	5.69	2.95	4.45	7.76	0.07	0.11
8	78.32	6.15	1.76	4.40	9.37	0.08	0.14
9	76.58	5.37	2.20	3.58	12.27	0.07	0.17
10	78.13	6.11	1.92	5.02	8.82	0.08	0.13
11	79.65	5.95	1.39	4.69	8.32	0.07	0.12
12	76.63	5.90	2.23	4.71	10.53	0.08	0.15
13	76.85	5.74	2.80	4.38	10.23	0.07	0.14
17	74.68	5.86	1.99	4.20	13.27	0.08	0.19
18	75.74	5.81	2.67	4.27	11.51	0.08	0.16
19	78.47	5.81	2.84	3.37	9.51	0.07	0.13
24	76.39	5.77	2.35	4.97	10.52	0.08	0.15
Average	77.07	5.79	2.35	4.31	10.48	0.08	0.15
Maximum	79.65	6.15	2.95	5.03	13.31	0.08	0.19
Minimum	74.30	5.32	1.39	3.58	7.76	0.07	0.11

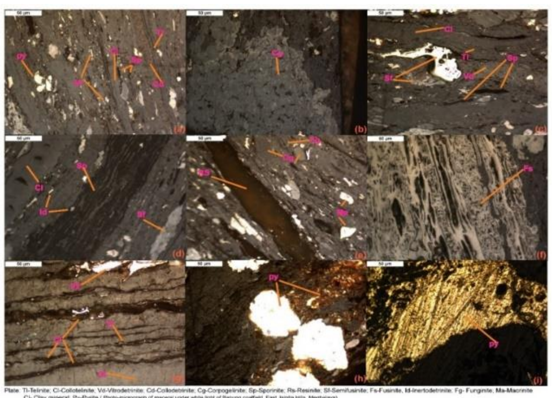

Fig. 5: Representative macerals microphotographs observed in Bapung coal samples

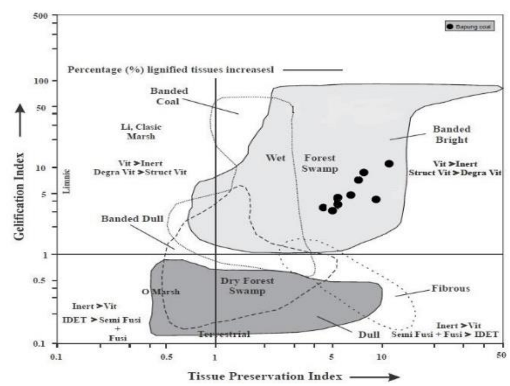

Fig. 6: Coal facies deciphered from gelification index (GI) and the tissue preservation index (TPI) in relation to depositional setting and type of mire for Bapung coal (after Diessel, 1986 and modified by Kalkreuth et al., 199) [Li = limited influx; O marsh = open marsh; Vit = vitrinite; Inert = inertinite; Semifus = semifusinite; Fus = fusinite; Idet = inertodetrinite; Struct = structured; Deg = degraded

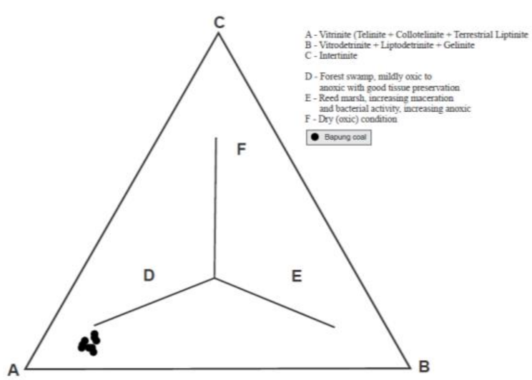

Fig. 7: Ternary diagram illustrating facies-critical maceral association in Bapung coal, Meghalaya and suggested peat environments (modified from Mukhopadhyay, 1986)

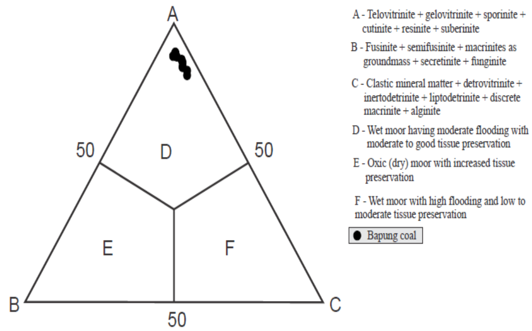

Fig. 8: Depositional condition of Bapung coal, Meghalaya based on maceral and mineral matter content (modified from Singh et al., 2012a)

Teichmüller (1982) believed that 'coal facies' depend on the paleoenvironmental conditions under which the precursor peats accumulate. Thus, plants are sensitive and react to the changes in the environmental conditions and therefore, petrographic study provides a precise tool for the facies study (Teichmüller and Teichmüller, 1982). Moreover, several researchers have related the petrographic components of coal with the paleoecological setting (Cohen and Spackman. 1972; Cohen et al., 1987; Grady et. al., 1993; Singh and Singh, 1996; Hawke et al., 1999; Shearer and Clarkson. 1998; Styan and Bustin. 1983; Singh et al., 2003, 2010a &b, 2012 a, b & c, 2013a &b, 2014, 2016, 2017a, b, c &d; Naik et al., 2016; Rajak et al., 2018 (in press)). For this purpose, different maceral indices have been used. Initially gelification index (GI) and tissue preservation index (TPI) were introduced by Diessel (1986) to characterize the depositional environments of Australian Gondwana coals. However, some scientists raised critical comments against the usage of such indices especially for Tertiary coals and lignites (Lamberson et al., 1991; Crosdale. 1993; Dehmer. 1995; Scott. 2002; Moore and Shearer. 2003; Amijaya and Littke. 2005). Modifications were subsequently made in the indices by some researchers to make it applicable for other coals (Calder et al., 1991). Kalkreuth et al. (1991) and Petersen (1993) further modified these indices and used them for low rank coals. For Bapung coals of Meghalaya, the modified

Table 4: Maceral composition with mineral matter content (in Vol %), random vitrinite reflectance, gelification index (GI) and tissue preservation index (TPI) of Bapung coal samples

Sample No.	CC1 (Vol %)	CC2 (Vol %)	CC3 (Vol %)	CC4 (Vol %)	CC5 (Vol %)	CC6 (Vol %)	CC7 (Vol %)	CC8 (Vol %)	CC9 (Vol %)
Telinite	0.0	0.1	0.3	0.7	0.5	0.0	0.4	0.3	0.8
Collotelinite	78.2	76.2	77.5	75.2	76.0	81.5	73.5	80.2	79.5
Gelinite	1.1	0.1	1.1	0.0	0.5	0.0	2.1	0.0	0.0
Corpogelinite	0.1	1.8	0.7	0.5	1.6	<1	0.2	0.1	1.3
Collodetrinite	2.3	<1	0.5	0.2	0.1	1.7	0.1	2.1	<1
Vitrodetrinite	<1	1.1	<1	0.7	0.2	0.6	0.2	0.5	0.2
Total Vitrinite	81.7	78.2	80.1	77.3	78.5	82.6	76.5	82.2	81.8
Sporinite	2.23	1.12	1.94	1.07	0.68	1.46	1.88	1.4	0.75
Resinite	1.02	0.4	1.01	0.2	0.6	0.7	0.1	0.3	0.5
Cutinite	0.0	<1	0.0	0.0	<1	<1	0.0	0.0	<1
Total Liptinite	3.25	1.52	2.95	1.27	1.28	2.16	1.98	1.70	1.25
Fusinite	1.1	1.2	1.0	0.9	0.2	0.1	0.8	3.0	0.3
Semifusinite	1.0	0.4	1.1	0.4	1.5	0.8	2.0	1.0	1.0
Macrinite	6.2	12.8	9.2	16.5	14.5	10.2	15.0	9.0	12.1
Inertodetrinite	0.2	0.2	0.1	0.1	0.0	0.0	0.1	0.0	0.2
Sclerotinite	0.1	0.2	0.0	0.1	0.3	0.0	0.1	0.0	0.1
Total Inertinite	8.6	14.7	11.4	18.0	16.4	11.1	18.0	13.0	13.7
Mineral Matter	6.3	5.5	5.6	3.3	4.2	4.0	3.4	3.2	3.1
%VRr	0.66	0.62	0.58	0.67	0.59	0.61	0.65	0.63	0.57
TPI	12.54	5.98	8.55	4.61	5.36	8.07	4.93	9.35	6.57
GI	9.5	5.3	7.0	4.2	4.8	7.4	4.2	6.3	5.9

indices were calculated using following formulae:

GI = Vitrinite/Inertinite
TPI = (Telinite + collotelinite + Fusinite + Semifusinite)/(Collodetrinite + macrinite + inertodetrinite)

Bapung coals are characterized by moderate GI and TPI values. A moderate GI indicates a continuous presence of water cover in the basin during Bapung coal formation. The facies model shows that these coals evolved mainly from wet forest (Fig. 6). Presence of high telovitrinite content in these coals also reveals this fact because this maceral subgroup is derived from partially gelified woody tissue and indicates wood producing plants as well as biochemical gelification. Marchioni and Kalkreuth (1991) relate the biochemical gelification to high moisture condition. Further, Diessel (1982) believe that brighter components of coal are formed under wet conditions. The present study is also in agreement with the earlier work (Mishra and Ghosh, 1996; Singh et al., 2012c, 2013a) who demonstrated that the coals of NE India evolved under wet forest swamps in marshy environments. Mishra (1992) has revealed through palynological records that during Palaeocene and Oligocene periods there was growth of green forest vegetation under humid tropical conditions in India. Lack of forest fire could have been the reason for low inertinite content in these coals. To understand the peat forming environment, a petrography based ternary model given by Mukhopadhyay (1986, Fig. 7) was taken into account. The samples of Bapung coals are located close to 'A' corner of the plot which is dominated by telovitrinite (telinite and collotelinite) and terrestrial liptinite indicating forest swamp having more anoxic environment with good tissue preservation. This is further confirmed in a recent model proposed by Singh et al. (2012a) which is based on maceral composition and clastic mineral matter content. The amount of clastic minerals directly relates to the water cover in the basin and the plots of Bapung coal indicate that this coal evolved under wet moor condition having moderate flooding with moderate to good tissue preservation (Fig.8). This is also in agreement with the GI and TPI values (Diessel, 1986; Kalkreuth et al., 1991; Petersen, 1993).

Moreover, Bapung coals are enriched in sulphur (3.58-5.03%; mean 4.31 wt %) and elevated pyrite content is commonly seen under microscope indicating the association of peat with brackish water condition. This type of association has been reported by several workers (Bustin and Lowe, 1987; Casagrande, 1987). Dasgupta and Biswas (2000) reported the prevalence of hallow brackish water condition during the formation of Barail Formation. This has been further substantiated by the studies on modem peats formed under marine influence (Querol et al., 1989; Phillips et al., 1994).

CONCLUSION

Petrographic and geochemical investigations were conducted on the samples of Bapung coals from Meghalaya. The results reveal that these coals are 'medium rank C'/'bituminous C' in rank. They are dominantly rich in vitrinite (76.5% to 82.6% on mmf basis) with low contents of liptinite and suboderdinate/moderate inertinite. Moderate GI and TPI values are indicative of a wet forest origin for these coals. The petrography based ternary facies model further supports this contention and infer the formation of Bapung coal formation under high water cover in the paleomire with good tissue preservation. Moreover, association of peat with marine sediments appeat yo have elevated sulfur content in these coals.

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Weathering and Source Rock Characteristics of the Upper Disang Sedimentary Rock of the Indo-Myanmar Ranges, NE India

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Abstract

The Eocene Disang Group occupies a vast area of Manipur and extends in parts of Tista and Tirap valley in Arunachal Pradesh, Nagaland Hills, and small portions of North Cachar Hills (Assam) and continues up to Chin Ranges of Myanmar Ranges. The Disang Group is characterized by a group of monotonous sequences of dark grey to black splintery shales and has intercalation of siltstones and light to brownish grey, fine- to medium-grained sandstones of especially in the upper horizons, occasionally giving rise to rhythmic character. ICV vs. CIA, K_2O/Na_2O vs. Fe_2O_3+MgO and TiO_2 vs. Al_2O_3 diagrams reveal that sediments from the Tista and Tirap river valleys in Arunachal Pradesh and towards the central portion of the Naga Hills in Nagaland are more weathered and recycled than sediments from the study area (most of Imphal valley or Manipur valley in Manipur). The sediments for the study area were dominantly derived from the unweathered rising Indo-Myanmar Ranges. The pre-Himalayan rocks might have been supplied sediments for the Disang Group. Sediments were also possibly derived from the uplifted fold thrust belt of Myanmar's landmass comprising of igneous and metamorphic basement complex with older sedimentary sequences with minor contributions of detritus from Mishmi Hills region lying to the NE of the Arunachal Pradesh. The Disang sediments were deposited in different sedimentary environments from tidal flat to nearshore lagoon and neritic shallow marine environment and different in composition might have been related to variation in source rock for these sediments which was deposited in the Indo-Myanmar basin formed by rifting and crustal stretching on the continental margin of the Myanmar landmass.

Keywords: Depositional Environment, Tectonic Setting, Upper Disangs, Indo-Myanmar Ranges, NE India

INTRODUCTION

Geochemical data can provide valuable information about the weathering, composition of sediments, the source area characteristics and the environment of the depositional basins (Pettijohn et al., 1972; Taylor and McLennan, 1985; Floyed et al., 1991). Geochemistry of the sediments provides clues for provenance interpretations (Bhatia, 1983; Taylor and McLennan, 1985; Armstrong-Altrin et al., 2017; Chaudhuri et al., 2020). Geochemistry is, therefore, more suitable for the interpretation of provenance of both sandstone and shale (Wronkiewicz and Condie, 1987; Garver and Scott, 1995; Fedo et al., 1995). Discriminant plots based on the oxides of Ti, Al, Fe, Mg, Ca, Na and K are useful for distinguishing different provinces (Roser and Korsch, 1988; Saha et al., 2018). Being immobile, titanium oxides, alumina and Fe are particularly useful for provenance interpretations (Hayashi et al., 1997, Devi, 2021). Different binary and ternary plots of major element oxide (Si, Al, Ti, Fe, Mg, Ca, Na, K) provide significant information about palaeoweathering, palaeoclimate, nature of source rocks, tectonic setting and depositional basin environment (Potter et al., 2005; Suttner and Dutta, 1986; McLennan et al., 1980; Schieber, 1992; Roser and Korsch, 1986; Roaldest, 1978).

The Indo-Myanmar Ranges (IMR) have been considered as an accretionary prism evolved due to subduction of the Indian plate below the Myanmar plate (Soibam 1998; Singh, 2012). The Indo-Myanmar Ranges comprise of Disang Group (Eocene), Disang-Barail Transition sequence (Late Eocene-Early Oligocene) and Barail (Oligocene), Ophiolites and associated Upper Cretaceous sediments. In front of the rising IMR, a basin called Surma Basin was formed and Surma Group of rocks was deposited. The Disang Group occupies a vast area of Indo-Myanmar Ranges, Northeast (NE) India comprises of Naga-Patkai Hills, Manipur Hills, Mizo-Chin Hills and Arakan-Yoma Hills and extends towards Eastern Himalaya (Arunachal Pradesh). The Disang Group is subdivided into two formations namely, Lower Disang and Upper Disang formations. The shales and sandstones of the Upper Disang were deposited in a shallow marine basin during Eocene under tropical warm humid climate condition (Singh et al., 2017a). Detailed study on Disang Group can highlight how the Indo-Myanmar basin, in turn, IMR was developed and tectonic activity that occurred during Eocene or earlier. However, no detailed study has been carried out on the Disang Group as a whole from north to south of Disang exposure. The available works were confined on small area like Tista and Tirap river valleys in Arunachal Pradesh (between 95^{O} $20^{/}$E, $26^{O}50^{/}$N and $95^{O}11^{/}$ E, $26^{O}40^{/}$N,), the central portion of the Naga Hills in Nagaland ($94^{o}12^{/}$E, $25^{o}30^{/}$N and $94^{o}30^{/}$E, $25^{o}41^{/}$N) and some parts of Manipur (93.29°E, 24.37°N, 94.15° E, 25.37° N, $94^{O}11^{/}$ E , $24^{O}41^{/}$ N and 93°39'39.6"E , 24°20'40.4"N, most of the Imphal valley of in Manipur). Therefore, in the present paper the geochemical data from north to south of Disang exposure from Tista and Tirap river valleys (Majumder and Chetia, 2011; Gogoi and Sarmah, 2013), the central portion of the Naga Hills (Imchen et al., 2014) and study area (Figure 1) are compared to infer depositional environment and source area characteristics of the Indo-Myanmar Ranges.

The IMR is about 1250 km long and about 100-150 km wide. However, geochemical data of Disang Group of IMR are very meagre. Disangs exposed in the Tista and Tirap river valleys in

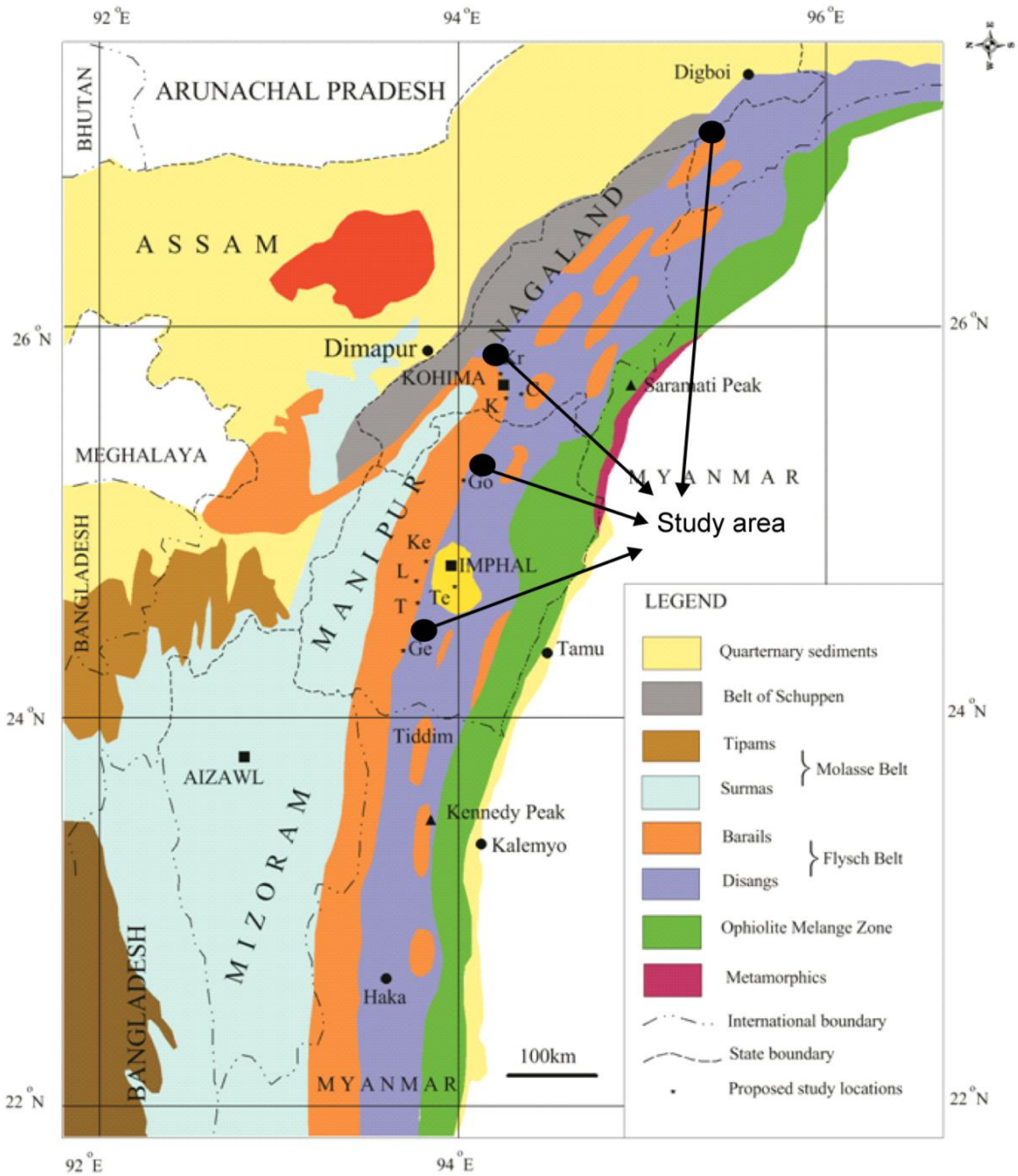

Figure 1: Geological map of Northeast India (Soibam et al., 2015) showing study areas i.e. Arunachal Pradesh, Nagaland and Manipur.

Arunachal Pradesh is undifferentiated, samples from the central portion of the Naga Hills in Nagaland and the study area in Manipur represents the Upper Disang Formation. This paper can also highlight the usefulness of geochemistry in the study of weathering and source rock characteristics of the Upper Disang sedimentary rocks of the Indo-Myanmar Ranges, NE India.

Geological Setting

The crustal stretching on the continental margin of the Myanmar landmass led to the formation of a basin, Indo-Myanmar basin, followed by the deposition of Disang and Barail sediments having thickness of an order of about 6-10 km. The Disang Group consists of a monotonous sequence of dark grey to black splintery shales with occasional rhythmic shales and siltstones/fine grained sandstones (Figure 2), especially in the upper horizon, forming the principal lithounits (Table 1) of the Imphal valley of Manipur. Disang sandstone and shales show sedimentary structure of ripple marks (Figure 3), tidal bundles and planner-beds. The Upper Disang shales also yielded foraminifera, *Modiscus sp., Trachommine sp., and Bulnina sp*. which are indicative of a shallow marine environment (Rao, 1983). Evidently, the Upper Disang

Figure 2: Field photographs showing succession of the of Disang Group.

Figure 3. Outcrop showing ripple marks on shale exposure Sandstone-shale alteration

of Manipur and adjoining regions of Naga Hills and river valley in Arunachal Pradesh (Table 2) witnessed tectonic instability with episodic relatively deep-water condition followed by uplift and shallowing of the basin under oscillating tectonic impulses related to complex tectonic activities of the region (Soibam et al. 2013). The Disang-Barail transition sequence consists of siltstone, sandstone and shale. The Barail Group of fine to medium grained, multi-storeyed, thickly bedded sandstones, are intercalated with siltstone and shale overlying the Disang-Barail Transition. The Surma Group of rocks overlies the Barail Group (Soibam, 1998; Soibam, 2000; Singh et al., 2017). These groups are characterised by intercalation of massive sandstone and shales with siltstone. The Tipams are moderately coarse grained, ferruginous, massive, sometimes faulted sandstones and overlies the Surma Group with stratigraphic break (Soibam, 2000; Singh et al., 2017; Singh et al., 2019). The stratigraphic succession of the Manipur is shown in the Table 1.

Methodology

Major element oxides for 21 (twenty-one) samples from Tista and Tirap river valley in Arunachal Pradesh (between 95^{O} 20$^{/}$E, 26^{O}50$^{/}$N and 95^{O}11$^{/}$ E, 26^{O}40$^{/}$N) were analysed by X-ray fluorescence spectrometry (XRF) at USIC, Guwahati University in PAN analytical make, Model Axios, using beads prepared from the powdered sediment samples (1 g of each sample), mixed with 4 g lithium tetraborate and 1g lithium carbonate and analytical software X-40 was utilized for data management (Majumder and Chetia, 2011).

Table 1. Stratigraphic succession of Manipur (after Soibam, 2000)

Recent-Pleistocene	Alluvium		Clay, silt, sand, gravel, pebble, boulder deposits
Late Miocene	Tipam Group		Mottled clay, mottled sandy clay, sandy shale, clayey shale and sandstone.
Miocene to Late Oligocene	Surma Group	Bokabil Formation (~1400m) Bhuban Formation (~1400m)	Shale, sandy shale, siltstone, ferruginous sandstone, massive to bedded ferruginous sandstone. Alternations of sandstone and shale with minor conglomerates.
--- Unconformity-------------------------------			
Oligocene to Late Eocene	Barail Group	Renji Formation (~800m) Jenam Formation (~1200m) Laisong Formation (~1200m)	Massive to thickly bedded sandstone. Alternations of shale and sandstone with carbonaceous matters. Intercalation of bedded sandstone with shale. Flysch sediments.
Late Eocene to Late Paleocene	Disang Group	Upper Disang Formation (~2000m)	Splintery shale and intercalation of shale, siltstone and sandstone showing occasionally rhythmite characters with fossils. Flysch sediments.
?Late Paleocene to Late Cretaceous		Lower Disang Formation (~2000m)	Dark grey to black shale with minor sandstone bands. Flysch sediments
--- Unconformity ----------------------------			
?Early Eocene to Cretaceous	Ophiolite Mélange Zone		Ultramafics with minor mafic - felsic rocks and marine sediments comprising radiolarian chert and limestone along with podiform chromitites.
---Unconformity --------------------------			
(Pre-Mesozoic or Older)	Metamorphic Complex		Low to medium grade metamorphic rocks of various composition-phyllitic schist, quartzite, micaceous quartzite, quartz-chlorite-mica-schist and marble.
--- (?) Unconformity ---------------------			
?Early Mesozoic rocks or Pre-Cambrian rocks	Basement Complex		Unseen

For geochemical analyses, samples of 15 (fifteen) sandstones and 10 (ten) shales from the central portion of the Naga Hills (94°12′E, 25°30′N and 94°30′E, 25°41′N, Nagaland) were thoroughly washed, dried and homogenized and finely ground (<250 ASTM mesh) and analyzed using pressed powdered pellets glued with polyvinyl alcohol. Element oxides analyses for bulk chemical composition of the samples were determined using an X-ray fluorescence spectrophotometer (Imchen et al., 2014).

Bulk mineral composition of 6 (six) shale samples from the Upper Disang Formation of Gelmoul area (Figure 1, GPS 24°20'40.4"N: 93°39'39.6"E) were determine by X-ray powder diffraction (XRD) at the Wadia Institute of Himalayan Geology (WIHG), Dehradun. XRD analysis was carried out on a PAN alytical, X'pert PRO X-ray Diffractometer at room temperature, using a rotating Cu target with a voltage 45 kV and a current of 40mA. The mineral identification was carried out comparing the measured data to a reference database, viz., Inorganic Crystal Structure Database (ICSD) in PAN alytical X'Pert High Score (Plus) v3.X database.

Table 2. Comparison of the Disang Group from different area of NE India.

	Arunachal Pradesh Majumder and Chetia, 2011; Gogoi and Sarmah, 2013	Nagaland Imchen et al., 2014	Manipur Soibam 1998; Rajkumar and Klein, 2014; Singh et al., 2017b
1.Location	$26^{O}50^{/}$-$26^{O}40^{/}$ N $95^{O}20^{/}$-$95^{O}11^{/}$E, $27^{0}0^{/}$ -$27^{0}10^{/}$N $95^{0}20^{/}$-$95^{0}30^{/}$ E	$25^{o}30^{/}$-$25^{o}41$ N $94^{O}12$-$94^{O}30^{/}$E	$24^{O}20^{/}$-$40^{O}4$N $93^{o}39^{/}39.6$”E
2.Thickness	300m	1800m	(~2000m)
4.Field investigation	Presence of sediments with characteristic framboidal structure and enrichment in organic matter	Small pyrite crystals, flute casts, ripple marks, etc.	Planner-bedded, ripple marks, tidal bundles, mud flasers.
3. Sediment	Recycled	Recycled	Fresh (Juvenile)
4. Source rock type	Igneous rocks of andesitic composition, volcanic and/or granitic	Granite/granite gneiss with basic and ultrabasic sources	Phyllite, chlorite schist, mica schist, gneisses with mafic and ultramafic rocks
5. Redox condition	Reducing	Reducing	Oxidising
6.Depositional basin	Shallow marine	Shallow marine	Shallow marine
7. Tectonic setting	Active continental margin to passive continental margin	Active-margin	Active margin

Table. 3. Major element oxides of the Upper Disang shale of Manipur (northern part, Singh 1995).

Sp.No.	30	63	90	93	123	125	129	127	137
SiO_2	69.92	67.98	66.71	64.85	71.45	74.08	78.10	79.52	74.14
TiO_2	0.70	0.97	0.72	0.64	0.77	0.62	0.42	0.60	0.64
Al_2O_3	15.00	20.55	16.87	15.15	14.29	13.35	10.36	10.47	14.26
Fe_2O_3	7.76	7.13	5.14	9.25	3.14	3.70	4.21	3.11	2.97
MnO	0.13	0.64	0.08	0.61	0.19	0.10	0.02	0.03	0.62
MgO	1.20	0.84	0.52	0.61	1.51	1.15	0.35	0.40	0.74
CaO	0.07	0.66	0.04	0.13	0.98	0.15	0.13	0.04	0.23
Na_2O	3.40	1.88	8.51	8.32	6.21	5.09	2.33	4.53	5.22
K_2O	0.91	0.96	0.38	0.99	1.85	1.18	1.05	0.40	0.63
ICV	0.95	0.64	0.91	1.36	1.03	0.90	0.82	0.87	0.77
CIA	69.09	79.42	53.81	50.26	50.49	57.40	66.58	56.79	59.54

Table 3 continued

Sp.No.	141	153	166	148	Average	UCC
SiO_2	53.66	78.48	73.95	75.48	71.41	66.52
TiO_2	0.86	0.30	0.48	0.52	0.63	0.5
Al_2O_3	32.60	9.96	13.17	12.15	15.24	15.2
Fe_2O_3	7.54	4.77	4.34	4.01	5.16	4.5
MnO	0.42	0.07	0.05	0.15	0.24	
MgO	0.61	0.42	0.83	0.94	0.78	2.2
CaO	0.15	0.01	0.10	1.58	0.33	4.2
Na_2O	6.65	3.65	6.61	4.37	5.14	3.9
K_2O	0.70	0.43	0.65	0.81	0.84	3.4
ICV	0.52	0.97	0.99	1.02	0.90	
CIA	73.15	60.56	52.84	52.62	60.20	

Major element oxides of 28 (twenty-eight) samples from the study area were analysed by Atomic Absorption Spectrophotometer (AAS). For this analysis, 0.5 g of the powder sample is weighed into a 50 ml mouth plastic bottle and 20 ml of concentrated HCL was added. The mixture was allowed to stand for 35 minutes with occasional shaking. 4 ml of 40 p.c. HF was added and the solution maintained at 50-60ºc for 15 minutes. 4ml of conc. HNO_3 was added and the solution maintained at 50-60ºc for 30 minutes. 0.5 gm of boric acid was added, and the solution kept for cooling. The solution was transferred to a 100 ml volumetric flask and made upto the volume (Athanasopoulos, 1986). It was run into the AAS and ppm values were recorded for different elements. SiO_2 and Al_2O_3 were analyses gravimetrically in the Department of Chemistry, Manipur University, using the procedure suggest by Basset et al. (1978). Out of 28 samples, only 13 (thirteen) samples were used for this study. Lithostratigraphic column of the Upper Disang Formation from the study area showing the sample locations is presented in figure 4. The results of geochemical analysis of the rock samples from the study area is presented in Table. 3.

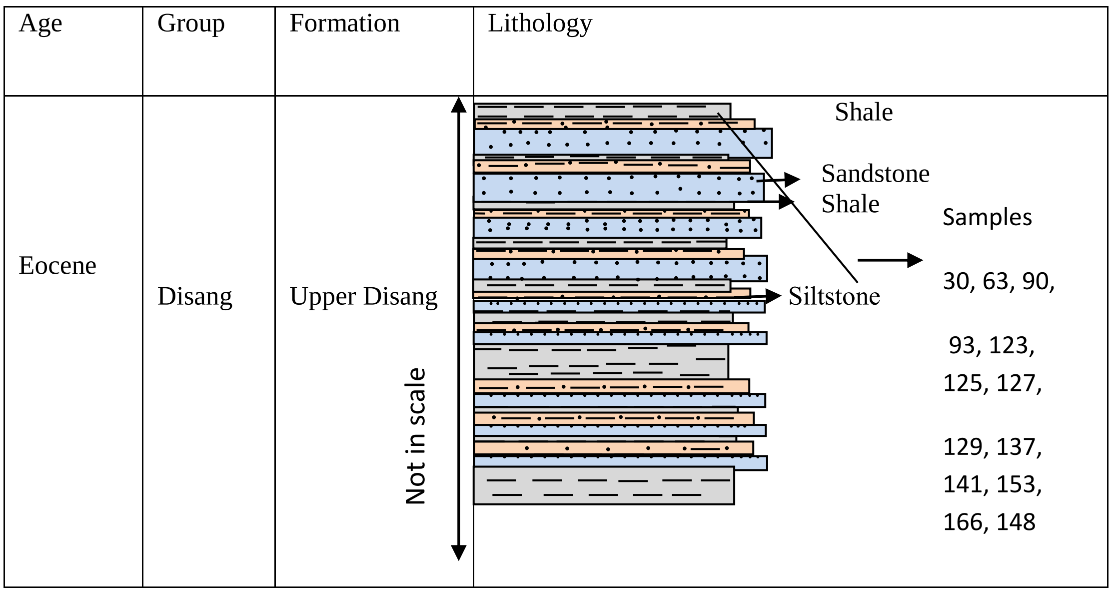

Figure 4: Lithostratigraphic column of the study area.

RESULTS

Major element oxides (wt %) and the Chemical Index of Alteration (CIA) with Index of Compositional Variability (ICV) of Disang shale of Imphal Valley of Manipur Hills are presented in Table 3. The shale samples have relatively higher SiO_2 concentrations than upper Continental Crust (UCC). Immobile oxides like Al_2O_3 and TiO_2 show slightly higher values compared to UCC. In comparison to upper Continental Crust (UCC), the Disang shales are characterized by slight enrichment of Fe_2O_3 indicating an increase in the abundance of Fe-bearing clay minerals or iron oxide minerals like magnetite, leucoxene that can result in high concentration of Fe_2O_3 and Na_2O.

Three bivariant diagrams were used to know the type of the sediments and probable source rock composition. ICV vs. CIA (Index of compositional variability vs. Chemical Index of Alteration) diagram (Potter et al., 2005, Figure 5) was used as important tools to know the relationship between degree of weathering and original source rock composition. If CIA (Chemical Index of Alteration) is very low and ICV (Index of compositional variability) is high, it indicates that the sediments are unweathered and derived from source rocks which were mostly of the juvenile igneous rocks and if, CIA is high and ICV is low, source rock is highly weathered Potter et al., 2005; Cox et al., 1995; Barshad, 1966). The samples

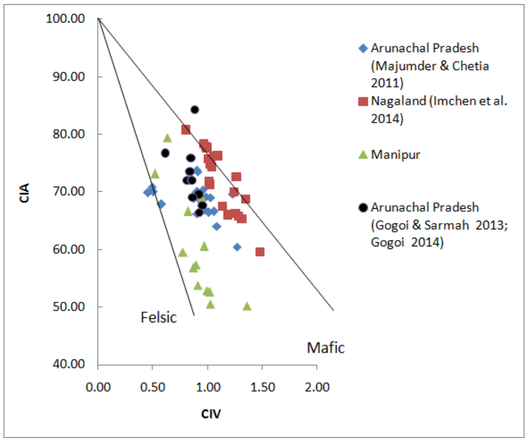

Figure 5: ICV vs. CIA diagram (Potter et al., 2005).

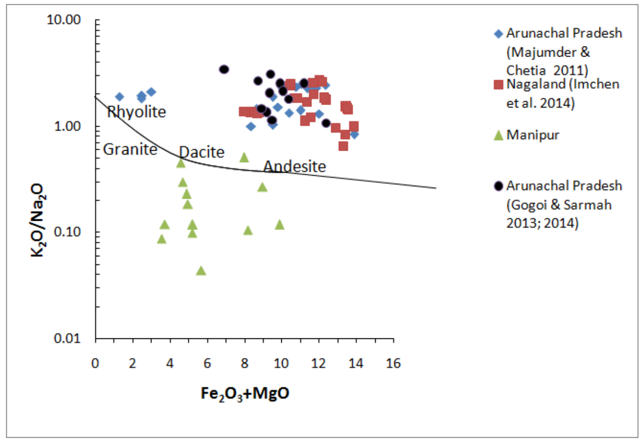

Figure 6: K_2O/Na_2O vs. Fe_2O_3+MgO diagram (Roser & Korsch, 1988).

from Tista and Tirap river valleys (between 95^O 20$'$E, 26^{O}50$'$N and 95^{O}11$'$ E, 26^{O}40$'$N, Arunachal Pradesh), the central portion of the Naga Hills (94º12$'$E, 25º30$'$N and 94º30$'$E, 25º41$'$N, Nagaland) were plot mostly on the mafic line and the samples from the study are scattered indicating the samples were predominantly derived from felsic source rock composition and some samples were from mafic source composition whereas others are of mixture of both felsic and mafic source rocks. Variation in source rocks causes different sediment chemical composition. The sediments from Tista and Tirap river valleys in Arunachal Pradesh were derive from volcanic and/or granitic source area and the provenance study also suggests that the mafic sediments were derived from rising of the Indo-Myanmar Ranges (Gogoi and Sarmah, 2013). Majumdar and Chetia (2011) suggest that the sediments (provenance) were derived from igneous rocks of andesitic composition. The bulk of the sediments from the Disang Group in the Naga Hill have been contributed from the nearby mafic and ultramafic source of the Indo-Myanmar range, which probably emerged above sea-level during the Mid-Eocene (Imchen, 2014). Sediment derived from the nearby east (IMR) were rapidly deposited on the seafloor causing rapid mixing which lead to textural and chemically immaturity and sediments from the west were transported for great distance by turbidity currents into an easterly deepening sedimentary depositional basin (Imchen, 2014). The Upper Disang sediments from the study area have more felsic composition and are chemically immature. These sediments were dominantly derived from rising of the Indo-Myanmar Ranges. The present study suggests that the pre-Himalayan gneissic and metabasic rocks presently forming the Higher and Lesser Himalaya might have also contributed felsic sediments. The pre-Himalayan rocks and Myanmar landmass with ophiolite of the Indo-Myanmar ranges might have supplied sediments for the Disang Group. Sediments were also possibly derived from the uplifted fold thrust belt of Myanmar's landmass comprising of igneous and metamorphic basement complex with older sedimentary sequences with minor contributions of detritus from Mishmi Hills region lying to the NE of the Arunachal Pradesh. During the deposition of Disang sediments, the Indian plate was sub ducted beneath the Myanmar plate and collided with Asian plate, the sedimentation occured in the sedimentary basin formed on the Myanmar continental margin. Depositional setting in which Disang sediments were deposited may be explained by pulsatic stretching of the basin and witnessed the tectonic instability with episodic relatively deep water condition followed by uplift and shallowing of the basin under oscillating tectonics on the western continental margin of the Myanmar landmass (Soibam et al., 2013).

K_2O/Na_2O vs. Fe_2O_3+MgO diagram (Roser and Korsch, 1988, Figure 6) also shows the Disang samples from between (95^O 20$'$E, 26^{O}50$'$N and 95^{O}11$'$ E, 26^{O}40$'$N Arunachal Pradesh and 94º12$'$E, 25º30$'$N and 94º30$'$E, 25º41$'$N Nagaland were weathered and recycled whereas those Manipur samples were fresh and unweathered. This, in turn, indicates that terrestrial or continental sediment were more in part of Arunachal Pradesh and Nagaland as compared to Manipur. The sediments from the study area were derived from the unweathered rising Indo-Myanmar Ranges. TiO_2 vs. Al_2O_3 diagram (McLennan et al., 1980; Schieber, 1992, Figure 7) indicates that the Upper Disang sediments plot between the basalt and mixed granite and basalt source rocks. Different source rocks contributed sediments to the Disang Group of sediments of the Indo-Myanmar Ranges.

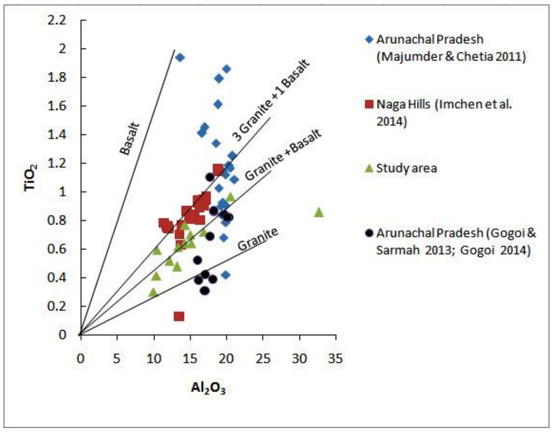

Figure 7: TiO_2 vs. Al_2O_3 diagram (McLennan et al., 1980; Schieber 1992).

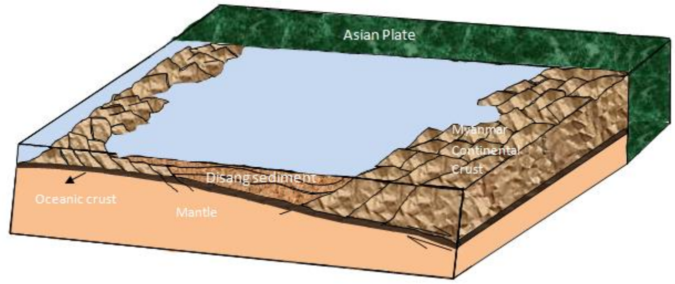

Figure 8: Cartoon showing the Disang deposition in the Indo-Myanmar basin on Myanmar Continental margin (modified from Soibam and Khuman, 2008)

DISCUSSION

Comparison of the Disang Group from different parts of NE India provides information on type of sediments, redox condition, depositional basin environment and tectonic setting of the Indo-Myanmar basin, and in turn, the Indo-Myanmar Ranges during Eocene (Table 2). The sediments from Tista and Tirap river valleys (Arunachal Pradesh) and the central portion of the Naga Hills are more weathered and recycled than sediments from study area. The sediments of the study area were dominantly derived from felsic source rocks. There are different views on the depositional environment of the Disang Group. Rao (1983), Ghose et al. (1984), Archaryya (1986), Vidhyadharan et al. (1989) considered that the Disang sediments were deposited on the distal shelf in an epicontinental sea. From petrographic and geochemical studies, Majumder and Chetia (2011), Imchen et al. (2014) suggested that the depositional environment of the Disang Group was a nearshore, shallow water lagoon. The sediments of the Disang rocks of southern Manipur were deposited in a nearshore neritic shallow marine environment (Singh et al., 2017). The depositional environment for the Upper Disang Formation appears similar to the modern tidal-flats environment (Singh, 2013). Disangs were deposited in tidal flat environment and the depositional environment of the Disang Group was a reducing and anoxic with minor fluctuations in sea-level (Majumder and Chetia, 2011). Pyrite crystals are present in various horizons of the Upper Disang Formation, indicating anoxic conditions in the depositional environment (Imchen et al., 2014). The Upper Disang sediments were deposited in an oxidising environment in shallow marine basin (Singh et al., 2017). Sediments from Nagaland and Arunachal Pradesh were recycled and weathered.

In the process of subduction and collision between Indian and Asian plates, and subsequently with Myanmar plate Figure. 8, it isbelieved that the Naga Hill segment had collided with opposite continental Myanmar plate and received major supply of sediments both from the orogenic highland, immediately north of it, associated with the Himalayan suture zone and, from Myanmar plate. Progressive development of the suture belt led to longitudinal and textural facies changes within the Group. Due to the advanced stage of collision, the Naga Hill segment exhibits reduced upper mantle activity. However, pre-Himalayan gneissic and metabasic rocks of one-time passive margin setting and presently forming the Higher and Lesser Himalaya, respectively cannot be rule out. The pre-Himalayan rocks and Myanmar landmass might also have supplied sediments for the Disang Group. Sediments were possibly derived from the uplifted fold thrust belt of Myanmar's landmass comprising of igneous and metamorphic basement complex with older sedimentary sequences with minor contributions of detritus from Mishmi Hills region lying to the NE of the Arunachal Pradesh. It is suggested that the Upper Disang of Manipur was deposited in a shallow marine basin that developed as a fault controlled continental margin basin or a second order basin. Major thrust fault may be reactivation of the ancient continental margin rifts and this rifting resulted in the formation of restricted second and third order basins (Maclntyre, 1991). The current study also records 4-5 km depth of burial and hydrothermal activity or alteration might have occurred at about 150^o (Singh et at., 2017).

Conclusions

The study was focussed on depositional environment and source rock composition during deposition of the Eocene Disang sedimentary rocks (Indo-Myanmar Ranges) of NE India. The Disang sediments were deposited in the Indo-Myanmar basin on the Myanmar continental margin. The results have revealed that sediments from Tista and Tirap river valleys (Arunachal Pradesh) and the central portion of the Naga Hills are more weathered and recycled than sediments from study area. The sediments were dominantly derived from rising of the Indo-Myanmar Ranges. The Pre-Himalayan gneissic and metabasic rocks presently forming the Higher and Lesser Himalaya also contributed sediments to the Disang sediment of Arunachal Pradesh. The Myanmar continental landmass comprising of igneous and metamorphic basement complex with older sedimentary sequences may also have supplied sediments to the Disang Group. Sediments were deposited on tidal flat, lagoons and nearshore neritic shallow marine environments. The Upper Disang basin witnessed the tectonic instability with episodic fluctuation of deep water conditions followed by uplift and shallowing of the basin under oscillating tectonic impulse.

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Assessment of Velocity pattern of Lithotectonic Segments of the Kashmir Himalaya: Constraints from GPS measurements

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Abstract

We present the estimated horizontal velocities of different lithotectonic segments of the NW Himalaya using data recorded by the eighteen GPS observatories installed in the Jammu and Kashmir region. The data was acquired from 2016 to 2019 and was processed using high precision GAMIT/GLOBK software. With respect to ITRF08 reference frame, the site motion in the region varies from 35 mm/yr to 45 mm/yr towards north-east. The India fixed site motion was estimated using the Ader's Euler pole of rotation. This yielded site motion varying from 2.4 to 11 mm/yr towards south-west and is consistent with the reported plate motion in the Northwest Himalaya. Further study with additional GPS networks is expected to provide precise estimates of deformation in the locked and creeping zones of the main Himalayan thrust in the Northwest Himalaya.

INTRODUCTION

The Jammu and Kashmir region lies close to the northern edge of the Indian Plate active margin. The tectonics of the region is controlled by the collision of the Indian Plate with the Eurasia Plate resulting in the progressive differential deformation of various segments of the Himalayan Arc. Global Positioning System (GPS) has been used as a useful tool in investigating global plate motions and regional tectonic movements (Argus and Heflin, 1995; Larson et al., 1997). A few tectonic studies using GPS have been done for the region (e.g., Jade et al., 2020, Kundu et al., 2014; Schiffman, 2013). Compared with other regions of the Himalaya, geodetic or neo-tectonic characteristics of the Kashmir region have not been well known because of the lack of adequate GPS network; however, Stevens et al. (2015) used published GPS data from several studies for determining interseismic plate coupling on the Main Himalayan Thrust (MHT) along the entire Himalayan arc. In the current study we used GPS data from the 18 permanent GPS stations (8 new GPS observatories and 10 GPS observatories from Kundu et al., 2014) to investigate the horizontal velocities in Jammu and Kashmir and their relationship with the tectonic settings of the region. We analyzed three years of data (2016 to 2019) from our 8 new GPS sites constructed on geologically stable monuments. These observatories are located at Jammu (JAMU), Rajouri (RAJO), Poonch (PUCH), Bani (BANI), Bhadarwah (BHAD), Doru Shahabad (DORU), Pampore (PAMP) and Tangdhar (TANG). Finally, the station velocities relative to the ITRF08 reference frame were converted to Indian Reference frame (IRF).

The main Himalayan thrust (MHT) often referred as decollement is commonly considered as the store house of earthquakes (Bilham et al., 1997; Jouanne et al., 1999; Avouac, 2003; Bettinelli et al., 2008) whose splays constitute the mega thrusts like Main Frontal Thrust (MFT), Main Boundary Thrust (MBT) and Main Central Thrust (MCT). During interseismic span the locking is mainly considered to be stored at the brittle and frontal part of MHT (Seeber and Armbruster, 1981; Ni and Barazangi, 1984; Molnar, 1990). The seismic processes viz., pre-, co- and post seismic deformation in earthquake cycle have long been measured by geodetic methods, predominantly via continuous GPS (cGPS) readings. The cGPS allows determining the kinematics of the thrusts to understand the earthquake scenario in the region with reasonable accuracy. The horizontal surface velocity driven position time series is used to measure precise plate motion when it is linear and non transient. For even decades, the secular horizontal plate motion at a particular place can be disturbed by post-seismic irregularities (Freymueller et al., 2008), which is reflected in the present study at the Tangdhar (TANG) site located in the north Kashmir. Generally a mega seismic event is very improbable to alter the consistency of plate motion rate well over million years (Gordon and Stein, 1992; DeMets et al., 2010). The concept of secular motion is well associated with the pace of tectonic plate motion, however it is contradictory as the available geodetic data lags duration when compared with the occurrence period of earthquake that can be decades to hundred years (McCaffrey, 2008). Moreover the sudden transient episodes act as the main cause that disrupt the linear motion of tectonic plate, and the available geodetic data is short and unclean, hence it is hard to partition these modeled motion from the steady and continued plate motion (McCaffrey, 2009). Regardless, the global accessibility to the geodetic observations is still accruing to the substantiality required to graph the strain rate distribution and to establish the parameters for deformation with exact tectonic structures (Bastos, 2010).

The two major earthquakes recorded in Kashmir region were 1555 and 2005; the 2005 Kashmir earthquake epicentered at Muzaffarabad, arised at Indo-Kohistan seismic zone on a 75 km mega thrust (Gahalaut, 2009). While considering the 1555 earthquake would have released the past stored strain energy and further a fresh accumulation of strain with derived present-day moment rate in the region, the residual amount of stored energy, if measured presently can suggest whether the region has enough potential to generate a devastating earthquake of Mw>8 or 9 in the near future. To accomplish the goal of estimation of strain budget that leads to mega earthquake in the region, it is imperative to understand accurately the velocity field. The new velocity field of the Jammu and Kashmir region presented in this paper is based on the data from eighteen cGPS sites including 8 GPS observatories of Jammu University and 10 GPS observatories of Kundu et al. (2014) in the Jammu and Kashmir region.

DATA ANALYSIS

The data was processed using high precision GAMIT/GLOBK software (King and Bock, 2005). The GPS observations were recorded as 24 hour file with 30 seconds sampling interval. To enhance the stability of overall network and to connect the regional sites data to global reference frame, 20 sites (YAKT, TIXI, PIMO, TCMS, KARR, PERT, ULAB, XMIS, CUSV, COCO, LHAZ, NRIL, URUM, LCK4, HYDE, IISC, DGAR, SUMK, POL2, KIT3) from permanent International GNSS Service (IGS) were included in the processing. The IGS data was acquired from Scripps orbital and processing centre (SOPAC). The GAMIT program was used as source for various input files required to obtain the daily basis loosely constrained position estimates. GLOBK program takes account of all the loosely constrained results and create error and outlier free coordinate time series and velocity estimates

GPS time series

The time series and velocity vector are the two tools that make the base for any geodetic study. The time series plots were generated in the International Terrestrial Reference frame 2008 (ITRF08) and Indian fixed reference frame. A time series is a plot that presents how coordinates shift with time. The X-axis shows the time and Y-axis shows the displacement and slope represents each day position (Position in three dimensions: North-South, East-West, and Vertical i. e., up-down). The inclination of position dots represents the trend of the sites motion and for each plot (North-South, East-West, Vertical) northward is positive and southward is negative. If the trend of slope is positive, the site motion is northward and for negative it is southward (Fig. 1). The present study displays motion in the northeast and southwest direction at all the 18 sites in ITRF08 and IRF respectively (Fig: S1-S16). To view the Position Time Series, click here https://drive.google.com/file/d/1Tb6SyPbPX39zajC0MYAcE-749q8VIxr_/view?usp=sharing). The site motion shows a transient and non-linear behaviour at each displacement component.

This yielded site motion varying from 2.4 to 11 mm/yr towards south-west. In India fixed reference frame a small quantity of displacement was observed at JAMU site located at the edge of the Indian plate, which is likely due to deformation in the frontal lithotectonic segments of the Kashmir Himalaya. The estimated site velocity of our eight new sites is consistent with the reported plate motion by Kundu et al. (2014) (Table 1) whereas, the site TANG is located in the downdip rupture zone of the 2005 Kashmir earthquake that shows a large southward motion different from the adjoining sites (URII and MULG). The possibility of slope instability at TANG site is least as it is situated at the hard basement rock and also spur slope is very gentle. This observed anomalous motion near TANG site is also reported by Kundu et al. (2014) and Jade et al. (2020) with respect to their observatories. Similar postseismic deformation has been reported along the ruptured zone of Kashmir 2005 earthquake by Jouanne et al. (2011). The derived site motion (9.3 mm/yr towards N195º) using continuous GPS data from 2016 to 2019 at TANG is small against the reported motion (15.4 mm/yr towards N207º) at the nearby site KERN using campaign data from 2010-2011 (Fig. 3). This difference is obviously due to small duration (one year) in case of KERN site. However in either case the results are anomalous as compared to the adjoining sites. This large southward anomalous behaviour could also be related to the complex structural setup (thrust system and strike slip faults in the region) around the western syntaxial bend adjoining the TANG and KERN locations. However, this requires a detailed understanding of the influence of post seismic deformation and tectonic setting of the region. Installation of additional observatories shall help in the characterization of this anomalous motion in the westernmost part of the Kashmir valley.

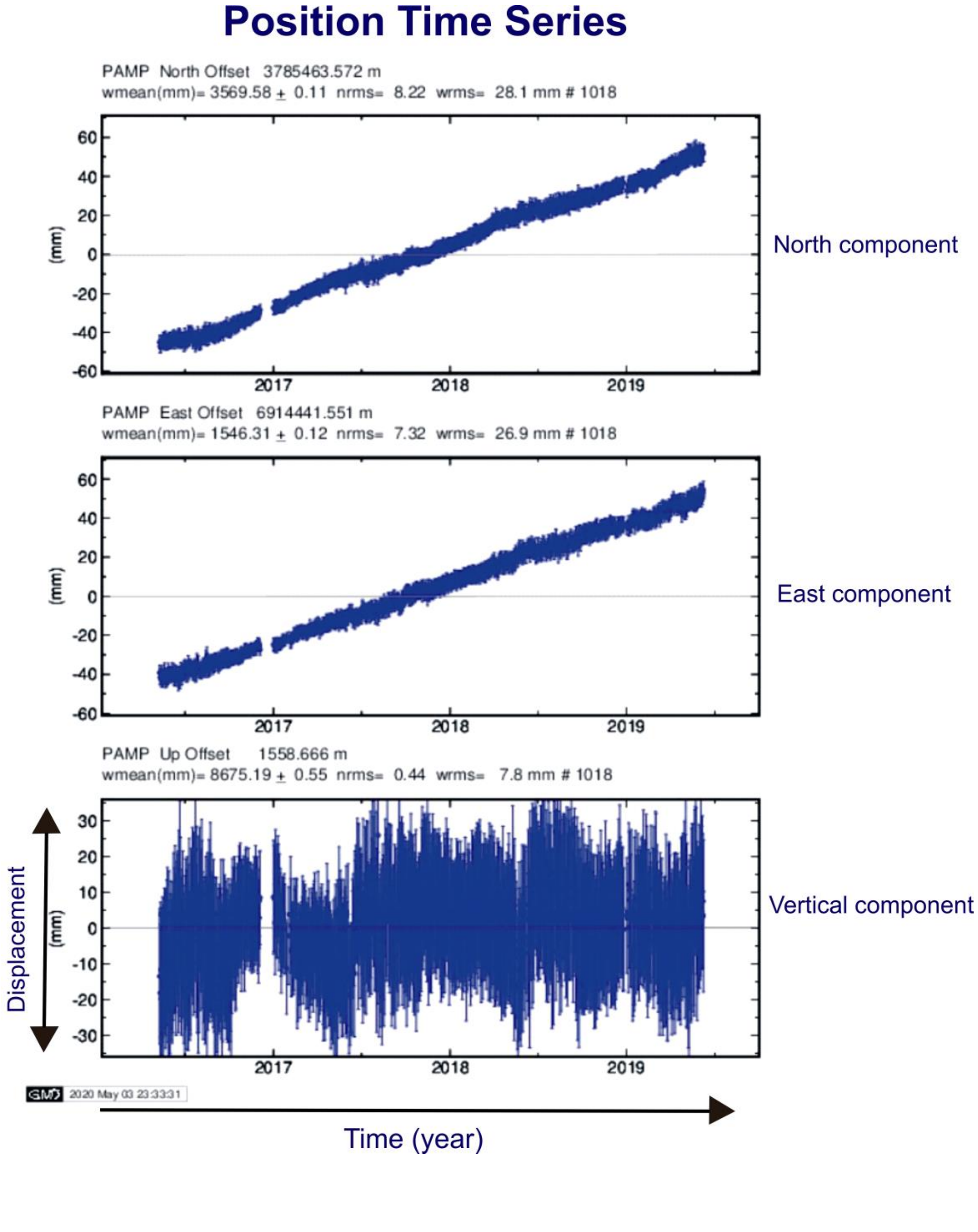

Fig. 1 The time series plot of Pampore site (PAMP) in Kashmir shows north, east and Up (vertical) component. The plot represents the motion in north east direction in ITRF2008.

Plate motion in the region

The India fixed site motion was calculated using the Euler pole of rotation recommended by Ader et al. (2012) with parameters like latitude 51.4±0.3°N, longitude -1.34±3.31°E, Rotation rate 0.5029±0.0072°/Myr. The displacement-time series shows significant seasonal variations at each site. In ITRF08 reference frame, the site motion in the region varies from 35 mm/yr to 45 mm/yr towards north-east (Fig. 2). We used the Euler pole of Ader et al. (2012), which was also used by Kundu et al. (2014), to calculate the site motion in fixed India plate.

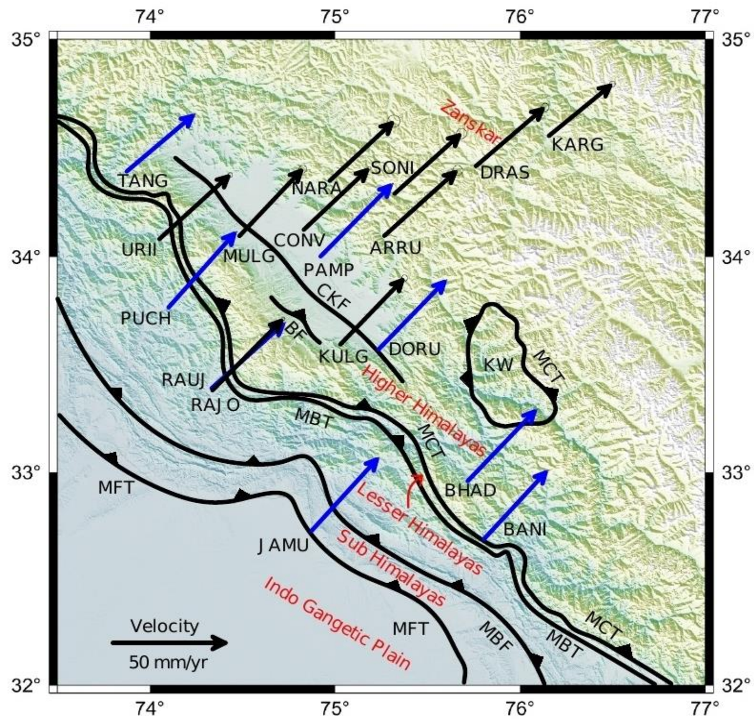

Fig. 2: Horizontal site velocity in the study area in ITRF08 reference frame. The new GPS sites data is represented by blue colour vectors. The black vectors represent the site velocity reported by Kundu et al. (2014).

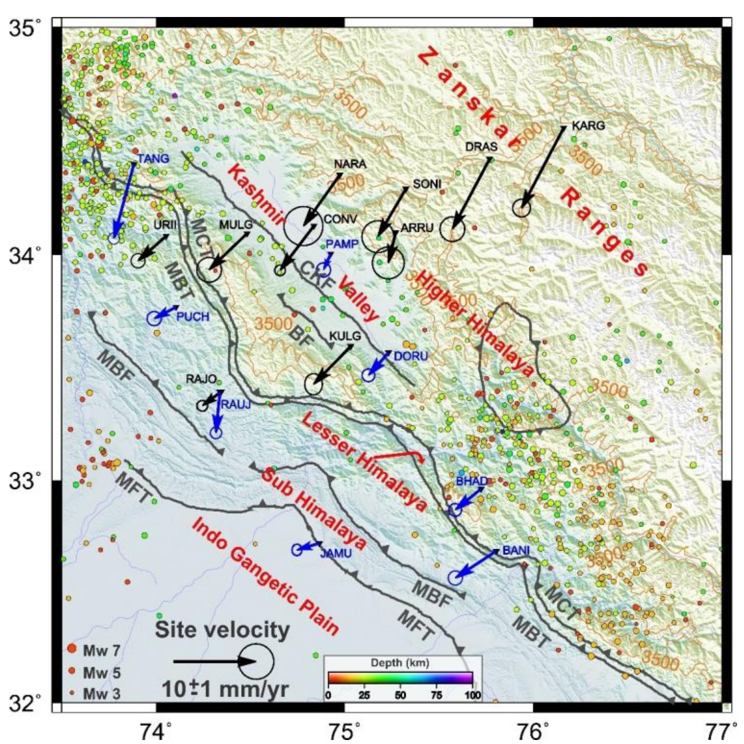

Fig. 3: The figure shows the plate motion in the fixed India plate frame (using Euler pole of Ader et al., 2012) at eight newly installed continuous GPS sites in the Kashmir Himalaya. The filled circles show the seismicity in the region during 1970 to July 2020 listed in the ISC catalogue. The size and colour of the circle indicate the magnitude and focal depth of the earthquakes respectively. The 3.5 km of topographic elevation is shown by orange colour curve. The black curved lines indicate major fault units in the region, i.e., MFT-Main Frontal Thrust; MBF- Main Boundary Fault; MCT-Main Central Thrust; BF-Balapora Fault; CKF- Central Kashmir Fault.

Table. 1: Horizontal site velocity in the study area derived from ITRF08 and IRF.

Sites	Long	Lat	GPS site velocity (mm/yr)			
			ITRF08		Fixed India Plate	
			East	North	East	North
JAMU	74.867	32.718	29.6 ± 0.07	33.0 ± 0.08	-2.74 ± 0.07	-0.82 ± 0.08
RAJO	74.339	33.393	31.3 ± 0.08	28.8 ± 0.08	-0.48 ± 0.08	-4.96 ± 0.08
PUCH	74.106	33.770	28.9 ± 0.1	33.0 ± 0.1	-2.64 ± 0.1	-1.4 ± 0.1
BANI	75.804	32.683	27.7 ± 0.1	30.7 ± 0.1	-4.97 ± 0.1	-3.28 ± 0.1
BHAD	75.723	32.961	29.3 ± 0.09	31.4 ± 0.09	-3.13 ± 0.09	-2.55 ± 0.09
DORU	75.233	33.568	29.6 ± 0.09	31.2 ± 0.09	-2.44 ± 0.09	-2.75 ± 0.09
PAMP	74.926	34.005	30.8 ± 0.1	31.9 ± 0.1	-0.87 ± 0.1	-1.95 ± 0.1
TANG	73.883	34.400	28.7 ± 0.08	24.7 ± 0.08	-2.42 ± 0.08	-8.99 ± 0.08
KARG	76.161	34.559	27.0 ± 0.5	22.8 ± 0.5	-5.1 ± 0.5	-9.7 ± 0.5
DRAS	75.768	34.423	29.4 ± 0.7	25.6 ± 0.7	-4.5 ± 0.7	-8.5 ± 0.7
SONI	75.325	34.292	28.7 ± 0.9	26.6 ± 0.9	-3.4 ± 0.9	-5.8 ± 0.9
ARRU	75.271	34.100	31.3 ± 0.9	28.7 ± 0.9	-0.9 ± 0.9	-3.7 ± 0.9
KULG	75.032	33.596	27.5 ± 0.5	29.3 ± 0.6	-4.5 ± 0.5	-4.6 ± 0.6
NARA	74.974	34.353	27.5 ± 1.1	26.2 ± 1.1	-4.4 ± 1.1	-6.2 ± 1.1
CONV	74.837	34.129	27.9 ± 0.3	26.9 ± 0.3	-4.1 ± 0.3	-5.4 ± 0.3
MULG	74.483	34.095	27.5 ± 0.7	29.8 ± 0.7	-4.6 ± 0.7	-4.4 ± 0.7
RAUJ	74.346	33.394	30.0 ± 0.3	30.6 ± 0.3	-2.3 ± 0.3	-1.7 ± 0.3
URII	74.054	34.084	30.5 ± 0.4	28.3 ± 0.4	-3.4 ± 0.4	-3.0 ± 0.4

Conclusion

The present study indicates gradual increase in the site velocity (Fixed India plate) from southwest to northeast in the Kashmir region, which is similar to the other segments of the Himalayan region (Jade et al., 2020; Kundu et al., 2014; Schiffman et al., 2013). Moreover, in the ITRF frame our velocity results are similar to those of other parts of the Himalaya (Bilham et al., 1997; Jouanne et al., 1999; Banerjee and Burgmann, 2002; Avouac, 2003; Ader et al., 2012; Schiffman et al., 2013; Kundu et al., 2014, Jade et al., 2020) which most likely suggests the buildup of strain on the underlying seismically active detachment, where great and major Himalayan earthquakes are assumed to occur (Seeber and Armbruster, 1981). If the fault fragment is creeping up to the surface, contrary to the locked segment that generate comparatively flat geodetic velocity gradient across the fault, fault-crossing geodetic velocity show sharp gradient or offset (Y Li, 2020) and in the present study the gradual variation in the azimuth of site velocity from northeast to southwest was observed which represent oblique convergence in the Kashmir region. In the fixed Indian plate, the region with lower site motion probably indicates higher plate coupling, which eventually highlights certain targets for subsequent studies for strain accumulation and seismic moment buildup. Further the lateral high and low coupling variations along the Himalayan Arc will also counsel the segmented behaviour of Main Himalayan thrust. Additionally, with the use of continuous GPS data and measured slip deficit can help in finding out the probable earthquake zones on MHT and shall help in mitigation of future damage due to potential mega-events in the region.

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Obituary

Dr. Ashok Kumar Srivastava

(29- 12 – 1959 – 19 – 02 – 2022)

It is with great sorrow that I have to announce that, Dr. Ashok Kumar Srivastava, has returned to his heavenly adobe on 19th February, 2022. He was being treated by a team of doctors at Kokilaben Hospital in Mumbai for brain hemorrhage, for three months. He suffered a fall on stairs at his home on 2nd October 2021, and was admitted to a local hospital in Amravati for about a month, after which he was moved to Mumbai for further treatment. Despite our best efforts to make him stay, the decision of the almighty to call him back to his celestial world stood supreme. He left us in peace, surrounded by family.

Dr. Srivastava was the fifth child to Late Sri Sriram Srivastava and Late Smt. Tapeshwari Devi, born on 29th December, 1959 in Gorakhpur, UP. Born in a reputed family and *Kayastha* community, he was encouraged in academics from his early childhood. His father was the bank manager in the District Co-operative Bank, Gorakhpur, UP, and his mother took care of the family. He was married to Late. Smt. Dr. Ranjana Srivastava, and is survived by two sons, Utkarsh and Shadwal.

In his school days, he was always inquisitive and curious about science. He did his schooling from Dayanand Anglo-Vedic Inter-College and his graduation from Dayanand Anglo-Vedic Degree-College, Gorakhpur, UP. He completed his B. Sc. (Zoology, Botany and Chemistry) and later earned an M. Sc. in Geology in 1982, from Gorakhpur University, Uttar Pradesh.

After completing M. Sc. in geology, he pursued doctorate in Geology at Lucknow University. He was awarded with a Ph. D. for his work on “Sedimentological studies of the Triassic succession of Malla Johar area, Tethys Himalaya, Uttar Pradesh with special reference to diagenesis”, under the supervision of Prof. Surendra Kumar (Department of Geology, Lucknow University) in 1989.

He was appointed as Lecturer in the Department of Geology, Sant Gadge Baba Amravati, Maharashtra in December 1991, where he served as a founding member. He pursued his career at Amravati University, and attained the rank of Professor in 2008.

Under his guidance, Dr. Srivastava supervised 9 doctorates and about 100 M. Sc. students, and completed 8 research projects funded by agencies like DST, UGC and CSIR. His research interests were mainly in sedimentology, palaeobiology, hydrogeology, Antarctica glacial sediments and tephra, in which he produced more than 100 articles in reputed international journals.

Along with his scholastic credentials, Dr. Srivastava had received a number of National and International honors, including recommendation for Commonwealth Academic Fellowship in 2004 by the UGC. He participated in the 21st Indian Antarctic Expedition as a member of Indian Scientific Expedition to Antarctica, by Department of Ocean Development, Ministry of Earth Sciences, Government of India, in 2002. After having an exceptional career with Amravati University, he retired from service in May 2020. However, he was involved in research on the paleoclimate and paleo-vegetation in the Purna alluvial basin, Central India during the Quaternary period.

Apart from his interests in academics, Dr. Srivastava admired the Indian Classical Music (Shastriya Sangeet). He had a large collection of ghazals from famous Indian and Pakistani ghazal artists. His hobbies included travelling, cooking, and gardening. He had been to a number of places across India for academic as well as recreational purpose. He was fond of Indian cuisine and liked to cook in his leisure time.

Dr. Srivastava believed in the value of karma. He always took life as a Journey, where at times one needs to keep moving ahead without getting distracted by the paths left behind and worrying about the results. He always used to teach, **"One who strives for excellence shall always receive what he desires; no matter how many times one might fail, sooner or later, he will eventually succeed".**

While the pain of his demise is immeasurable, he taught us through his actions and words that the journey of one's soul does not stop at death. I hope that his soul will find a place in Vaikuntha, and be freed from the endless cycle of life and death on this material world.

He lived a dignified life, full of well-deserved achievements earned through hard work and commitment. I consider myself fortunate to be guided by a man of his grace and dignity. I am sure that he will continue to provide us his guidance and blessings from the heaven above.

Om Shanti.

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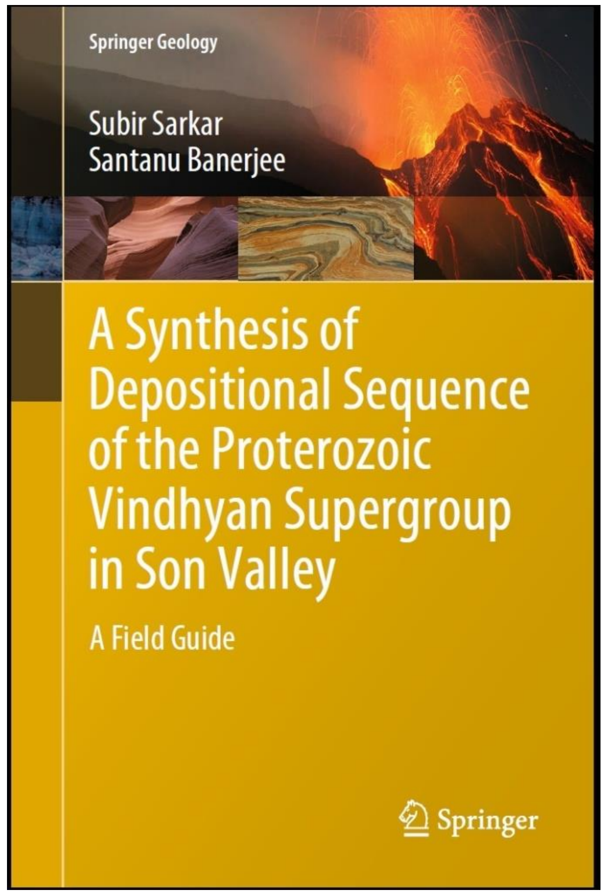
BOOK REVIEW

A Synthesis of Depositional Sequence of the Proterozoic Vindhyan Supergroup in Son Valley: A Field Guide

Subir Sarkar and Santanu Banerjee

Springer Geology, 2020, 188p. ISBN 978-981-32-9550-6, **DOI**: 10.1007/978-981-32-9551-3

Field geology involves making observations, recording data from exposures and analyzing them to depict some inferences. In an unknown territory this process may be guided by experienced field leader/s. But what about the field trips in such a terrain without a skilled person? Under such circumstances a field guide becomes useful, if available. The Vindhyan Supergroup is the thickest Precambrian sedimentary succession of India and the duration of its deposition is one of the longest in the world. Therefore, it is believed to contain valuable information on the evolution of the atmosphere, climate, and life on our planet. Proterozoic Vindhyan Basin grabs geologist's attention for its extraordinarily well exposed sedimentary succession, easy accessibility and being a treasure house of sedimentary structures. However, there are only a few field guides published so far on Vindhyan rocks. Among them the book by Bhattacharyya, Chanda and Bose (1986) covering the upper Vindhyan of Maihar exclusively is out of print. The other one by Kumar and Gupta (2002) focuses on Precambrian biogenic structures. It holds an overall good coverage but lacks deeper insight in different important aspects of stratigraphy and sedimentology. The present field guide sets significant emphasis on stratigraphy, facies analysis, palaeogeographic shifts, event deposits (seismites, tsunamiites, tempestites and tidalites) and microbial mat structures. The book contains detailed route maps, geological maps and plenty of color photographs (total 75) besides hand-sketches, tables and several illustrations showing wide variations in sedimentary structures (including those related to microbial activities on siliciclastic deposits). The book covers, in detail, both the lower and upper Vindhyan rocks; also both northern and southern flanks of the basin with adequate sedimentological detailing and different facets of stratigraphy. This 188-page yet pocket-sized book is easy to carry during field investigations. Moreover, it is also available as an e-book.



The book consists of five chapters with references at the end of each. Chapter 1 introduces the Vindhyan Basin and describes its geological background keeping focus on outcrop distribution, lithostratigraphy, age, tectonics and biotic as well as volcanic records within the Vindhyan rocks. Chapter 2 discusses on facies and palaeogeography in relation to different formations of the Vindhyan Supergroup and also puts light on sequence stratigraphic framework of the Vidhyan succession. Chapter 3 describes seven selected traverses through the outcrops of Vindhyan Supergroup covering all the formations stretched from west to east of the basin; offering a gamut of Vindhyan stratigraphy to the readers. Each traverse includes several stops to visit every possible nearby outcrops to examine the broad characteristics of each of the constituent formations. Chapter 4 deals with several selected well-exposed sections, each of which is based on a special focus providing detailed facies analysis of carbonate and siliciclastic successions, description of event deposits like seismite and tsunamiite. It also provides unique variations in stromatolite morphology within a carbonate formation and distribution pattern of different architectural elements within a fluvial outcrop. Coordinates of all the locations mentioned within chapters 2, 3 and 4 have been provided at the end of each. Chapter 5 provides a compact yet comprehensive synopsis on the variability of microbial mat structures preserved within the siliciclastic deposits of Vindhyan Supergroup.

My overall impression regarding the book is first-rated that deserves to be a bestseller. I believe this well-planned and well executed field guide would be very useful to the students, researchers, academicians and professionals related to sedimentology for field visits in this area. The book should also appeal to the non-specialist who wants to visit/traverse the impressive and vivid Vindhyan rocks on their own.

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