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George Devries Klein (Jan 21, 1933 - April 30, 2018)

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Preface to the Special Issue dedicated to George Devries Klein by the Journal of the Indian Association of Sedimentologists (JIAS)

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The Journal of the Indian Association of Sedimentologists (JIAS) published its first online issue on June 30, 2018. It is available on www.indiansedimentologists.com. In that issue, an extended tribute to G. D. Klein by Shanmugam (2018a) was published. The tribute was widely received by the global geosciences community. Consequently, the Managing Editor and the Editorial Members have decided to publish a special Issue dedicated to George Devries Klein in celebrating his life and achievements. This special issue is the product of that effort. We have selected five articles from a pool of 15 submitted contributions for this issue that closely reflect Klein's research interests. The five topics are (1) climate change (Gerrit J. van der Lingen), (2) deep-water processes (G. Shanmugam), (3) petroleum geology (Naresh Kumar), (4) Diagenetic evolution of onshore Campanian Sandstone (Sargam Chatterjee, R. Nagendra and Malli Vijay) and (5) Gondwana basins of extra-peninsular eastern India (Hrishikesh Baruah, Ranjeeta Kar, Sarat Phukan, Pradip Kumar Das, Manab Deka, Tulika Dey). A biographical sketch of Klein is summarized in Table 1. JIAS has managed to publish this Special Issue on December 31, 2018, in just eight months after Klein's passing on April 30, 2018. In addition, this issue includes memorials to Professors Virendra Kumar Srivastava (S M Casshyap and M. Raza), Robert Louis Folk (Kitty Milliken, Earle McBride and Lynton Land), and Robert Henry Dott, Jr. (Marjorie A. Chan and Steven G. Driese).

Table 1. A biographical sketch of George Devries Klein (1933-2018). Compiled from Klein et al. (2018) and Shanmugam (2018a and 2018b).

Introduction		
George Devries Klein was an iconic sedimentary geologist. He was one of the foremost sedimentary geologists in the world on the application of many facets of earth science. He was an accomplished process sedimentologist, sequence stratigrapher, sandstone petrologist, tectonics specialist, basin analyst, regional geologist, petroleum geologist, and climate scientist.		
Subject	**Date**	**Details**
Born	January 21, 1933	The Hague, the Netherlands
Died	April 30, 2018	Guam
Family immigration	1939	From the Netherlands to Australia
Family immigration	1947	From Australia to the USA and settled in Larchmont, New York
Citizenship	1947-2018	USA
Education		
Primary and junior high school	1943-1946	Scotch College, in Melbourne, Australia
Mamaroneck Senior High School	1947=1950	Mamaroneck, New York, USA
B.A. degree in geology	1954	Wesleyan University, Middletown, Connecticut, USA
M.A. degree in geology	1957	University of Kansas, Lawrence, Kansas, USA
Ph.D. degree in geology	1960	Yale University, New Haven, Connecticut, USA
Doctoral thesis	1960	"Sedimentology and sedimentary petrology of the Triassic of the Maritime provinces of Canada". And he made a reconnaissance of the intertidal flats of the Bay of Fundy.
Doctoral advisor	1957-1960	John E. Sanders
Employment		
Research Geologist	1960-1961	Sinclair Research Laboratories, Inc., Tulsa, Oklahoma, USA
Assistant professor	1961-1963	University of Pittsburgh, Pennsylvania, USA
Assistant professor	1963-1966	University of Pennsylvania in Philadelphia, USA
Tenured Associate professor	1966-1969	University of Pennsylvania in Philadelphia, USA
Associate professor	1970-1972	University of Illinois at Urbana-Champaign, Illinois
Full professor	1972-1993	University of Illinois at Urbana-Champaign, Illinois. Retired as Professor Emeritus in 1993.
Supervisor of Ph.D. and M.S. degree students	1970-1993	Ph.D. students : 7 External Ph.D. students : 5 M.S. students : 14

Executive Director	1993-1996	New Jersey Marine Sciences Consortium and director of the New Jersey Sea Grant College, Fort Hancock, New Jersey, USA
Known for his wide spectrum of expertise		He was one of the foremost sedimentary geologists in the world on the application of many facets of earth science. He was an accomplished: 1) process sedimentologist, 2) physical oceanographer, 3) sequence stratigrapher, 4) sandstone petrologist, 5) tectonics specialist, 6) basin analyst, 7) regional geologist, 8) petroleum geologist, and 9) climate scientist.
Selected Scientific Contributions		
Lake sedimentation	(Klein, 1959)	Sedimentary structures in the Blomidon Formation, a Triassic lake deposit
Sandstone petrology	(Klein, 1961)	Depositional environments and sandstone petrology of Triassic sedimentary rocks, western Nova Scotia
Flysch sedimentation	(Klein, 1966)	Dispersal and petrology of sandstones of Stanley-Jackfork boundary, Ouachita foldbelt
Estuarine sedimentation	(Klein, 1967)	Comparison of Ancient and Recent tidal flat and estuarine sediments
Tidal sedimentation	(Klein, 1970, 1971)	Introduction of "Tidalite" facies for the first time. 1970: Depositional and dispersal dynamics of intertidal sand bars 1971: sedimentary model for determining paleotidal range
	Application of Klein's tidalite concept to petroleum reservoirs	Mobil: Estuarine facies, Cretaceous, Sacha Field, Ecuador (Shanmugam et al., 2000) Reliance Industries Ltd.: Submarine canyon-fill facies, Pliocene, Krishna-Godavari Basin, Bay of Bengal, India (Shanmugam et al., 2009)
Resedimented pelagic carbonate and volcanoclastic sediments	(Klein, 1975)	Resedimented pelagic carbonate and volcanoclastic sediments and sedimentary structures in Leg 30 DSDP cores from the western equatorial Pacific.
DSDP Leg 58	(Klein, Kobayashi et al., 1980)	Initial Reports of the Deep Sea Drilling Project, v. 58
Diagenesis	(Klein, 1985)	Sediment diagenesis
Tectonics	(Klein, 1993)	Quantitative Discrimination of Tectonic and Climatic Components of Pennsylvanian Sea-level Change
John E. Sanders	(Klein, 2000)	Research guidelines learned from John E. Sanders
Climate change	(Klein, 2016)	Geological Aspects of Long- and Short-Term Climate Change Relevant to Pacific Tropical Islands

Publications	1959-2009	Most of his contributions are archived at the University of Illinois. Details are available at: https://archives.library.illinois.edu/archon/?p=collections/controlcard&id=2148 His contributions during the period 1959-2009 are: 1) Number of published scientific books and edited volumes: 11 2) Number of published articles: 145 3) Number of unpublished technical reports: 49 4) Number of published review articles and abstracts: 141
Consulting and short courses		
President	1996-2013	SED-STRAT Geoscience Consultants, Inc. Houston, Texas, USA
Short courses	1961-2016	Klein taught popular short courses on sandstone depositional models and basins analysis for AAPG, SEG and other professional organizations. He presented technical talks at meetings throughout his professional life.
Awards, Honors, and notable contributions		
A Visiting Fellowship	1969	Wolfson College at Oxford University, England, UK
Outstanding Paper Award	1970	SEPM (Journal of Sedimentary Petrology), USA
An associateship	1974 and 1983	Centre for Advanced Study of the University of Illinois
A Citation of Recognition	1980	The Illinois House of Representatives, USA
Science Fellowship	1983	The Japan Society for the Promotion of Science Fellowship, Japan
Founding member	1985	Geological Society of America's Division on Sedimentary Geology
Fulbright Fellowship	1989	Fulbright Fellowship to the Netherlands, The Netherlands
The "Lawrence L. Sloss Award" for Sedimentary Geology	2000	Geological Society of America, USA
The "Legend of Sedimentology" Award	2013	The Houston Geological Society, Texas, USA.
Retirement	2013-2018	Guam
Family		
Parents	---	Alfred R.H. and Doris Devries Klein
Spouse at the time of his passing	---	Suyon Cheong Klein, who is originally from Seoul in South Korea
Two sons from an earlier marriage	---	Richard L. Klein of Washington, D.C., and Roger N. Klein of Champaign, Illinois
Sister	---	Mrs. Marianne Mandel of Bethesda, Maryland
Legacy	Forever	In his passing, the global geology community has lost a great scientist, teacher, friend, philosopher, critic, guide, and patriot. In an era of 'groupthink', George Klein represented a rare tribe of free-thinking scientists. Fortunately, he left us with a legacy rich in enduring doctrines that future generations will ever be grateful.

Acknowledgements

I thank the following who helped us during various stages of development of this Special Issue: G. M. Bhat, Bashir Ahmad Lone, Abhijit Basu, Graham Shields, G.N. Nayak, B.P. Singh, Santanu Banerjee, Erfan Mondal, R. Nagendra, Nallappa Reddy, and Armstrong Altrin. In particular, I would like to acknowledge the dedicated services of Bashir Ahmad Lone from the start to finish.

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Post-modernism and climate change

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Abstract:It is an honor to be able to contribute to a special issue of the Journal of the Indian Association of Sedimentologists, in commemoration of our colleague Professor George Devries Klein. As a good geologist, he was critical of the "scientific" way the belief in catastrophic man-made global warming was promoted by the IPCC and its followers (here called the "IPCC narrative"). He was what is sometimes called a "climate skeptic". In this article I discuss the influence of post-modern philosophy on the IPCC narrative. Postmodernism rejects scientific achievements of the Enlightenment. Any scientific criticism of the IPCC narrative is strongly rejected, even calling climate skeptics criminals. Some skeptics have even lost their jobs. According to the IPCC narrative the science has been settled and no further debate is tolerated. This is of course an anti-science standpoint. Some prominent geologists have been in the forefront of criticizing the IPCC narrative, publishing their scientific objections in many books and articles.

Keywords: George deVries Klein, Post-modernism, Enlightenment, Climate Change, IPCC, NIPCC.

Introduction.

Professor George Devries Klein and I met for the first time in 1973, when we were both on the scientific crew of Leg 30 of the Deep Sea Drilling Project, on board the *Glomar Challenger*.

Figures 1 and 2. I could only find two photographs of Professor Devries Klein from that expedition. On the left one he is photographing one of the sediment cores. The photo on the right was taken in de core lab of the ship. Professor Devries Klein is on the right, I am on the left.

The second, and last time I met him was during the 1978 International Sedimentological Congress in Jerusalem, where I presented a talk on Leg 30 sediment cores from the Coral Sea, north-east of Australia.

Contact was re-established in 2016. George had retired to Guam and had discovered on the Internet that I had published a critical book on climate change in 2016, titled *The Fable of a Stable Climate*. He ordered the book and we have been in contact until his death last April. We discovered that we were both *climate skeptics* (although we prefer to call ourselves *climate realists*). He sent me the PowerPoint of his 2016 presentation *some geological aspects of climate change relevant to Pacific Tropical Islands,* at the Island Sustainability Conference at the University of Guam.

Postmodernism

The first time I wrote about post-modernism was in the final chapter of my book *The Fable of a Stable Climate*, titled "Epilogue – Black Swans". On page 403 I wrote:

> "Another way of looking at this could be to contrast "proper science" with "post-modern science". With "proper science" I am referring to scientific principles and philosophies established over centuries. Proper science deals with facts, observations, experiments, numerical representations of the natural world around us, and, most important, the

continuous testing of hypotheses and theories. As already said, proper science must adhere to the principle of *falsifiability*. [Note: earlier in the chapter I discussed the scientific philosophy of Karl Popper, as expressed in the principle of *falsifiability*].

Post-modern science calls into question conventional notions of truth and reality. It states that there is no objective truth. All scientific theories and hypotheses are simply narratives, often culturally determined, and one narrative is as good as another. Science is just another tall tale. It comes down to a rejection of objectivity and realism.

Such post-modernist thinking has also invaded education. The idea is that students can find out by themselves the truths about scientific theories, by just using "common sense", unencumbered by what scientific theories had been developed in the past. Whatever they come up with is just as valid as the "old" theories. Such an approach was of course common in "pre-science" times. To give an example, thousands of years ago the Egyptians observed that the sun went under in the west and came up again in the east. Common sense told them that at night the sun travelled through the underworld. A whole religion was built on that premise. Pharaohs, after death, had to travel through the underworld, meeting all sorts of obstacles. To get safely through it, they needed all sorts of spells and assistance. How to go about it was recorded in the "Book of the Dead". In more recent times, before Copernicus, it was thought that the Earth was flat and the centre of the universe, and that the sun turned around the Earth. That's what common sense told them.

D.F. Mercer (*The Scientific Review of Alternative Medicine, Vol 4(1): 29-32, 2000)* wrote an excellent article on the effects of post-modern ideas on medicine, how it blurred the distinction between "proper" medical science and alternative medicine. He writes that postmodern ideas *"renders medicine open to infiltration from unscientific, emotionally, and ideological motivated individuals. Postmodern equates and allows for different forms of knowledge"*. The same could be said in relation to climate science.

Another related concept to "post-modern science" is "post-normal science" (Ticker, *Principia Scientific, 21 August 2013)*. In relation to climate change, Ticker calls the IPCC dogma *"a perversion of the standard definition of science as commonly understood. It appears to be an elaborate and dishonest attempt to pass off the preferences of a single group as some kind of pseudo-science. It brazenly casts aside the need for any factual basis and declares in the most unambiguous terms that whatever values it chooses to promote constitutes a truth unimpeachable by reality and a set of values that none dare challenge"*.

A consequence of "post-modern" scientific thinking is also that one can change observations and data at will. Whatever the outcome, all results are equally valuable. This approach is often used by the promoters of the dogma of catastrophic man-made climate change."

Postmodernist philosophy has its origin in the French philosophers Michel Foucault (1926-1984) and Jacques Derrida (1930-2004). Both were politically left. Foucault was for a time a member of the French Communist Party and later became a Maoist. Derrida was associated with far left organisations. Although he sympathised with the French Communist Party, he never became a member. He took part in the 1968 student uprising in Paris.

Their philosophy greatly influenced academic humanities departments, especially women and gender studies. This was especially the case in the United States. However, this is not the place to discuss their postmodern philosophy in detail. In the present context we are concerned with its influence on science, especially their rejection of the principles and philosophies of the Enlightenment.

The enlightenment

There are different opinions about when the Enlightenment started. It seems reasonable to put that beginning at the publication of Copernicus' book De *Revolutionibus Orbium Coelestium* (On the Revolutions of the Heavenly Spheres) in 1532. In it he stated that the centre of the universe was not Earth, but that the Sun was near its centre. This was direct challenge to the till then accepted Earth-centred astronomy of the Greek philosopher Claudius Ptolomy (100-160). As this astronomical worldview was also the official standpoint of the Roman Catholic Church, scientists accepting the Copernican view came into conflict with the church. The most famous case is that of the Italian astronomer Galileo Galilei (1564-1642) whose astronomical observations supported those of Copernicus. However, Church Inquisition consultants pronounced Copernican theory heretical. In 1616, Galileo was ordered not to "hold, teach, or defend in any manner" the Copernican theory.

The Enlightenment period was also called the *Age of Reason*. During the Enlightenment the *scientific method* was developed. Its basic principles are reason, logic, observations, measurements, objectivity, universality, developing hypotheses or theories, testing and reproducibility. Science philosophers, like Karl Popper (1902-1994) and Thomas Kuhn (1922-1996). developed philosophical underpinnings. For instance, Karl Popper developed the *theory of falsifiability*. He developed this theory to distinguish science from pseudo-science. In short, this theory states that *"A proposition or theory cannot be considered scientific if it does not admit the possibility of being shown false"*. To put this in another way, "A scientific statement must be able to be tested and proven wrong". One of the corollaries is also that scientific observations and experiments must be reproducible[1].

The Enlightenment has brought enormous benefits to mankind. Science has blossomed, technology has blossomed. In many countries, it has brought liberal democracies. For instance, the US Declaration of Independence and their Constitution were based on Enlightenment principles.

Postmodern Philosophy's Rejection of the Enlightenment

Postmodern philosophers Michel Foucault and Jacques Derrida rejected the Enlightenment scientific principles. They were influenced by German philosophers like Kant, Heidegger, Nietsche and Hegel, who rejected objectivity. They argued that it is not possible to know reality. Subject and object are being separated. We cannot know outside reality. Logic and evidence are subjective. Postmodernism went as far as to believe that all scientific knowledge is only a narrative, a social construct, and one theory is a valid as the next one. There is no objective truth.

This postmodern "philosophy" has become quite extreme in relation to climate science. It doesn't accept that all scientific opinions are equality valid, but that only one opinion or theory is acceptable. The climate change narrative, as espoused by the UN International Panel on Climate Change (IPCC) is considered as the only valuable narrative. We will call it the *IPCC narrative*. This narrative is also characterised by its extreme intolerance. This narrative states that human emissions of greenhouse gases, especially carbon dioxide, are causing catastrophic global warming. Many scientists dispute this, based on good scientific arguments, but they have been subjected to *ad hominem* attacks. Over the years I collected the following abuses: "climate change deniers", "cash-amplified flat-earth pseudo-scientists", "the carbon cartel", "villains", "cranks", "refuseniks lobby", "polluters", "a powerful and devious enemy", "and profligates". The list is endless. We are being told that *the science is settled*, which an anti-science statement is of course. They are hostile to dissent and debate. It is sad that most universities and science academies have bought into the IPCC narrative.

Outlawing Climate Change "Denial"

David Roberts of Grist magazine wrote on September 19, 2006: *"When we've finally gotten serious about global warming, when the impacts are really hitting us and we're in a worldwide scramble to minimize the damage,* *we should have war crimes trials for these bastards* (the "bastards" being the climate skeptics) – *some sort of climate Nuremberg".* Former US Secretary of State John Kerry said that global warming skeptics should be disqualified from "high public office." He called climate change a *weapon of mass destruction.* It is ironic that at present the highest public office in the United States, that of President, is filled by a climate skeptic.

In 2014, the President of the British Science Association, Sir Paul Nurse, urged researchers (the right ones of course – GJvdL) to *"call offenders (i.c. skeptics) out in the media and challenge them in the strongest way possible. And, when they are serial offenders, they should be crushed and buried".* Even worse, in 2012, Richard Parncutt, professor of systematic musicology at the University of Graz, Austria, suggested that man-made global warming deniers should be sentenced to death. He posted his opinion on his university website. He wrote: *"I have always been opposed to the death penalty in all cases. Even mass murderers (like Breivik) should not be executed, in my opinion. GW (global warming) deniers fall into a completely different category from Behring Breivik* (a Norwegian who murdered young socialists in a holiday camp - GJvdL)*. They are already causing the deaths of hundreds of million future people. We could be speaking of billions, but I am making a conservative estimate. If a jury of suitably qualified scientists estimated that a given GW denier had already, with high probability (say 95%), caused the deaths of over one million people, then s/he would be sentenced to death".*

An Australian columnist proposed that climate change denial should be outlawed. She wrote: *"David Irving is under arrest in Austria for Holocaust denial. Perhaps there is a case for making climate change denial an offence. It is a crime against humanity, after all"* (this clearly shows that the denigrating term "climate change denier" equates with "Holocaust denier"). Environmental activist Robert F. Kennedy Jr said during the recent New York City's People's Climate March (21 September 2014) that "*there should be a law that lets authorities punish sceptics and deniers – those who engage in "selling out the public trust ... These guys are doing the Koch Brothers bidding and are against all evidence of the rational mind, saying global warming does not exist. They are contemptible human beings ... I think it's treason".*

A New Zealand social scientist, Dr Jarod Gilbert, in 2016 called for climate change denial to be called a crime. He said: *"There is no greater crime being perpetuated on future generations than that committed by those who deny climate change".* The term "climate change denier" is of course absurd. No scientist denies climate change. Climate change has been occurring since the beginning of the Earth.

More insidious is the fact that some scientists have lost their job because they dared to doubt the veracity of the IPCC narrative. A French meteorologist, Philippe Verdier, lost his job as weather man with France Télévision, because he had published and promoted a book critical of the IPCC narrative, titled *Climat Investigation* (climate investigation). He was sacked just before the Paris 2015 COP21 conference. He was charged by the TV network with having violated ethical rules.

Another case is that of Professor Peter Ridd of James Cook University, Townsville, Australia. He has recently been fired because of his opinions on the Great Barrier Reef (GBR). He was fired by his university for allegedly multiple breaches of its code of conduct. He was also censured for denigrating research carried out at the James Cook University's *Centre of Excellence for Coral Reef Science* and the *Australian Institute of Marine Science.* He was also accused of scientific misconduct.

The GBR has been used extensively as an example of the disastrous effects of man-made global warming. However, as marine scientist and one of the world's pioneers in studying coral reefs, Dr Walter Starck, wrote in a Quadrant Online paper[7] that *"many claims of threats to the GBR are based on speculation and flat-out fabrications of researchers, bureaucrats and activists seeking grants and donations". "The Reef is fine".* Similar opinions were expressed by Peter Ridd, based on observations by himself and his students. He recently wrote an article explaining his views, titled *The Extraordinary Resilience of*

Great Barrier Reef Corals, and Problems with Policy Science in the book *Climate Change: The Facts 2017* [8]. He decided to fight his sacking in court. As this is an expensive business, he started an initial fund-raising petition. Within a few days he raised $95,000, a clear sign of the massive support he is receiving. However, he became aware that he needed much more to support his case. A second fund-raising action amassed a staggering $260,000 in a few months.

The actions against Professor Peter Ridd are not surprising. Apart from exposing the ideology-steered alarmist coral reef science, he also was a threat to science funding. Alarmist coral reef scientists have claimed that $16 billion is required to "save the GBR". Last January, the Australian Government announced a $60 million plan to help improve the "health of the GBR".

I could mention many more intolerant, anti-science examples. These clearly show that the IPCC narrative has nothing to do with real science. It is based on ideology and denies all the sound scientific principles developed over several hundred years since Copernicus.

The Marxist characteristics of postmodern climate change science has been noted by several authors[4,5,6]. It can be illustrated by remarks from climate change activists:

Maurice Strong, a leader of the international green movement, said: *"Isn't the only hope for the planet that the industrialized civilizations collapse? Isn't it our responsibility to bring that about?"* Timothy Wirth, ex-President of the UN Foundation, made it quite clear: *"We've got to ride this global warming issue. Even if the theory of global warming is wrong, we will be doing the right thing in terms of economic and environmental policy."*

Christiana Figueres is a Costa Rican diplomat. She was appointed Executive Secretary of the UN Framework Convention on Climate Change (UNFCCC) on May 17, 2010.The UNFCCC organises annual climate conferences, called COPs (Conferences of the Parties to the UNFCCC). The first one was held in Berlin in 1995. This year's COP24 will be held in Katowice in Poland, from 2-14 December.

During COP20 in Lima Peru in 2014. Christiana Figueras chaired that conference. In her opening address she said, among other, the following*: "The calendar of science loudly warns us that we are running out of time",* and *"Here in Lima we must plant the seeds of a new, global construct of high quality growth, based on unparalleled collaboration building across all previous divides. History, dear friends, will judge us not only for how many tonnes of greenhouse gases we were able to reduce, but also by whether we were able to protect the most vulnerable, to alleviate poverty and to create a future with prosperity for all"*. During an earlier climate conference in Bonn, Germany, she said: *"This is the first time in the history of mankind that we are setting ourselves the task of intentionally, within a defined period of time, to change the economic development model that has been reigning for at least 150 years since the Industrial Revolution"*. The real agenda is concentrated political authority, an old Marxist dream. Global warming is the hook. It's about a new world order under the control of the UN. It is opposed to capitalism and freedom and has made climate change catastrophism a household topic to achieve its objective. Figueres is on record saying democracy is a poor political system for fighting global warming. Communist China, she says, is the best model.

Actions by Geologists to Counter the IPCC Narrative

The most glaring aspect of the catastrophic global warming scare is its historic amnesia. That's why many geologist are climate sceptics. They know about the geological history of climate change. One of my own lectures is titled *"Four billion years of climate change"*. This gives a totally different perspective on global warming (and cooling).

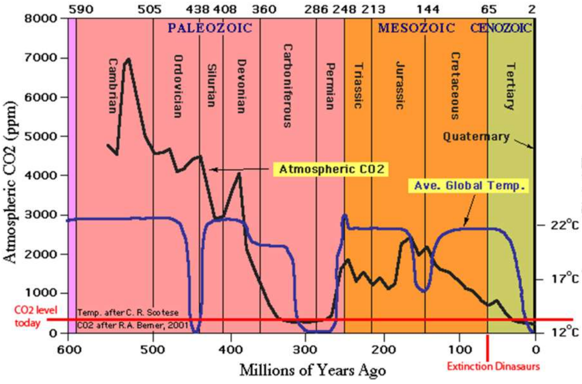

Figure 3. This graph shows atmospheric global temperature (blue line) and atmospheric CO_2 (black line) over the last 600 million years. It does not show any correlation between temperature and CO_2. These data are based on geological data and uncertainty increases further back in time. (Source: www.geocraft.com/WVFossils/Carboniferous_climate.html)

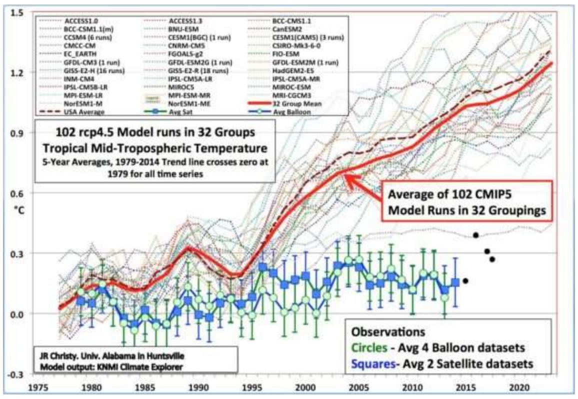

Figure 4. The IPCC narrative is almost exclusively based on non-validated computer models. This graph shows 102 models used by the IPCC and compared to actually observed temperature data from weather balloons and satellites (blue and green). (Source: J.R. Christy, University of Alabama in Huntsville

Historically seen, the present minor warming is nothing unusual. Devries Klein in his Guam lecture[3] used several illustrations similar to the ones I use. I will reproduce here two very important ones.

Many well- qualified geologist have joined the fight against the pseudo-science of the IPCC narrative. Professor George Devries Klein was one of them. But one of the most important and effective one was the late Bob Carter, professor of geology at James Cook University in Townsville, Australia. He was one of the co-authors of the publications by the Nongovernmental International Panel on Climate Change (NIPCC), sponsored by CO_2 Science and the Heartland Institute. The NIPCC is an international panel of nongovernment scientists and scholars who have come together to present a comprehensive, authoritative, and realistic assessment of the science and economics of global warming, independent of ideology. Because it is not a government agency, and because its members are not predisposed to believe climate change is caused by human greenhouse gas emissions, NIPCC is able to offer an independent "second opinion" of the evidence reviewed – or not reviewed – by the IPCC on the issue of global warming.

Their first publication, *Nature, not human activity, rules the climate* was published in 2008. Their latest important publications are titled *Climate Change Reconsidered II.* So far, three major volumes have been published: *Physical Science* (2013), *Biological Impacts* (2014), and *Fossil Fuels – Benefits and Costs of Fossil Fuels* (2017). Apart from Professor Bob Carter, other lead authors of this series are Professor S. Fred Singer and Dr Craig D. Idso.

Professor Carter also published two climate-change-critical books, titled *Climate: the Counter Consensus* and *Taxing Air – Facts & Fallacies about Climate Change.*

One of the most active critics of the IPCC narrative is the prominent Australian geology professor Ian Plimer. So far he has published five critical books. The two most important ones are *Heaven & Earth*[11] and *Climate change delusion and the great electricity rip-off.*

Because we have knowledge about the climate history of Earth, and because we adhere to the scientific method developed during the Enlightenment, geologist have a duty to critically analyse the climate science as being promoted by the followers of the IPCC narrative.

About the Author

Dr Gerrit van der Lingen studied geology at Utrecht University in The

Netherlands. He did his PhD on an area in the Spanish Pyrenees. His first job was in Surinam in South America, where he worked in Amazon jungle for three years. In 1965 he came to New Zealand to join the Sedimentology Laboratory of the NZ Geological Survey. He was a Council Member of the *International Association of Sedimentologists* from 1971 to 1978, and an Editorial Board Member for the journal *Sedimentary Geology* from 1972 to 1982. He took part in expeditions Legs 21 (1971) and 30 (1973) of the Deep Sea Drilling project on board the *Glomar Challenger.* Since 1990 he worked as a private consultant and was a Research Associate at the University of Canterbury. From 1991 till 2002 he was involved in paleoclimate research, studying ocean sediment cores from the Tasman Sea and Southern Ocean. In 1998 he took part in an expedition to the Tasman Sea and Southern Ocean on board the German research vessel *Sonne.* He retired from paid research nine years ago, but remains active as a man-made-global warming agnostic, giving lectures and writing articles. He is a foundation member of the New Zealand Climate Science Coalition.

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Bioturbation and trace fossils in deep-water contourites, turbidites, and hyperpycnites: A cautionary note

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Abstract: Bioturbation and trace fossils have been claimed to be an important attribute of deep-water contourites, turbidites, and hyperpycnites. However, these biogenic features have nothing to do with fluid mechanics of depositional processes of contour currents, turbidity currents, or hyperpycnal flows. Bioturbation can be both syn- and post-depositional in timing. Therefore, the presence of ichnological signatures in the ancient sedimentary record is irrelevant for interpreting deep-water deposits as a product of a specific process.

Keywords: Bioturbation; Contourites; Hyperpycnites; Trace fossils; Turbidites

Introduction

Since the birth of modern deep-sea exploration by the voyage of H.M.S. Challenger (December 21, 1872–May 24, 1876), organized by the Royal Society of London and the Royal Navy (Murray and Renard, 1891), oceanographers and sedimentologists have made considerable progress in understanding the world's oceans and related deposits. Nevertheless, the physical processes that are responsible for transporting sediment downslope into the deep sea are still poorly understood. This is simply because the physics and hydrodynamics of these processes are difficult to observe and measure directly in deep-marine environments.

During the past five decades, there have been claims on the relationship between ichnological facies and sedimentary environments (Seilacher, 1964; Ager, 1971; Nilsen and Abbott, 1979; Gonthier et al., 1984; MacEachern et al., 2010; Greene et al., 2012; Knaust, 2012; among others). Ichnological signatures (bioturbation and trace fossils) are common in a variety of depositional facies, such as turbidites (Nilsen and Abbott, 1979), contourites (Gonthier et al., 1984; Wetzel et al., 2008; Rodríguez-Tovar and Hernández-Molina, 2018a), tempestites (Ager, 1971; Zhao et al., 2017), hyperpycnites (Mulder et al., 2003; Buatois et al., 2011), and even seismites (Moretti, 2000; Fortuin and Dabrio, 2008; see also Shanmugam, 2016a). The fundamental issues here are:

1) Are bioturbation and trace fossils controlled by fluid mechanics of a specific process?
2) If fluid mechanics do control ichnological signatures, how to distinguish the contourite facies from the associated facies, such as turbidites and hyperpycnites on the basis of bioturnation and trace fossils?

The above two basic issues are still unresolved (Shanmugam, 2016b). Amid this knowledge vacuum, Rodríguez-Tovar and Hernández-Molina (2018a) have published a paper entitled "Ichnological analysis of contourites: Past, present and future". Clearly, the impressive title implies the global importance of ichnological analysis of contourites. However, their theoretical approach, without empirical data, is misleading. Therefore, the primary purpose of this paper is to point out some basic problems in emphasizing the importance of ichnofacies in contourites, and associated turbidites and hyperpycnites. In this regard, I will review the basics of what we know and what we don't know in each case. Hopefully, this cautionary note would deter future workers from promoting the flawed link between

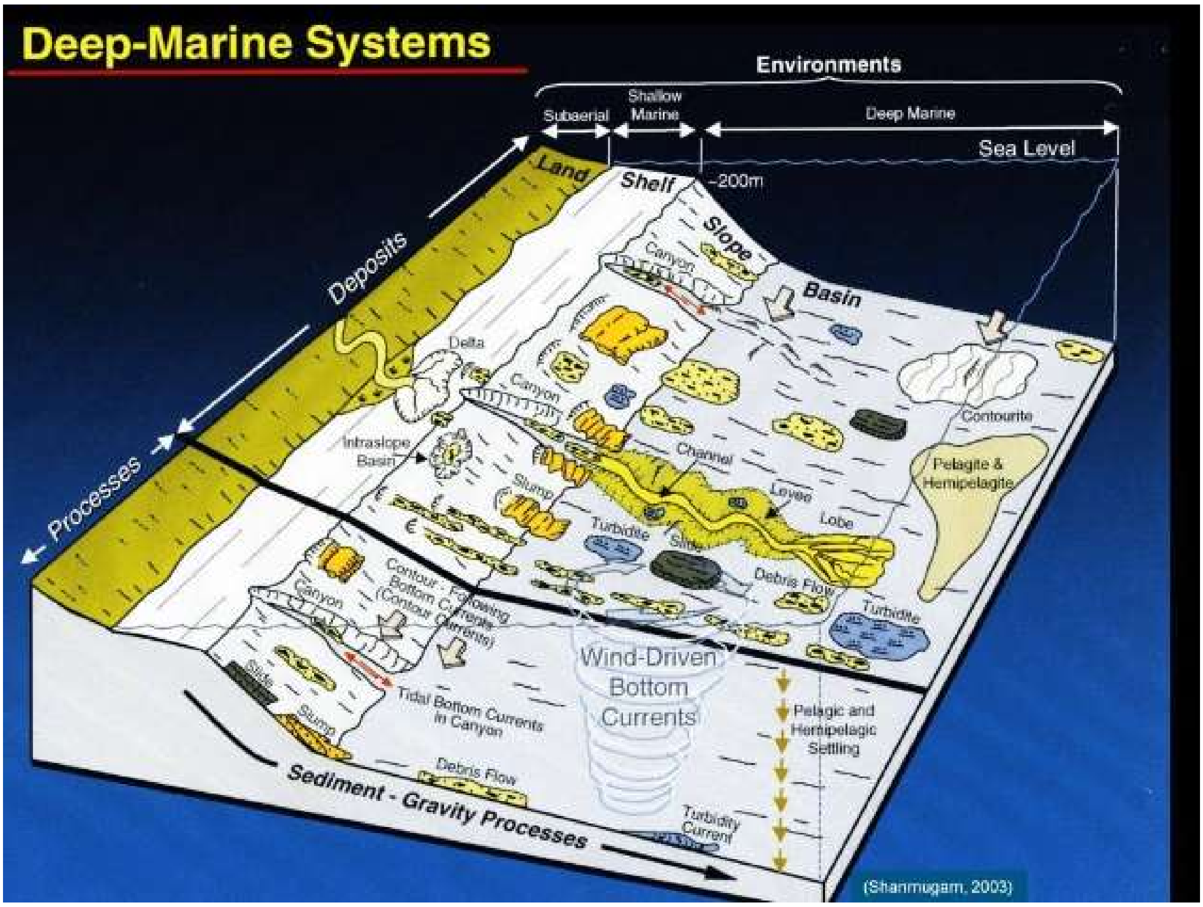


Fig. 1. Schematic diagram showing complex deep-marine sedimentary environments occurring at water depths deeper than 200m (shelf-slope break). In general, sediment transport in shallow-marine (shelf) environments is characterized by tides and waves, whereas sediment transport in deep-marine (slope and basin) environments is characterized by gravity-driven downslope processes, such as mass transport (i.e., slides, slumps, and debris flows), and turbidity currents. Bottom currents, composed of thermohaline contour-following currents, wind-driven currents (circular motion), up and down tidal bottom currents in submarine canyons (opposing arrows), and baroclinic currents (not shown) related to internal waves/tides (Shanmugam, 2013). From Shanmugam (2003). Elsevier.

ichnology and a specific deep-water depositional facies.

Deep-water processes

Deep-water environments (> 200 m in bathymetry, seaward of the continental shelf) are characterized by gravity-driven downslope processes, which comprise slides, slumps, debris flows, and turbidity currents (Fig. 1). In addition, there are four basic types of deep-water bottom currents, namely (1) thermohaline-induced geostrophic bottom currents (contour currents), (2) wind-driven bottom currents, (3) tidal bottom currents, and (4) baroclinic currents associated with internal waves and

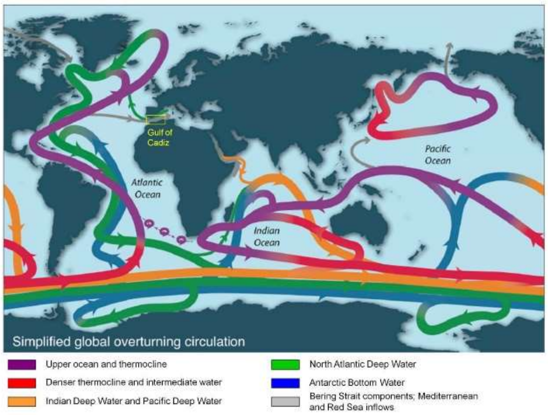


Fig. 2. Map showing the global overturning circulation (GOC). The location of Gulf of Cadiz is added in this article. This site served as the type locality for the contourite facies model odified after Talley (2013), with permission from the Oceanography Society.

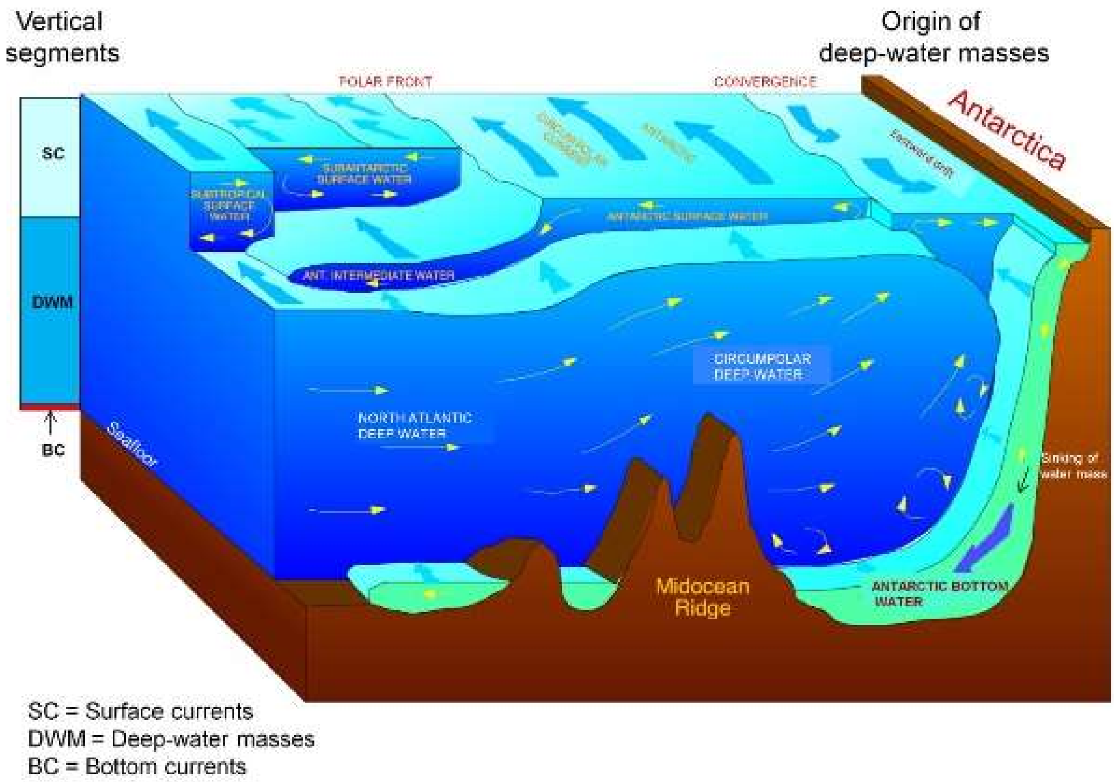


Fig. 3. A conceptual model of the Southern Ocean showing three vertical segments, composed of the upper surface currents, the middle deep-water masses, and the lower bottom currents, forming a vertical continuum (left). Note the origin of AABW by freezing of shelf waters (right). As a consequence, the increase in the density of cold saline (i.e., thermohaline) water triggers the sinking of the water mass down the continental slope and the spreading of the water masses to other parts of the ocean. Modified after Hannes Grobe, September 5, 2015. From Shanmugam (2012), with permission from Elsevier.

tides (Shanmugam, 2012, 2013). Also, Mulder et al. (2003) consider river-deriver hyperpycnal flows reach the deep sea. In this article, deposits of contour currents (i.e., contourites), turbidity currents (i.e., turbidites), and hyperpycnal flows (i.e., hyperpycnites) are the focus.

Contourites The thermohaline circulation (Fig. 2) and related deep-marine bottom currents (Fig. 3) in modern oceans became popular when Heezen et al. (1966) reported deep-water masses and related contour currents along the continental rise in the U.S. Atlantic margin. An example of such deep-water mass is the Antarctic Bottom Water (Fig. 3). In the U. S. Atlantic margin, both downslope- and alongslope- processes have been documented (Fig. 4). Hollister (1967), based on his detailed core study of the U. S. Atlantic margin, introduced the genetic term 'contourite' for deposits of thermohaline-induced geostrophic contour currents in the deep oceans.

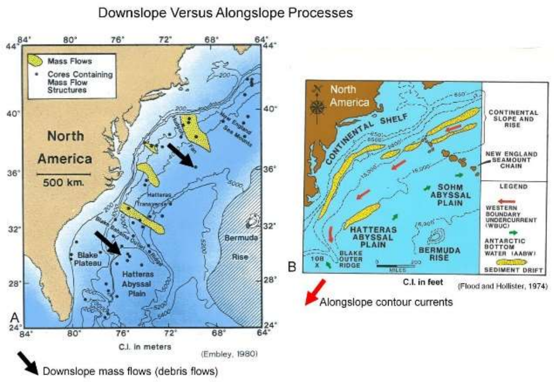


Fig. 4. Comparison of processes on the U.S. Atlantic Margin. A. Downslope mass flows and their deposits (i.e., debrites) (Embley, 1980). B. Alongslope contour currents and their deposits (i.e., contourites) (Flood and Hollister, 1974).

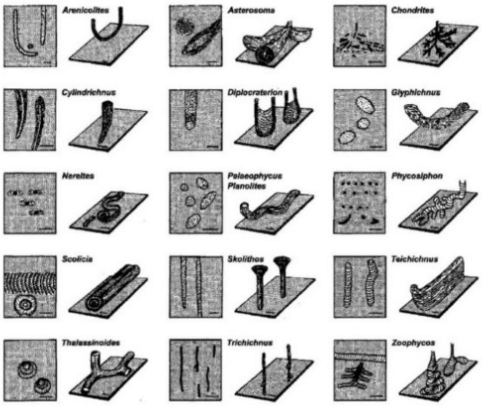


Fig. 5. Trace fossils commonly encountered in contourites. From Wezel et al. (2008).

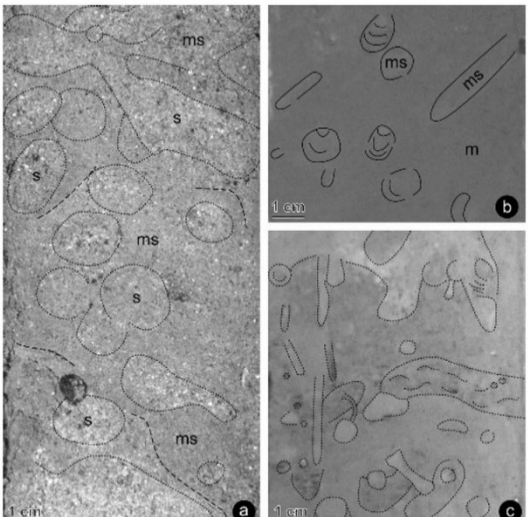


Fig. 6. Glacigenic sediments interpreted as contourites from the Iceland Shetland Channel. **(a)** Sand-rich facies, current-reworked sediments have been mixed by bioturbation to muddy sand (ms); subsequently, sand-enriched burrows (s) were produced. British Geological Survey core 61-04/39 (61°03.5' N, 3°25.1' W; 1125 m water depth) 274-290 cm (Late Pleistocene). **(b)** Sandy mud facies; sands have been mixed into mud, after a early phase of homogenization producing uniform sandy mud (m), distinct burrows containing some more sand (ms) have been formed, which may be ascribed to *Teichichnus* or *Thalassinoides*. **(c)** Muddy facies, light mud resting on grey mud, the contact has been heavily bioturbated, vertical tubes and halo burrows (*Palaeophycus*, *Planolites*, *Thalassinoides*) are common; British Geological Survey core 60. From

Wetzel et al. (2008) have documented ichnological signatures in contourites (Figs. 5 and 6). Although Rodríguez-Tovar and Hernández-Molina (2018a) have provided an in-depth discussion of terminologies associated with ichnological analysis, they have ignored the very basic conceptual and terminological issues associated with the term 'contourites'.

Consequently, important unresolved issues still exist:

- Contour currents and turbidity currents flow at right angle to each other (Fig. 7). Deposits of these hybrid flows at their intersection are poorly understood.

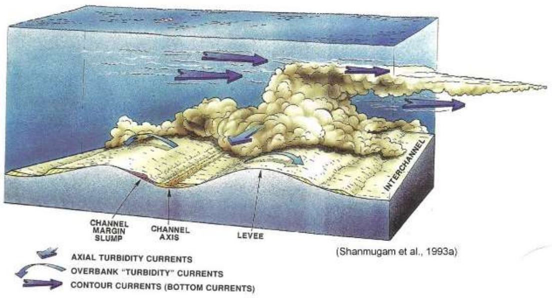


Fig. 7. Conceptual model showing the spatial relationship between downslope turbidity currents and along-slope contour currents. After Shanmugam et al. (1993), AAPG.

- Gulf of Cadiz (Fig. 8), which served as the type locality for the

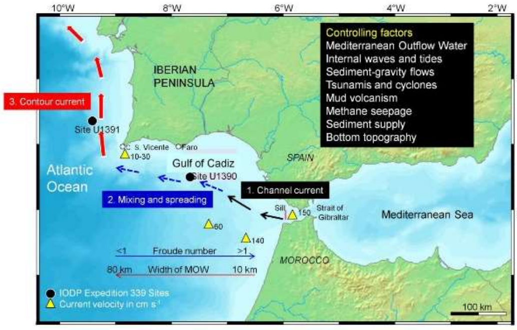


Fig. 8. Schematic diagram showing the location of Gulf of Cadiz and complex transport nature of the Mediterranean Outflow Water (MOW), involving three stages of evolution: (1) channel-current stage, (2) mixing and spreading (i.e., transition) stage, and (3) genuine contour-current stage (see Zenk, 2008, his Fig. 4.10). Figure from Shanmugam (2016b), with permission from Elsevier.

contourite facie model (Fig. 9) (Faugères et al. 1984; Gonthier et al. 1984), is a highly complicated oceanographic location for studying depositional and erosional aspects of genuine contour currents.

Although the Mediterranean Outflow Water (MOW) is considered to be the primary process of deposition of contourites, MOW is not a genuine contour current in the Gulf of Cadiz (Zenk 2008). It evolves through three stages, namely (1) channel current, (2) mixing and spreading, and (3) contour current (Fig. 8).

- Deposition at this site has been complicated by additional controlling factors, such as internal waves, tsunamis, cyclones, mud volcanism, and the Camarinal Sill, etc. (Fig. 8). For these reasons, the Gulf of Cadiz is not an ideal location for developing the contourite facies model with an emphasis on bioturbation (Fig. 9) (Shanmugam, 2016b).
- The term 'contourite' means different things to different people, depending on whose definition one chooses to use. For example, Hollister (1967) would use the term "contourites" for deposits of thermohaline-driven geostrophic contour currents (Fig. 10), whereas Lovell and Stow (1981) would use the term "contourites" for deposits of any kind of bottom currents (Fig. 10). According to Lovell and Stow (1981, 349): "*Contourite: a bed deposited significantly reworked by a current that is persistent in time and space and flows along slope in relatively deep water (certainly below wave base). The water may be fresh or salt; the cause of the current is not necessarily critical to the application of the term*." Clearly, their last phrase "*the cause of the current is not necessarily critical to the application of the term"* has broadened the meaning of the Hollister's (1967) narrow definition of the term contourites. In that broader sense, contourites can be produced by any kind of bottom current ((e.g., thermohaline-driven, wind-driven, tide-driven, and internal-wave driven). In fact, Stow et al. (2008) explicitly stated that "*Bottom (contour) currents are those currents that operate as part of either the normal thermohaline circulation or wind-driven circulation systems...*" In short, there is no consensus on the meaning of the term 'contourite'. In the absence of a clear definition of contourites, any ichnological analysis of 'contourites' by Rodríguez-Tovar and Hernández-Molina (2018a) is distracting and unnecessary (Shanmugam, 2018a).

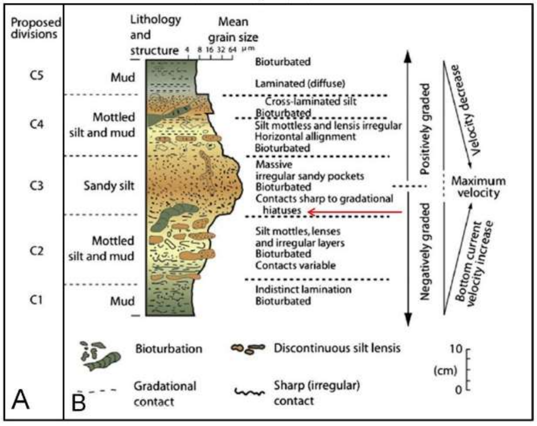


Fig. 9. The contourite facies model showing inverse to normal grading, intense bioturbation, and internal erosional surface (red arrow). Note intense bioturbation is not unique to contourites (Shanmugam, 2016b and 2017). A. Revised contourite facies model with five divisions proposed by Stow and Faugères (2008). B. Original contourite facies model by Faugères et al. (1984). Color version from Rebesco et al. (2014) with additional labels by G. Shanmugam.

It is true that contourites contain bioturbation and trace fossils (Figs. 5 and 6), but that does not mean bioturbation is a characteristic property of contourites. Importantly, bioturbation cannot be used as a criterion for interpreting deposit of a single process (i.e., contour currents). There are valid reasons for this skepticism:

- Ancient deep-water turbidites (e.g., in the Late Cretaceous Point Loma Formation near San Diego, California) are also extensively bioturbated and even contain the trace fossil *Ophiomorpha* (Nilsen and Abbott, 1979).

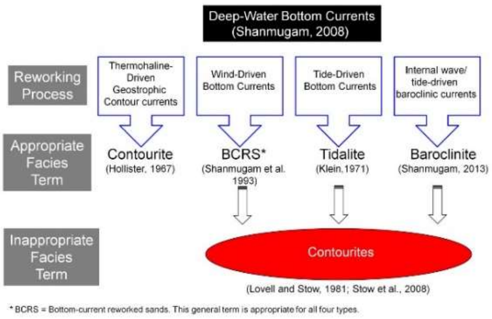


Fig. 10. Four types of bottom currents and their depositional facies. The facies term "contourites" is appropriate only for deposits of thermohaline-driven geostrophic contour currents in deep-water environments, but not for deposits of other three types of bottom currents (i.e., wind, tide, or baroclinic). Note that BCRS represent only sandy lithofacies, but may also be applicable to silty lithofacies. Figure from Shanmugam (2016b), with permission from Elsevier.

- Convincing cases of contourites without bioturbation have been documented in the rock record (Dalrymple and Narbonne, 1996).
- Mulder et al. (2003, 872) cautioned that "*In this case, the hyperpycnite can be mistaken with contourite beds defined by Gonthier, Faugères, and Stow (1984), particularly if bioturbation is intense*."
- Importantly, Hollister (1967, Appendix C, his p. 392) did not even include "bioturbation" as a basic sedimentary feature in the "Sediment Core Logs" of sediments that formed the very foundation for introducing the concept of contourites (his Fig. 1).
- All four types of bottom currents are characterized by traction structures (Fig. 11). The contourite facies model with emphasis on bioturbation (Fig. 9) defies the very first principle of process sedimentology, which is to interpret the fluid mechanics of depositional processes using primary physical sedimentary structures (Sanders, 1963), not bioturbation. The reason is that bioturbation can occur after deposition.

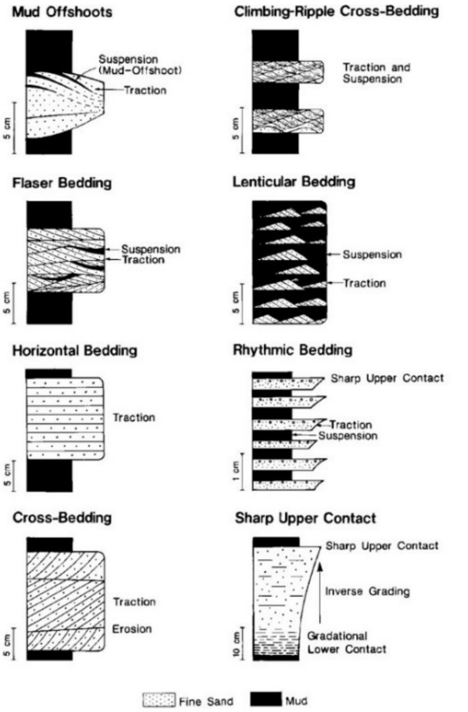


Fig. 11. Summary of traction features interpreted as indicative of deep-water bottom-current reworking by all types of bottom currents. Each feature occurs randomly and should not be considered as part of a vertical facies model. From Shanmugam et al. 1993, with permission from AAPG.

- It is worth pointing out that although Rodríguez-Tovar and Hernández-Molina (2018a) published a review of ichnology of contourites, the same authors (Rodríguez-Tovar and Hernández-Molina (2018b) conceded that "*Nowhere in our manuscript did we*

> *present bioturbation as an exclusive feature of contourites with respect to other deposits such as turbidites, debrites, etc."* Clearly, bioturbation and trace fossils are not diagnostic features of contourites.

In short, bioturbation is of no process sedimentological significance for interpreting ancient deep-water contourite facies.

TURBIDITES

Dott (1963) proposed the most meaningful and practical classification of subaqueous mass-transport processes. It is somewhat analogous to the most widely

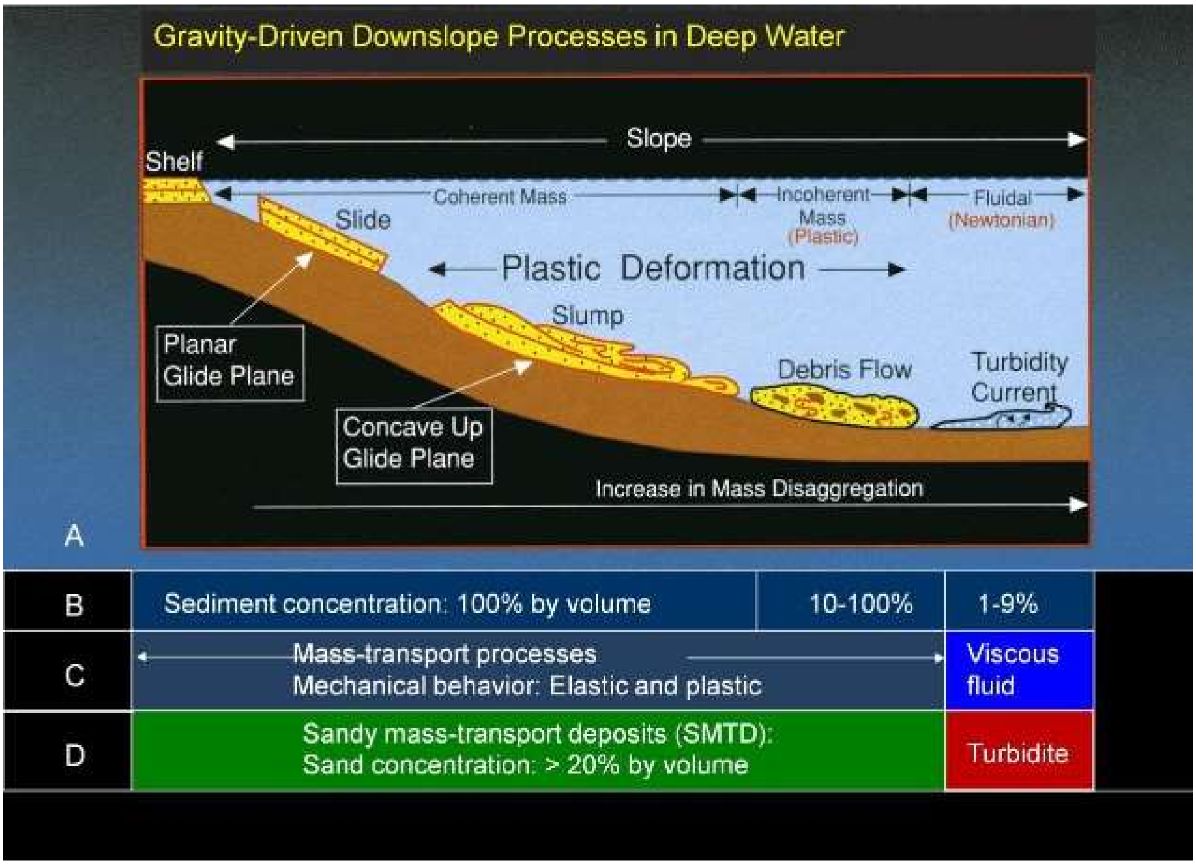


Fig. 12. (A) Schematic diagram showing four common types of gravity-driven downslope processes that transport sediment into deep-marine environments. A slide represents a coherent translational mass transport of a block or strata on a planar glide plane (shear surface) without internal deformation. A slide may be transformed into a slump, which represents a coherent rotational mass transport of a block or strata on a concave-up glide plane (shear surface) with internal deformation. Upon addition of fluid during downslope movement, slumped material may transform into a debris flow, which transports sediment as an incoherent body in which intergranular movements predominate over shear-surface movements. A debris flow behaves as a plastic laminar flow with strength. As fluid content increases in debris flow, the flow may evolve into Newtonian turbidity current. Not all turbidity currents, however, evolve from debris flows. Some turbidity currents may evolve directly from sediment failures. Turbidity currents can develop near the shelf edge, on the slope, or in distal basinal settings. From Shanmugam et al. (1994). (B) Sediment concentration (% by volume) in gravity-driven processes. Slides and slumps are composed entirely of sediment (100% by volume). Debris flows show a range of sediment concentration from 10 to 100% by volume. Note that turbidity currents are low in sediment concentration (<9% by volume, after Bagnold, 1962); implying low-density flows. These values are based on published data (see Shanmugam, 2000, his Figure 4). (C) Based on mechanical behavior of gravity-driven downslope processes, mass-transport processes include slide, slump, and debris flow, but not turbidity currents (Dott, 1963). (D) The prefix "sandy" is used for mass-transport deposits (SMTDs) that have grain (>0.06 mm: sand and gravel) concentration value equal to or above 20% by volume. The 20% value is adopted from the original field classification of sedimentary rocks by Krynine (1948). Modified after Shanmugam (2012).

accepted classification of subaerial mass-transport processes by Varnes (1958). The importance of Dott's (1963) classification is that mass-transport processes do not include turbidity currents (Fig. 12C). The underpinning principle of Dott's (1963) classification is the separation of solid from fluid mode of transport based on sediment concentration. In the solid (elastic and plastic) mode of transport, high sediment concentration is the norm (10-100% by volume, Fig. 12B). Mass-transport mechanisms are characterized by solid blocks or aggregate of particles (mass). In contrast, individual particles are held in suspension by fluid turbulence in turbidity currents (Dott, 1963; Sanders, 1965). Turbidity currents are characterized by low sediment concentration of less than 9% by volume, which was proposed by Bagnold (1962) (Fig. 12B). In other words, turbidity currents are innately low in flow density.

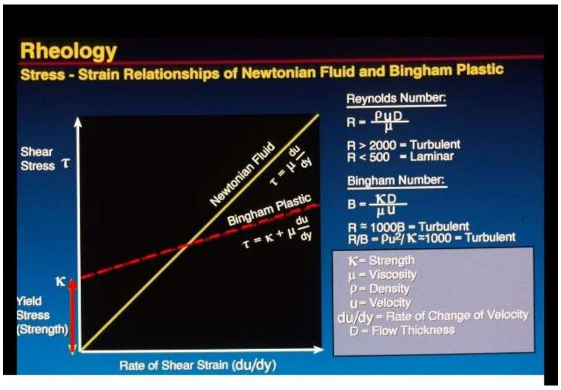


Fig. 13. Graph showing rheology (stress–strain relationships) of Newtonian fluids and Bingham plastics. Note that the fundamental rheological difference between debris flows (Bingham plastics) and turbidity currents (Newtonian fluids) is that debris flows exhibit strength, whereas turbidity currents do not. Reynolds number is used for determining whether a flow is turbulent (turbidity current) or laminar (debris flow) in state. Compiled from several sources (Dott, 1963; Enos, 1977; Pierson and Costa, 1987; Phillips and Davies, 1991; Middleton and Wilcock, 1994). From Shanmugam (1997).

In this article, the focus is on debris flows and turbidity currents because of their sedimentological importance. These two processes are distinguished from one another on the basis of fluid rheology and flow state. The rheology of fluids can be expressed as a relationship between applied shear stress and rate of shear strain (Fig. 13). Newtonian fluids (i.e., fluids with no inherent strength), like water, will begin to deform the moment shear stress is applied, and the deformation is linear. In contrast, some naturally occurring materials (i.e., fluids with strength) will not deform until their yield stress has been exceeded (Fig. 13); once their yield stress is exceeded, deformation is linear. Such materials (e.g., wet concrete) with strength are considered to be Bingham plastics (Fig. 13). For flows that exhibit plastic rheology, the term plastic flow is appropriate. Using rheology as the basis, deep-water sediment flows are divided into two broad groups, namely, (1) Newtonian flows that represent turbidity currents and (2) plastic flows that represent debris flows.

A turbidity current is a sediment flow with Newtonian rheology and turbulent state (Fig. 14) in which sediment is supported by turbulence and from which deposition occurs through suspension settling (Dott, 1963; Sanders, 1965; Middleton and Hampton, 1973; Shanmugam, 1996, 2006). Turbidity currents exhibit unsteady and non-uniform flow behavior (Fig. 15), and they are surge-

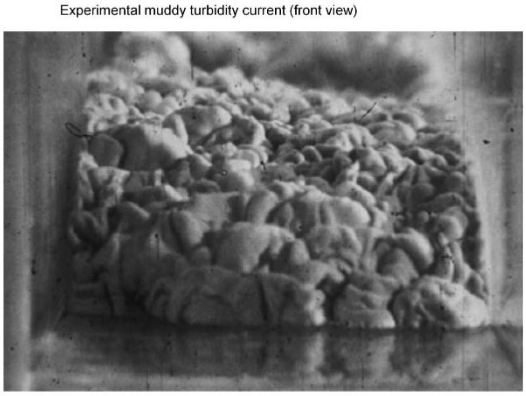


Fig. 14. Photograph of front view of experimental turbidity current showing flow turbulence. Photo from experiments conducted by M.L. Natland, and courtesy of G.C. Brown. Published in Shanmugam (2012) with permission.

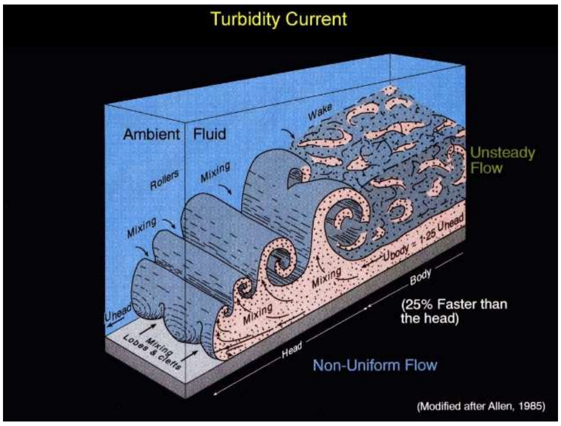


Fig. 15. Schematic illustration showing the leading head portion of an unsteady, nonuniform, and turbulent turbidity current. Due to turbulent mixing, turbidity currents invariably entrain ambient fluid (seawater) at their head regions. Modified from Allen (1985).

type waning flows. As they flow downslope, turbidity currents invariably entrain ambient fluid (sea water) in their frontal head portion due to turbulent mixing (Allen, 1985). With increasing fluid content, plastic debris flows may tend to become Newtonian turbidity currents (Fig. 12A). However, not all turbidity currents evolve from debris flows. Some turbidity currents may evolve directly from sediment failures. Although turbidity currents may constitute a distal end member in basinal areas, they can occur in any part of the system (i.e., shelf edge, slope, and basin).

Turbidity currents cannot transport gravel and coarse-grained sand in suspension because they do not possess the strength like debris flows. General characteristics of turbidites are:

- Fine-grained sand to mud Flute casts; however, flute casts are not unique to turbidites (see Klein, 1966; Shanmugam, 2002a)
- Normal grading (core and outcrop) (Fig. 16).
- Sharp or erosional basal contact (core and outcrop) (Fig. 16)
- Gradational upper contact (core and outcrop) (Fig. 16)
- Thin layers, commonly centimeters in thickness (core and outcrop)
- Sheet-like geometry in basinal settings (outcrop)
- Lenticular geometry may develop in channel-fill settings.

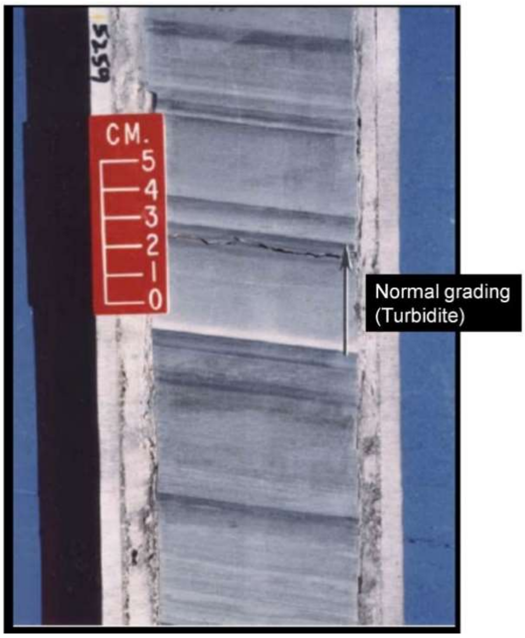


Fig. 16. Core photograph showing turbidite units with sharp basal contact, normal grading, and gradational upper contact. Arrow marks a normally graded unit with fine-grained sand at bottom (light gray) grading into clay (dark gray) near to Note that these thin-bedded units cannot be resolved on seismic data. Zafiro Field, Pliocene, Equatorial Guinea. From Shanmugam (2006) with permission from Elsevier.

In the Maritime Alps, Phillips et al. (2011) described the ichnology of the Grès d'Annot Basin, SE France in detail for the first time. In this case, deep marine palaeo environments from basin slope to basin floor settings are preserved. The Grès d'Annot Formation is a sand-rich, thick-bedded, and coarse-grained turbidite succession. Thick-bedded and channel sandstones contain low diversity trace fossil assemblages dominated by Ophiomorpha (Fig.17). Ophiomorpha in the Grès d'Annot Basin is inferred to have been produced by organisms mostly deposit feeding on buried organic-rich material during inter-turbidite intervals. *Ophiomorpha rudis* is the most prominent trace fossil found in the Grès d'Annot Basin and dominates the ichnofabrics in all locations within the basin. The deep-burrowing ability of the Ophiomorpha animal is considered to be an adaptation for exploiting buried organic nutrients found in inter-turbidite mudstones (Fig. 18).

Turbidite facies models

Conventionally, coarse-grained turbidites are considered to be deposits of high-density turbidity currents (Lowe, 1982). The problem is that high-density turbidity currents are nothing more than sandy debris flows in terms of fluid rheology and low state (Shanmugam, 1996, 2016c). Amid this controversy, ascribing trace fossils to coarse-grained or high-density turbidites in the Annot Sandstone (Figs. 17, 18) is problematic. Specific issues are:

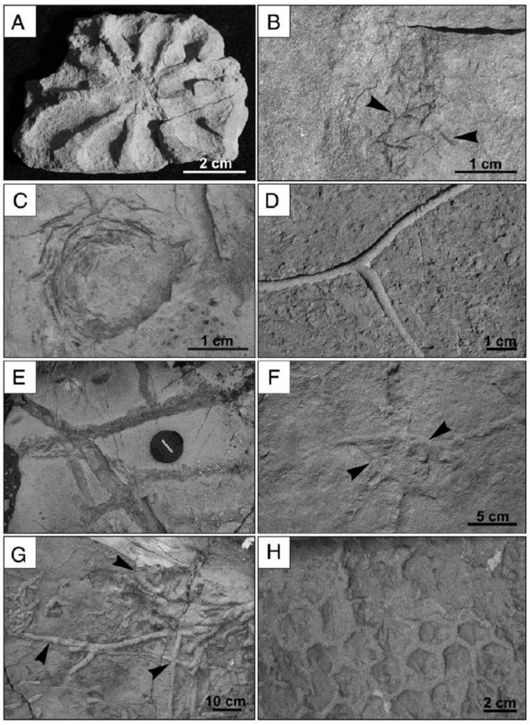


Fig. 17. Field images of documented trace fossils. A) *Asterosoma radicifo*rme found on top of a thin-bedded turbidite. Braux. B) Branched *Chondrites* is (arrowed) within a very fine-grained sandstone turbidite. Braux. C) Shell-lined *Diopatrichnus* from the uppermost Marnes Bleues Formation. Argenton. D) *Ophiomorpha annulata* on the sole of a thin-bedded sandstone turbidite. Montagne de Chalufy. E*)* *Ophiomorpha ?nodosa* on top of a coarse-grained sandstone turbidite. *Col de la Cayolle*. Lens cap is 5 cm wide. F) Knotted *Ophiomorpha rudis* on top of an inter-turbidite claystone. Baisse de l'Aiguille. G) Numerous *Ophiomorpha rudis* (arrowed) on the sole of a sandstone turbidite, Argenton. H) *Paleodictyon majus* on the sole of a thin-bedded, very fine-grained sandstone turbidite. *Col de la Cayolle*. From Phillips et al. (2011).

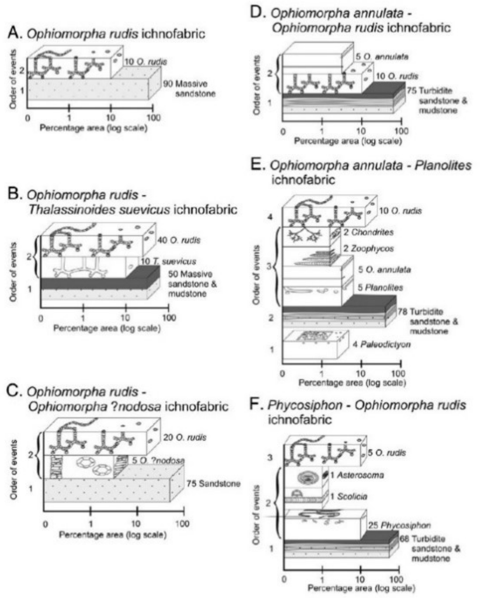


Fig. 18. Ichnofabric constituent diagrams for three ichnofabric associations and six ichnofabrics documented. The vertical axis indicates the order of events starting with either preturbidite ichnotaxa or turbidite deposition followed by colonization by post-depositional ichnotaxa. Numbers associated with each event indicate the percentage (by area) of the ichnofabric constituted by each event. From Phillips et al., (2011).

1. Turbidity currents are inherently low in sediment concentration or low in flow density (Fig. 19A), According to Bagnold (1962), typical turbidity currents can function as truly turbulent suspensions only when their sediment concentration by volume is below 9% or $C < 9\%$ (Fig. 19A). Therefore, true high-density turbidity currents cannot exist in nature (Shanmugam, 1996, 2000).
2. There is no agreement on the density value that separates "low-

density" from "high-density" turbidity currents (Fig. 19A).

3. A reexamination of the Annot Sandstone in the Peira Cava area in SE France, Maritime Alps, which served as the type locality for the 'Bouma Sequence', suggests deposition from sandy debris flows (Fig. 20), not classic turbidity currents (see Shanmugam, 1997 and 2002a).
4. Flume experiments have revealed that the so-called 'high-density turbidity currents' are indeed composed of a basal laminar layer, typical of debris flows (Fig. 19B), not turbulent turbidity currents. This experiment also provided evidence for deposition of floating

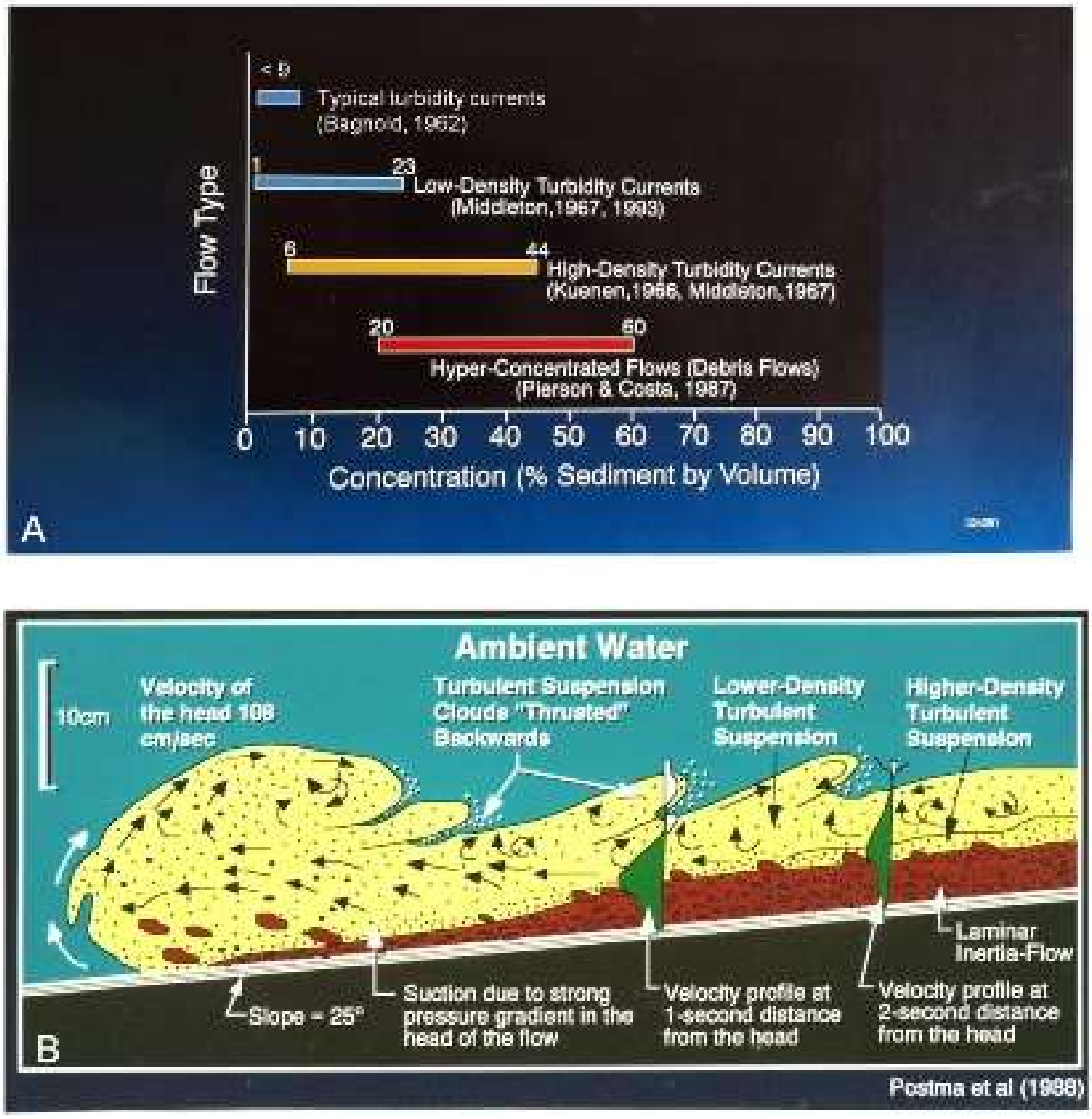


Fig. 19. A-Plot of sediment concentration for different flow types. Note that a typical turbidity current can exist only in sediment concentration less than 9% by volume (Bagnold, 1962). Note that "high-density turbidity currents" are nothing but "sandy debris flows" (Shanmugam, 1996). Modified after Shanmugam (1996). Reproduced with permission from SEPM; 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.” Figure from Postma et al. (1988). Publication: Sedimentary Geology. With permission from Elsevier.

clasts (Postma et al., 1988), common in debris flows

5. No one has ever documented empirical data on active 'gravelly or sandy turbidity currents' in modern oceans using vertical sediment concentration profiles and grain-size measurements.

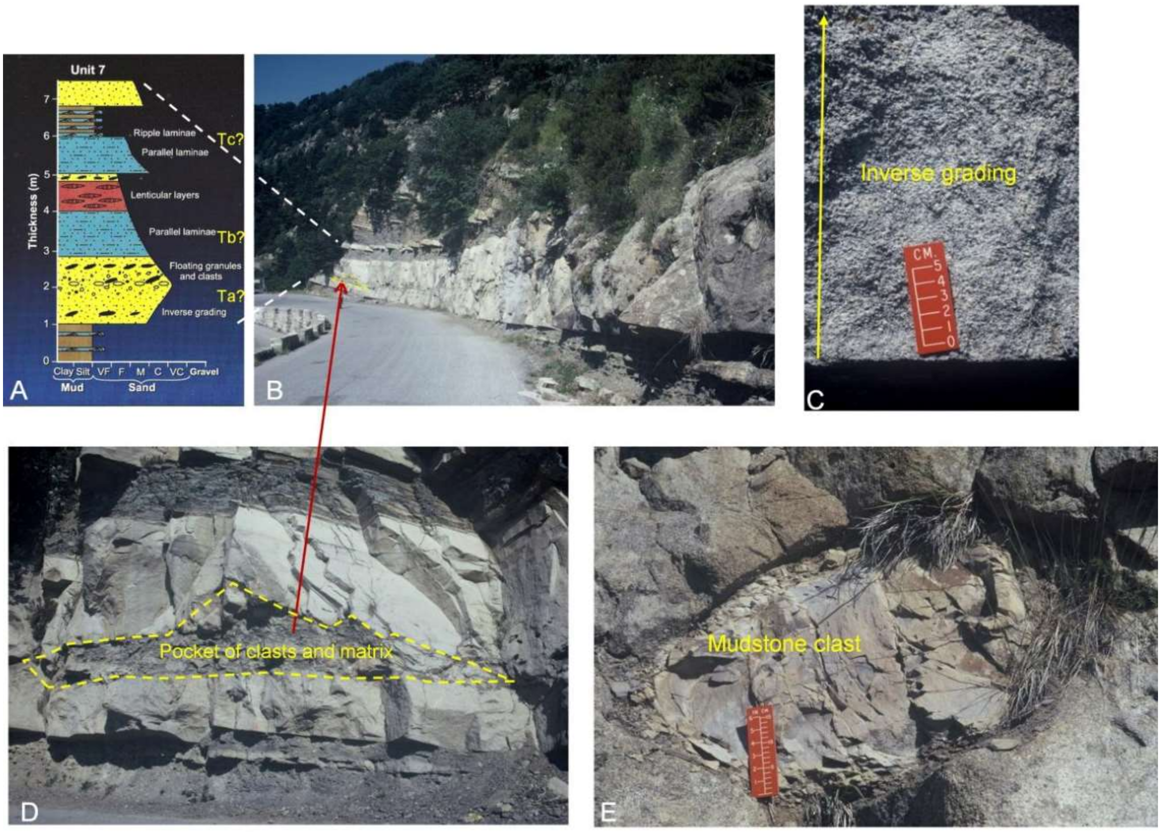
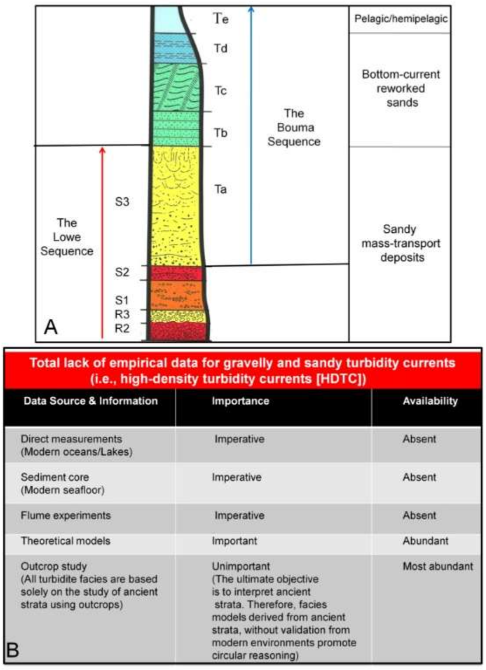


Fig. 20. A-Sedimentological log of amalgamated sandstone Unit 7 showing basal inverse grading overlain by an interval of complex normal grading with floating granules and mudstone clasts, parallel laminae, and lenticular layers. Note sudden increase in grain size at 5m. Note conventional description using Bouma notations (Ta, Tb, and Tc); B-Outcrop photograph of Unit 7 showing sheet-like geometry; C-Outcrop photograph of Unit 7 showing basal inversely graded interval in coarse- to granule-grade sandstone; D-Outcrop photograph of a pocket of clasts and matrix in the middle of the unit. Arrow shows stratigraphic position of photo; E-Outcrop photograph of Unit 7 showing a floating mudstone clast in the middle of the unit. Annot Sandstone (Eocenee-Oligocene), Peira Cava area, French Maritime Alps, SE France. Figures compiled from Shanmugam (2002a). Publication: Earth-Science Reviews. With permission from Elsevier.

6. No one has ever documented the vertical facies model showing the R1, R2, R3, S1, S2, and S3 divisions of the Lowe (1982) sequence and the Ta, Tb, Tc, Td, and Te divisions of the Bouma (1962) sequence in ascending order (Fig. 21A) in modern deep-sea sediments.

Given these uncertainties concerning the fundamentals of coarse-grained turbidites, the link between bioturbation and high-density turbidity currents is incongruous. In short, bioturbation is of no process sedimentological significance for interpreting ancient deep-water turbidite facies, be it low-density or high-density types..



Total lack of empirical data for gravelly and sandy turbidity currents (i.e., high-density turbidity currents [HDTC])

Data Source & Information	Importance	Availability
Direct measurements (Modern oceans/Lakes)	Imperative	Absent
Sediment core (Modern seafloor)	Imperative	Absent
Flume experiments	Imperative	Absent
Theoretical models	Important	Abundant
Outcrop study (All turbidite facies are based solely on the study of ancient strata using outcrops)	Unimportant (The ultimate objective is to interpret ancient strata. Therefore, facies models derived from ancient strata, without validation from modern environments promote circular reasoning)	Most abundant

Fig. 21. A. Schematic diagram showing an ideal turbidite bed with nine turbidite divisions by combining the five divisions of the "Bouma Sequence" (Bouma, 1962) and the five divisions of the "Lowe Sequence" of high-density turbidites (Lowe, 1982). According to Lowe (1982), S3=Ta. On the right-hand column, interpretations of these divisions are shown. Figure from Shanmugam (2012). B. Summary diagram revealing the total lack of empirical data for high-density turbidity currents (see Shanmugam, 2012 for details).

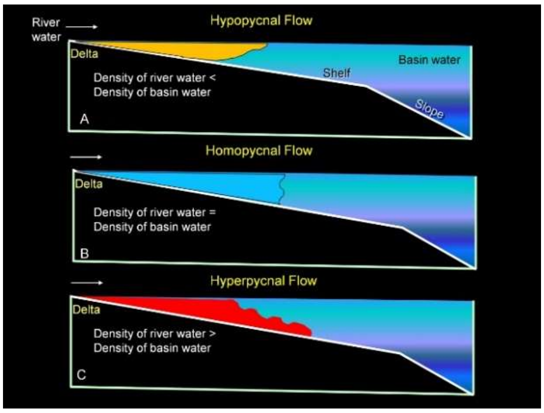


Fig. 22. Three types of density plumes based on concepts of Bates (1953). A. Hypopycnal plume in which density of river water is less than density of basin water. B. Homopycnal plume in which density of river water is equal to density of basin water. C. Hyperpycnal plume in which density of river water is greater than density of basin water. Figure From Shanmugam (2012).

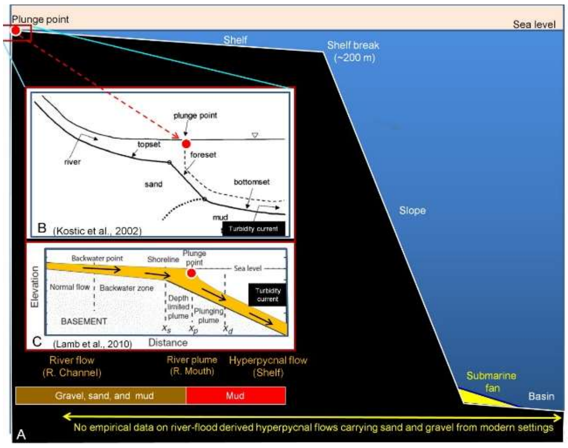


Fig. 23. Continental margin and flume experiments. A Conceptual diagram of a continental margin showing relative positions of plunge point (red filled circle) at river mouth and submarine fan at base-of-slope. Average shelf width = 80 km. Maximum shelf width = 1,500 km; B Schematic diagram, based on flume experiments conducted using fresh water as standing body, showing transformation of river current into turbidity current at plunge point (red filled circle). Note that this experiment using fresh water is applicable to fresh water lakes, but not to marine settings (sea or ocean). From Kostic et al. (2002) with additional labels; C Schematic diagram with backwater zone showing transformation of river plume into turbidity currents at plunge point (red filled circle). Note the close similarity between B and C on the initiation of turbidity currents at plunge point. In this study, the term "hyperpycnal flow" is used for flows seaward of the plunge point, instead of turbidity current. From Lamb et al. (2010) with additional symbols. From Shanmugam (2018b). Springer, Open Access.

Hyperpycnites

The term "hyperpycnite" (*i.e.*, deposits of hyperpycnal flows) was first introduced by Mulder *et al*. (2002) in an academic debate with me (Shanmugam, 2002b) on the origin of inverse grading by hyperpycnal flows. The importance of bioturbation in hyperpycnites has been discussed by several authors (Mulder et al., 2003; Buatois et al., 2011, among others). A brief review of hyperpycnites in terms of our understanding is in order.

Sedimentologic, oceanographic, and hydraulic engineering publications on hyperpycnal flows (Fig. 22) claim that (1) river flows transform into turbidity currents

Fig. 24. Dissipating plumes, Rio de la Plata Estuary, South America. From Shanmugam (2018c). Elsevier.

at plunge points near the shoreline (Fig. 23B)., (2) hyperpycnal flows have the power to erode the seafloor and cause submarine canyons (Lamb et al. 2010), and, (3) hyperpycnal flows are efficient in transporting sand across the shelf and can deliver sediments into the deep sea for developing submarine fans (Steel et al. 2016; Warrick et al. 2013; Zavala and Arcuri 2016) (Fig. 23A).

Importantly, these claims do have economic implications for the petroleum industry for predicting sandy reservoirs in deep-water petroleum exploration and production (Yang et al., 2017). However, these claims are based strictly on experimental or theoretical basis, without the supporting empirical data from modern depositional systems. In resolving this issue, Shanmugam (2018b, c) rigorously evaluated the merits of these claims by a global evaluation of density plumes that include hyperpycnal flows, based on 45 case studies that include 21 major rivers (e.g., Yellow River, Yangtze River, Copper River, Hugli River (Ganges), Guadalquivir River, Río de la Plata Estuary (Fig. 24), Zambezi River, among others). This global study suggests a complex variability in nature. Multiple flow types have been proposed (Fig. 25).

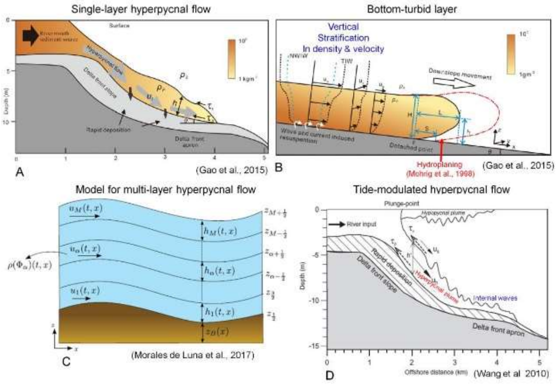
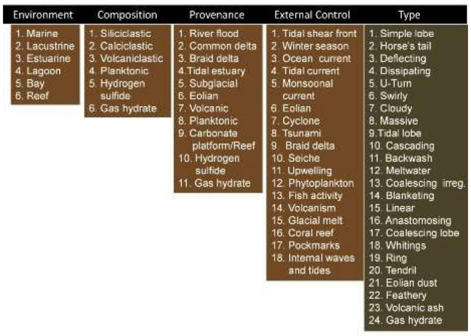


Fig. 25 Variable types of hyperpycnal flows. A Single-layer hyperpycnal flow, Yellow River, China. Color concentration = Suspended sediment concentration; h = Flow thickness; τt = Upper surface; τb = Bed shear stress. From Gao et al. (2015); B Bottom turbid layer with density and velocity stratification (i.e., debris flow with hydroplaning, red arrow added in this article, see text), Yellow River, China. Uw=Wave orbital velocity; Uc = Along shelf current magnitude; Ug = Velocity of gravity current; NWIW= Normal wind-induced wave velocity; TIW= Typhoon-induced wave. The red line represents the downslope variation trend of the bottom-turbid layer. From Gao et al. (2015) with additional labels; C Multi-layer hyperpycnal flow in numerical modeling (Morales de Luna et al. 2017). Note that multi-layer numerical modeling was also applied to hypopycnal flows. h = Height of a fluid layer; u = Velocity; ϕ = Particle concentration; ρ = Density. See Morales de Luna et al. (2017) for details of various parameters and related equations; D Tide-modulated hyperpycnal flow, Yellow River (Wang et al. 2010; modified after Wright et al. 1988), with permission from John Wiley and Sons. Color labels by G. Shanmugam. Note internal waves. Internal waves occur only along pycnoclines (Shanmugam 2013), but there is no indication of pycnoclines in this diagram.



Environment	Composition	Provenance	External Control	Type
1. Marine	1. Siliciclastic	1. River flood	1. Tidal shear front	1. Simple lobe
2. Lacustrine	2. Calciclastic	2. Common delta	2. Winter season	2. Horse's tail
3. Estuarine	3. Volcaniclastic	3. Braid delta	3. Ocean current	3. Deflecting
4. Lagoon	4. Planktonic	4.Tidal estuary	4. Tidal current	4. Dissipating
5. Bay	5. Hydrogen sulfide	5. Subglacial	5. Monsoonal current	5. U-Turn
6. Reef	6. Gas hydrate	6. Eolian	6. Eolian	6. Swirly
		7. Volcanic	7. Cyclone	7. Cloudy
		8. Planktonic	8. Tsunami	8. Massive
		9. Carbonate platform/Reef	9 Braid delta	9.Tidal lobe
		10. Hydrogen sulfide	10. Seiche	10. Cascading
		11. Gas hydrate	11. Upwelling	11. Backwash
			12. Phytoplankton	12. Meltwater
			13. Fish activity	13. Coalescing irreg.
			14. Volcanism	14. Blanketing
			15. Glacial melt	15. Linear
			16. Coral reef	16. Anastomosing
			17. Pockmarks	17. Coalescing lobe
			18. Internal waves and tides	18. Whitings
				19. Ring
				20. Tendril
				21. Eolian dust
				22. Feathery
				23. Volcanic ash
				24. Gas hydrate

Fig. 26. Summary diagram showing complex natural variability of plumes in terms of their environmental settings, their composition, their source, their external control, and types. This compilation of factors should be considered preliminary. For example, gas hydrate is included in more than one category. Modified after Shanmugam (2018b). Springer, Open Access.

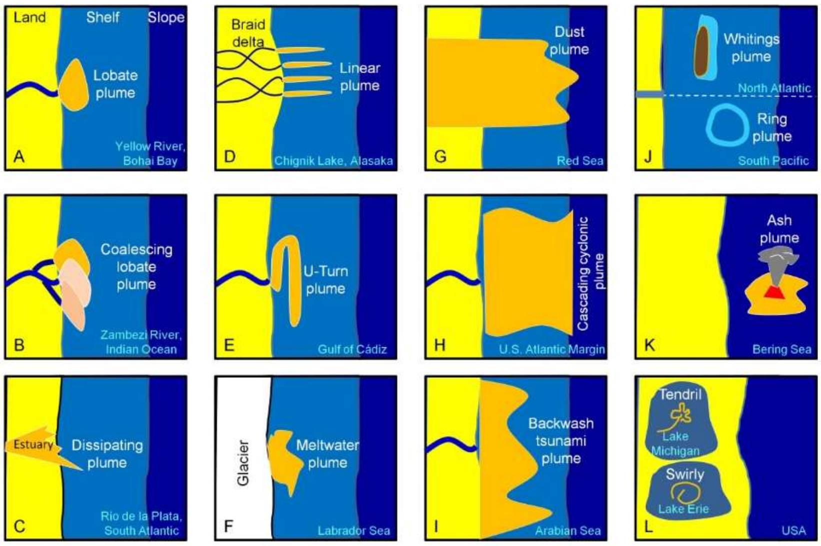


Fig**. 27.** Summary diagram showing 14 general types of plumes that include 12 marine examples and two lacustrine examples. From (Shanmugam, 2018b). Springer, Open Access.

For example, there are at least 16 types of hyperpycnal flows (e.g., density flow, underflow, high-density hyperpycnal plume, high-turbid mass flow, tide-modulated hyperpycnal flow, cyclone-induced hyperpycnal turbidity current, multi-layer hyperpycnal flows, etc.), without an underpinning principle of fluid dynamics (Shanmugam, 2018b).

A summary diagram (Fig. 26) of real-world examples show that density plumes (1) occur in six different environments (i.e., marine, lacustrine, estuarine, lagoon, bay, and reef); (2) are composed of six different compositional materials (e.g., siliciclastic, calciclastic, planktonic, etc.); (3) derive material from 11 different sources (e.g., river flood, tidal estuary, subglacial, etc.); (4) are subjected to 18 different external controls (e.g., tidal shear fronts, ocean currents,

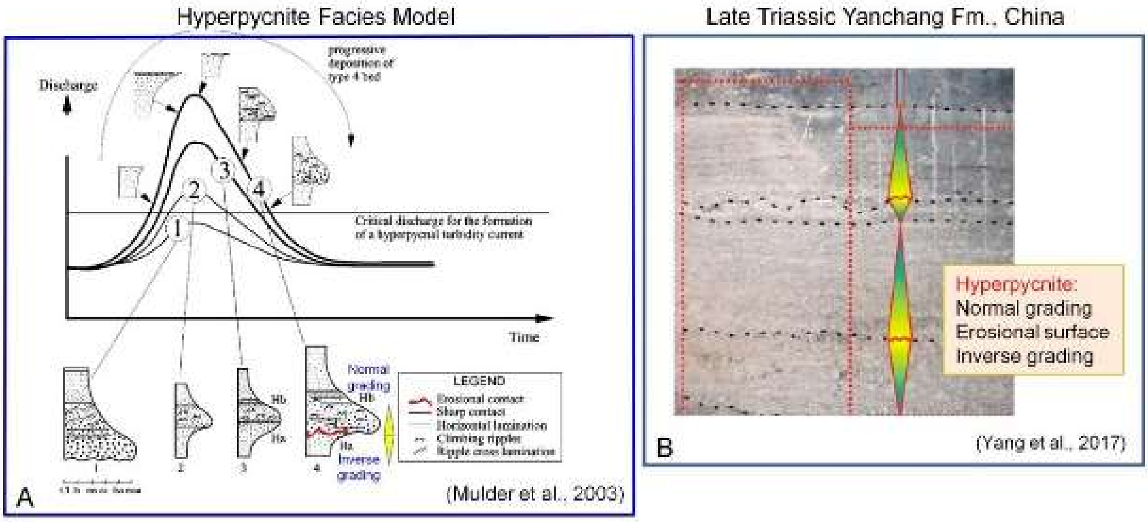


Fig. 28. A- Hyperpycnite facies model showing inverse to normal grading with erosional contact in the middle. In example 4 at the bottom, yellow triangles showing normal and inverse gradings are inserted by G. Shanmugam. From Mulder *et al.* (2003) with permission from Elsevier. B - An ancient example from China interpreted as a hyperpycnite showing inverse to normal grading with an internal erosional surace. The presence of an internal erosional surface within a single depositional unit by a single flow is antithetical to basic principles of stratigraphy and sedimentation (Krumbein and Sloss, 1963). The reason is that the presence of an internal erosional surface suggests that the lower inverse grading and the upper normal grading divisions could be deposited by two different events, separated by a hiatus. From Yang *et al.* (2017) with additional labels by G. Shanmugam.

cyclones, tsunamis, etc.); and, (5) exhibit 24 configurations (e.g., lobate, coalescing, linear, swirly, U-Turn, anastomosing, etc.) (Fig.26). These plumes do not transport sand from shoreline to the deep sea. The exceptions are cyclone, tsunamis, and eolian dust (Fig. 27).

In summary, available data do not support the notion that river-induced hyperpycnal flows transport sand across the shelf and deliver sand into the deep sea for developing submarine fans and related petroleum reservoirs.

Like turbidite and contourite facies models, hyperpycnite facies model (Fig. 28) suffers from numerous uncertainties (see Shanmugam, 2018b). Because there is no documented link between fluid mechanics of hyperpycnal flows and bioturbation, the presence of ichnological signatures in hyperpycnites is of no consequence from a depositional process viewpoint.

Concluding Remarks

Deep-water depositional facies are highly complex in their sedimentary features. This is because of a combination of factors, such as soil mechanics, fluid mechanics, elements of physical oceanography, etc., which influence deposition. Deep-water settings are prone to develop hybrid flows and, importantly, the link between flow mechanics and ichnology is an unknown entity yet. Amid these challenges, the promotion of ichnological signatures in a specific deep-water facies is of no depositional relevance.

Acknowledgements:

The late George Devries Klein (1933-2018) served as my mentor and friend during the past 40 years. I thank Prof. G. M. Bhat, Managing Editor of JIAS, for organizing this special issue in celebrating the contributions of George Klein. I wish to thank the journal reviewer Nallappa Reddy for a thorough review. I am grateful to my wife Jean for her general comments.

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Petroleum Potential of the West Coast of India

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Abstract: This paper suggests that high oil potential exists for the outer shelf/slope of Kutch, Saurashtra, and Mumbai offshore basins along the western Indian margin. During the early rifting (Late Cretaceous/Early Tertiary), area seaward of these offshore basins developed into a restricted seaway bordered by the Indian margin to the east, Laxmi Ridge to the west, an arm of the newly forming Mid Indian-Ocean Ridge to the north, and an extension of the Laccadive Ridge to the south. This narrow basin was filled by early-rift lagoonal and fluvial sediments. During the transition to post-rift (drift) stage, these sediments were buried by fine-grained clastics of the Indus Fan or sediment-gravity flows from the Indian peninsula. The total sediment thickness and the type of crust underlying the outer margin suggests that hydrocarbons were probably generated and migrated to traps that formed along the margin. In this regard, the existing production in the Mumbai offshore basin represents only the *distal* and *youngest* parts of the migratory path. Larger accumulations, closer to the kitchen area, should be expected in the earliest sedimentary sequences. In contrast, the southernmost of the marginal basins along the western coast of India, the KKL basin, did not go through a "restricted basin" phase and hence it is probably gas prone.

Keywords: Deep-water Hydrocarbon Potential, Western Indian margin, Early rifting history, Saurashtra/Mumbai offshore basins

Introduction

In 2013, India imported 85% of its oil. This dependence on imports has increased from 76.5% in 2005. Although oil prices have declined since 2015, but they bounced back in 2018 and the annual import bill for India may be in the US $80-100 billion range. This cost will only rise as the oil prices recover. Because the Indian economy has been growing fast in the past decades, the demand for oil and gas is expected to increase steadily in the nearby future (IEA,2015). In fact, quoting from International Energy Agency's World Outlook, Thambi (2017) mentions that the oil demand in India will increase by more than *four* times by 2040.

While the demand for oil and gas in India has increased due to the industry needs, exploration activity in the country has not kept pace. Almost 75% of India's sedimentary basins have yet to be adequately explored; and 50% of these basins do not have sufficient geological and geophysical data to assess their exploration potential.

In 2015, the proven oil reserves were less than 6 billion barrels and the gas reserves were 47 trillion cubic feet. At the same time, in 2011, the US Geological Survey estimated that the *mean undiscovered hydrocarbon* resource from just four major basins of India (Assam, Cambay Delta including Barmer Basin and Bombay Shelf, Krishna-Godavari, and Cauvery including Sri Lanka Shelf) amounts to 5.2 billion barrels of oil and natural gas liquids; and almost 80 trillion cubic feet of gas (Klett, et al. 2012). In other words, there is the potential to *double* the existing reserve base of India from further exploration in just a few selected basins. This paper primarily focuses on the potential to add significant resources from the basins on the *western coast* of India.

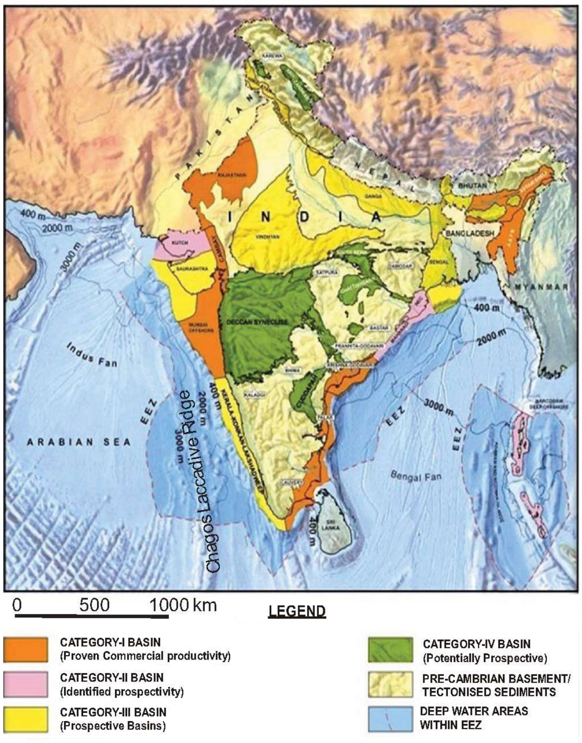

Figure 1. Map showing the sedimentary basins of India and features of the adjoining oceanic areas. The basins are color-coded (and categorized I, II, III or IV) on the basis of their prospectivity for hydrocarbons (Directorate General of Hydrocarbons, 2016). The north-south trending ridge offshore of the western Indian margin, between the 2,000 and 3,000m contours, is named the Chagos-Laccadive Ridge. Further details in text.

Based on the reinterpretation of published data, an opening model for the northern part of the western Indian margin is presented. As discussed later, the geometry of this part of the Indian margin might have been analogous to the early opening of the South Atlantic. Additionally, although a few researchers have addressed this for some segments of the worldwide margins including India's, the edge of continent-ocean boundary and its impact on the petroleum potential for the Western Indian margin has not been adequately discussed in the geological literature (e.g., Cornfield et al., 2010; Nemčok and Rybár, 2016) These concepts call for a new look at the Western Indian margin, and it is hoped that those who possess proprietary data will critically evaluate this model for further exploration in this area. As discussed later, examples exist in other parts of the world's margins where the *deep* and *ultra-deep* parts of the margins have the highest potential and unfortunately, that is where the Indian margin is woefully under-explored.

Regional Geology of the Western Indian Margin

As shown in Figure 1, the basins on the West Coast are: from North to South, Kutch (Identified prospectivity), Saurashtra (Prospective basin), Mumbai Offshore (Proven commercial productivity), and Kerala-Konkan-Lakshadweep (KKL) (Prospective basin) (see Categories in Fig 1, Directorate General of Hydrocarbons, 2016). So far, the Mumbai offshore basin is the only offshore basin among these with commercial production (Category I) although the Kutch offshore is expected to become Category I in the near future (Isaacs, 2017)

The western continental shelf and slope, to a depth of 400m, extends a few tens of kilometres in the south, near the Chagos-Laccadive Ridge, but widens northward to about 300 km across the Mumbai offshore basin (Figure 1). Beyond 400m depth, sediments of the Indus Fan overlie the deeper regions of the western offshore, primarily in the north. The most prominent feature of the western margin is the north-south trending Chagos-Laccadive Ridge which extends northward from the southern Indian Ocean and merges into the Indian margin approximately along the boundary between the Mumbai offshore basin and the KKL basin (Fig 1). The Chagos-Laccadive Ridge has been interpreted as a "hot-spot related" ridge and thus is underlain by oceanic crust (Talwani and Reif, 1998, Arora et al., 2012).

Table 1 lists the areas of the basins on the west coast of India and the number of exploratory wells in each. It is clear that the drilling density in these basins is quite low and the basins are very underexplored. In fact the number of wells between the 400- and 2000-m water depths along the entire >1,500 km margin is less than a dozen (Directorate General of Hydrocarbons, 2016). However, a fair amount of modern long-offset seismic data has been collected along the Indian margins and the Directorate General of Hydrocarbons (2016) has initiated a "Re-assessment of Hydrocarbon Resources of India" starting in October, 2015. This study incorporates all existing geological, geophysical and geochemical data and will include basin modeling . The results of this re-assessment are not yet available in public domain. Hence, it is too early to suggest that geological conditions including source, reservoir, trap and timing for large accumulations are not favourable in the deep margin. This paper presents arguments, based on published data and analogy from other margins, that on the contrary, the deep margin should be highly prospective.

Basin	**Offshore Area (Sq km)***	**No. of Exploratory Wells**	**Current Status**
Kutch	**42,000**	**25**	**3 disc, possible production by 2020**
Saurashtra offshore	**360,000**	**31**	**minor shows**
Mumbai Offshore	**174,000**	**115**	**25 producing fields**
Kerala-Konkan-Lakshadweep	**870,000**	**14**	**oil and gas shows**

Table 1. Offshore Basins on West Coast of India

source: http://dghindia.gov.in/index.php/page?pageId=67

**** The NDR source gives areas to 200m; area to 2,000m has been estimated using worldwide averages***

Tectonic Elements of the Western Indian Margin

Figure 2 is a tectonic map of the Indian offshore provinces along the west coast (modified from Roberts et al., 2012). Along the southern part of the margin, the Laccadive Ridge (Roberts et al., 2012) is separated from the shelf by an intervening rift zone and a basinal area (Lakshadweep Basin and Kori-Comorin Depression) (Figure 2). Farther north, a linear tectonic feature, the Laxmi Ridge, is separated from the Saurashtra offshore basin area by the Laxmi Basin. Another linear feature, the Kori-Comorin Ridge, forms the eastern boundary of the Laxmi Basin. To the east of the Kori-Comorin Ridge lies the northern extension of the Lakshadweep Basin, essentially straddling the area between 400- and 2,000m isobaths.

Based on gravity and crustal modeling and their trends, Talwani and Reif (1998) have pointed out that the Laxmi Ridge is *not* a north-westward extension of the Laccadive Ridge. Additionally, they have suggested that whereas the Laxmi Ridge appears to be a continental fragment, the latter is a hot-spot related ridge consisting of oceanic material (see also Arora et al., 2012). The significance of the nature of the underlying crust in the context of petroleum assessment of the western Indian margin is discussed below (see also Nemčok and Rybár, 2016).

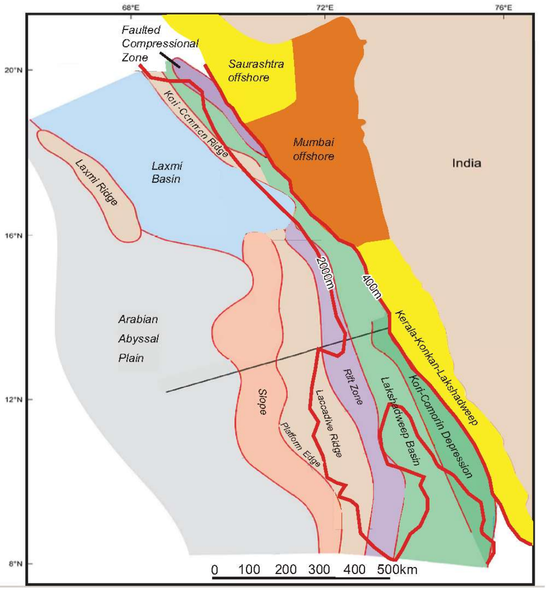

Figure 2. Tectonic elements on the west coast of India (modified from Roberts et al., 2010). The 400- and 2,000m bathymetric contours and the basin outlines are from Figure 1. The Laccadive Ridge (also referred in some publications as the Chagos-Laccadive Ridge) is also shown. The location of section (NE-SW line) is shown here for reference and will be discussed later in this paper.

Continent-Ocean Boundary

One of the most common tenets of petroleum occurrence is that large accumulations of hydrocarbons can only occur over continental crust. Generally, this may be true because sediment thickness over continental crust generally is greater than over oceanic crust, presence of source rock is more likely before a rifted margin evolves into an open marine stage, and the earth's heat flow through the continental crust is up to 2 times greater than through the oceanic crust. However, basin modeling by Rajmon and Egorov (2015) suggests that given sufficient sediment thickness and *time* (another critical factor for source-rock maturation, other than the heat flow), source rocks over oceanic crust could also reach sufficient maturity level to generate oil. According to their model (Rajmon and Egorov, 2015), the thermal maturity necessary to generate oil might be reached at a depth of > 2.8 km when the underlying crust is 20 km thick (extended continental crust). Their model predicts that the same level of maturity would be reached only at depths of 5km or more when the underlying crust is 6km thick (oceanic crust). and for the "transitional" crust, the requisite burial depth would be somewhere between 3 and 6 km. Other authors (e.g. James, 2011) have suggested that most of the deep and super-deep oil and gas accumulations (in water depths of >2 km) occur on "stretched" or "extended" (transitional) crust (~15 km thick). Accumulations in the Niger Delta, and recent discoveries offshore East Africa, represent examples of oil accumulations in transitional or oceanic crust (Rajmon and Egorov, 2015, Brownfield, 2016a,b).

Although a detailed discussion of the nature of continent-to-ocean transition is beyond the scope of this paper (see Nemčok and Rybár , 2016 for a discussion along the western Indian margin), as suggested above, the prospectivity of western Indian margin does not have to be limited to non-extended continental crust. Figure 3 is a map showing the continent-ocean boundary (COB) as mapped along the western Indian margin. The solid green line, labelled COB (from Seton et al. 2012) generally occurs along the region seaward of the 400-m bathymetric contour. This is the boundary used by Seton et al. (2012) in their worldwide plate reconstructions. In the gravity models published by Arora et al. (2012), the crustal thickness at this boundary, at approximately 30-km, is assumed to be non-extended.

The COB (Gravity) from Arora et al. (2012) is located significantly seaward of that from Seton et al. (2012) and where the crustal thickness is generally 15 km or more. Arora et al. (2012) have termed this COB as the seaward edge of "transitional" crust. Other authors (e.g. James, 2011) have termed this type of crust as "stretched" or "extended".

The crust in the Laxmi Basin has been suggested to be oceanic with sea-floor spreading magnetic anomalies (see summary and discussion in Ramana et al., 2015). However, Pandey and Pandey (2015) have examined the question of the nature of the crust in Laxmi Basin and have considered various models. Their study has also used long-offset multichannel seismic data that images deep crustal layers. They conclude that the crust in Laxmi Basin is indeed a stretched and thinned continental crust which was intruded by sub-continental mantle material. Hence, for the purpose of this study, we have assumed the Indian margin landward of the COB (Gravity) line to be of a transitional nature. Calves et al (2011) and Nemčok and Rybár (2016) on the basis of gravity modeling and seismic-reflection data also support this conclusion.

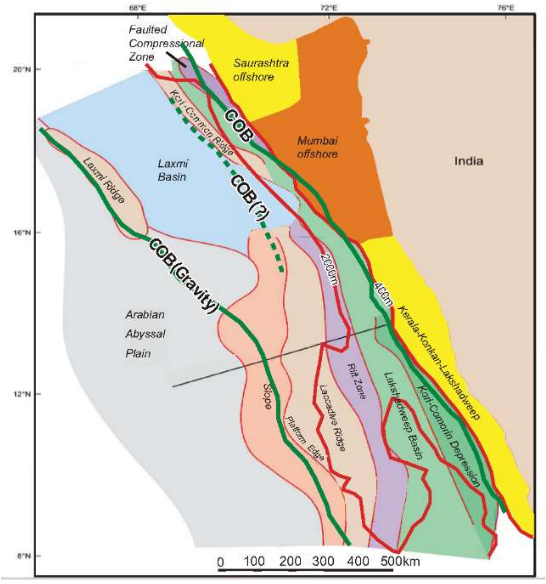

Figure 3. Tectonic elements on the west coast of India (modified from Roberts et al., 2010). The 400- and 2000m bathymetric contours and the basin outlines are from Figure 1. COB (continent-ocean boundary) has been added from Seton et al. (2012). The COB (Gravity) and COB (?) (dashed-green line) boundaries have been added from Arora et al. (2012). The COB (Gravity) is much farther seaward and could only be interpreted as the seaward edge of an extended continental crust. The dashed COB (?) has been suggested as marking the eastern edge of Laxmi Basin when the Laxmi Ridge separated from the Indian margin as a continental sliver (Talwani and Reif, 1998). Further details in text.

Sediment Thickness and Source/Reservoir considerations along the Western Indian Margin

One of the most critical parameters for oil and gas generation is sufficient sediment thickness so that source rocks are buried deeply enough to mature and expel hydrocarbons. Under most circumstances the minimum sediment load needed is 2km (for an approximate 50^0 C subsurface temperature, McCarthy et al., 2011), a depth at which available organic material would start generating hydrocarbons. Figure 4 shows isopachs of total sediment thickness along the western margin of India (blue lines). The 2km isopach is located seaward of the 400m depth by at least 100km or more along the entire western margin. This would suggest that given s*ufficient circumstances* to deposit source-rock material along the margin in deep waters (at least to 2,000m water depth) and extending on to the shelf, there should be sufficient overburden to generate hydrocarbons. However, the presence of source and reservoir rocks along the deep margin is poorly known. Figure 4 shows the relatively few wells that have been drilled in deep water (>400m) and the existing commercial accumulations in relatively shallow waters in the Mumbai offshore basin. In a study of the source rocks in the deep water along the Indian continental margin Pande et al. (2008) found that development of source facies seems to be poor in Tertiary sediments in the drilled deep-water locations along the western margin. However, their modeling studies demonstrated that Cretaceous and early Palaeocene sediments along the Kutch/Saurashtra basins and Early/Late Cretaceous sediments along KKL basin should be in the oil window. The oil generation activity is aided by intrusive activity in their model (Pande et al., 2008). However, the sample density, especially in the Cretaceous sediments, is very poor to discount the presence of source rocks in the deep water along the western Indian margin.

Figure 5 A is a tracing from a multichannel seismic line (Location on Fig 4), modified from Pandey and Pandey

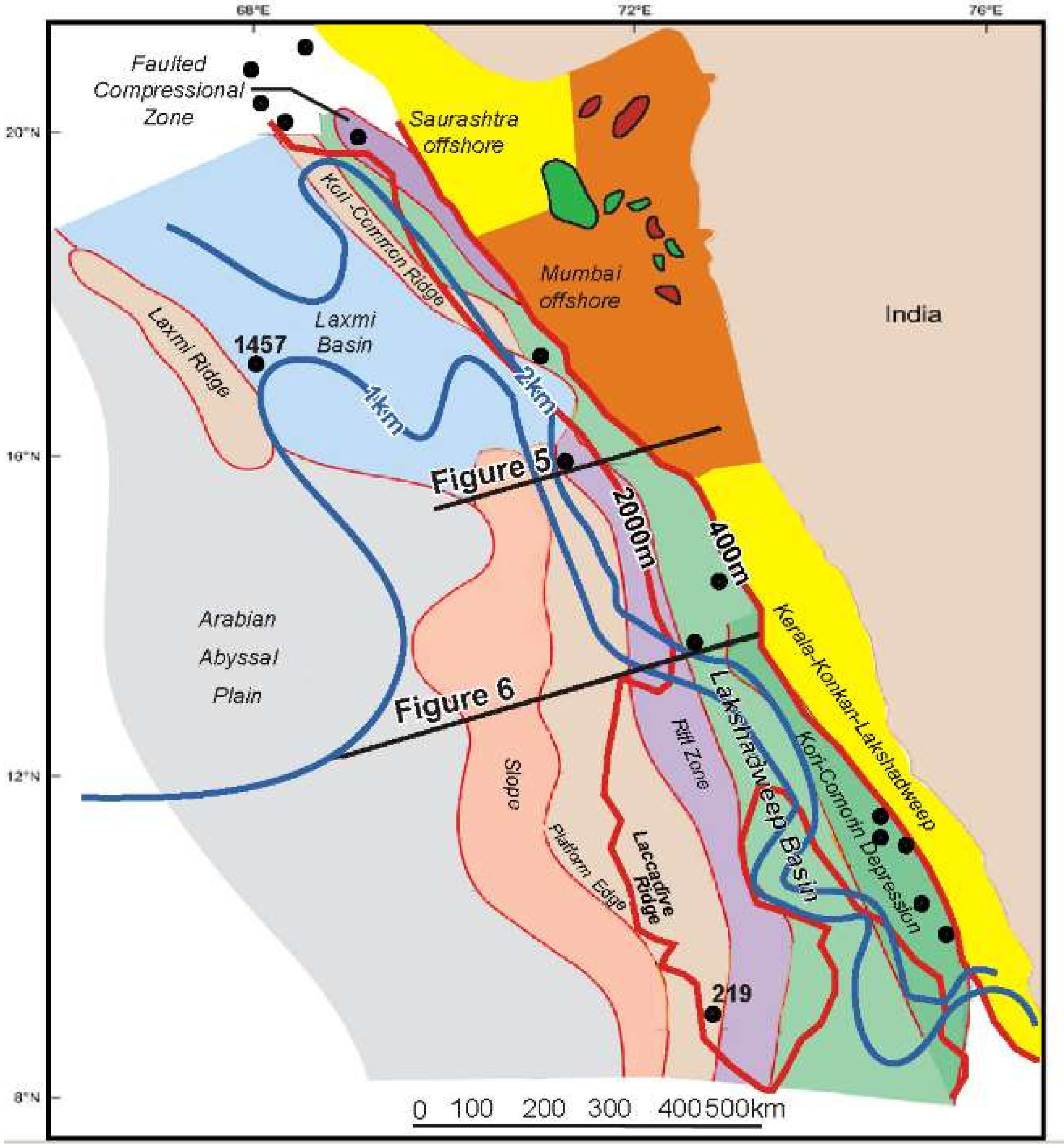

Figure 4. Tectonic elements and sediment thickness on the west coast of India (modified from Roberts et al., 2010). The 400- and 2000m bathymetric contours and the basin outlines are from Figure 1. Total sediment thickness (blue lines) of >1 km and >2 km are shown. These isopachs are based on worldwide sediment thickness map of Whittaker et al. (2013) and gravity-modeled sediment thickness along the western margin of India from Arora et al. (2012). Lines marked Figures 5 and 6 show the locations of the tracings from multichannel seismic lines in the next two figures. Black dots show the locations of exploratory wells drilled in waters deeper than 400m. Locations of Site 219 and 1457 farther offshore are also shown. Existing fields in the Mumbai offshore basin shelf are shown in green (oil) and red (gas) (DGH, 2016). Further details in text.

(2015). The line extends southwest from the Mumbai offshore basin shelf across the southern end of the Laxmi Basin. A series of faults and half grabens mark the region around 2,000m water depth. A series of detachment faults creates fault blocks located over the zone marked as stretched continental crust. Seaward of this zone, the crust is identified as transitional with intrusions (sills) and fault blocks containing relatively thin sedimentary sequence.

The outlined area of Figure 5A is shown in an enlarged view as Figure 5B. Two prominent unconformities are marked in Fig 5A: Rift Onset Unconformity (ROU), which separates pre- and syn-rift strata, and Breakup Unconformity (BU), which separates syn- and post-rift strata. According to Pandey and Pandey (2015), the rift basins show three syn-rift sequences: R1, earliest sediment that have been deposited, perhaps of late Palaeocene age, R2, possible carbonate build ups in these basins, and R3, representing clastics of perhaps Early-Eocene age. The blue marker in Fig 5B marks the BU (early-middle Eocene), separating the syn-rift from post-rift sequences. As shown in Figure 5B, the syn-rift sediments in the Laxmi Basin

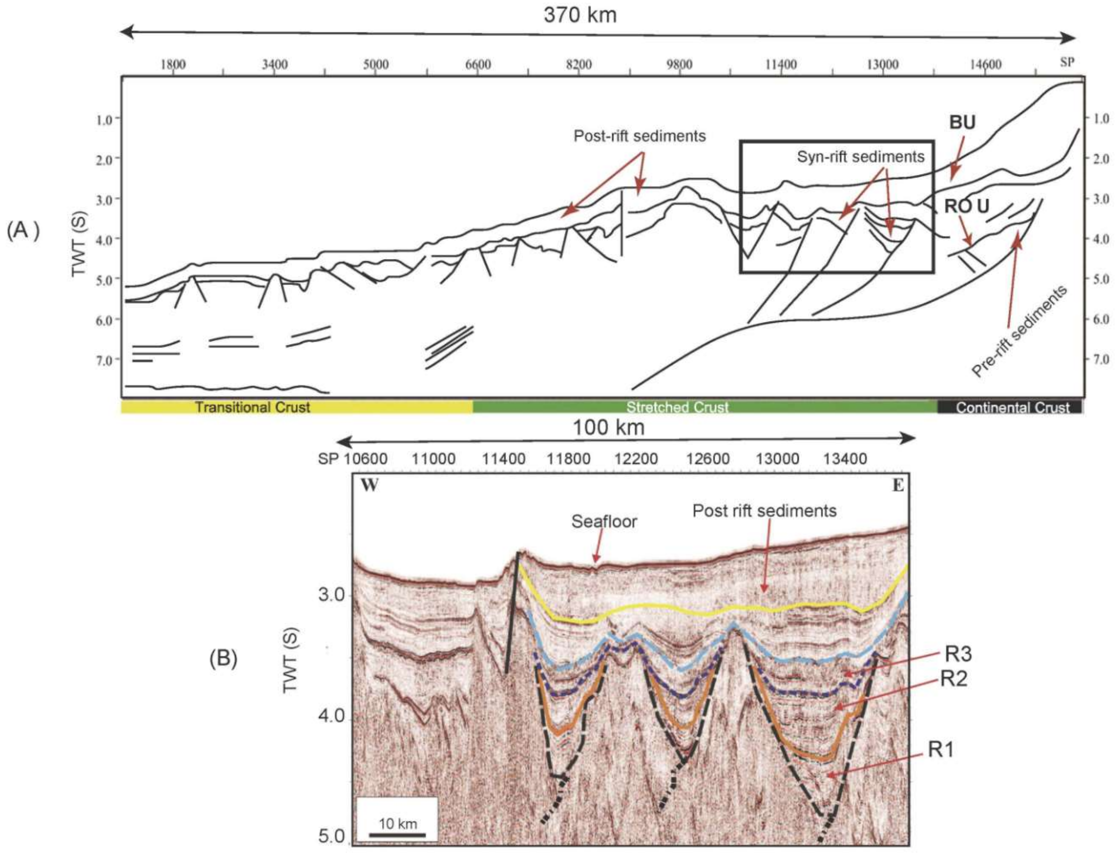

Figure 5. Multi-channel seismic line from the Mumbai offshore basin extending southwest into the southern edge of Laxmi Basin. Location shown in Figure 4. ROU is Rift-onset unconformity. BU is Break-up unconformity. See descriptions of R1, R2, and R3 sequences in text. Blue line in 5B marks the boundary between syn-rift and post-rift sediments. Yellow horizon is interpreted as middle-Miocene in age (modified from Pandey and Pandey, 2015).

were deposited onto growth faults while continental extension was underway. The total syn-rift sedimentary section itself is at least 2 to 3 km or more in thickness. A younger reflector (yellow), has been interpreted as middle Miocene in age marking an enhanced input of clastic sediments in the margin during the post-rift stage.

Just as in case of source rocks, existence of suitable reservoir rocks is limited by very few data points. It appears that the Eocene and younger sediments are mostly fine-granined and Oligocene sequence is very thin (Pande et al, 2008). However, the model discussed later would call for granite wash (Pande et al., 2008) and weathered basalt and coarser clastics deposited during the late Cretaceous/Late Palaeocene (R1 sequence, Figure 5B) to contain plausible reservoir rocks. And those are also the sequences that would have direct access to any matured source rocks. The depositional hiatus during Eocene or Mid Miocene (sequence R3 or yellow reflector, Figure 5B) would not impact the maturation and migration as that occurs only in late Tertiary, as shown by the modeling carried out by Pande et al. (2008).

Figure 6 is a tracing of a multichannel seismic line, extending from the KKL basin offshore in to the Arabian Abyssal Plain (modified from Scaife, 2012). This line also shows grabens filled with possibly synrift Mesozoic sediments (shown in orange). The transition from syn-rift to post rift occurs sometime during the early Tertiary (L. Miocene to Base Tertiary shown in blue), and post-rift sediments form the youngest part of the sequence (shown in yellow). This line also shows the Laccadive Ridge, which almost reaches the sea-level. As mentioned earlier, this is most likely an intrusive feature related to magmatic activity at a hotspot (Talwani and Reif, 1998) and not integrally a part of the extended transitional crust along the western margin of India.

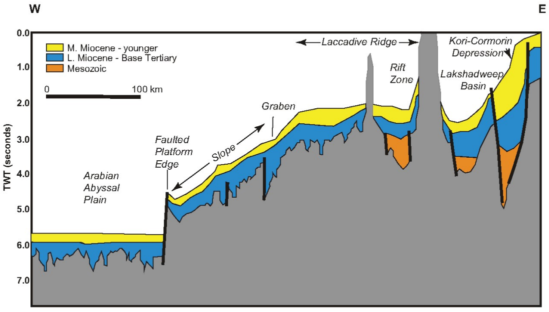

Figure 6. Tracing of multi-channel seismic line from the Kerala-Konkan-Lakshadweep (KKL) basin extending southwest into the Arabian Abyssal Plain (Location on Figure 4, modified from Scaife, 2012). The inferred age interpretation of the sedimentary section is shown in Orange (Mesozoic), Blue (L. Miocene - Base Tertiary), and Yellow (M. Miocene- younger). The total sedimentary thickness shown is 3 seconds of Two-way Time (approximately 3 km or more). Further details in text.

Petroleum Systems in Western Indian Offshore Basins

Because of sparse deep-water drilling in the offshore western Indian basins, the ages and lithologies of the oldest sediments in these basins is poorly known. In the Saurashtra offshore basin, there are less than half a dozen wells. Of course, in the Mumbai offshore basin, commercial production and development has been ongoing on multiple oil and gas fields (Figure 4), but even here, the deepest parts of basin remain untested. For the KKL basin, a total of 14 wells are listed on the Directorate General of Hydrocarbons website (dghindia.gov.in) (see Table 1 and Figure 4).

Figure 7 is a simplified stratigraphic chart for the western offshore basins (Roberts et al., 2010, Scaife, 2012). The chart identifies potential source rocks of Triassic (?), Early Jurassic, Late Jurassic, and early-Cretaceous ages. Potential reservoir rocks might be present in the Triassic, Jurassic, Early Cretaceous and Early Tertiary-age rocks. However, the correlation of stratigraphy on the shelf with that of deep water is still mostly speculative because of paucity of deep-water drilling (Figures 4, 5, and 6). The Deccan lava flows at the Cretaceous-Tertiary boundary overlie the youngest potential source rocks of Early Cretaceous age. Although Deccan lava flows cover a large area onshore (approximately coinciding with the Deccan Syneclise basin, Figure 1), the extent of these lavas offshore had not been known until the modern multichannel, long-offset seismic data became available offshore western India (Biswas, 2012, Bastia and Radhakrishna, 2011). However, because of the presence of Deccan Traps, the quality of data, as well as its interpretation has been problematic until recently. Some of the recent long-offset multichannel seismic data, coupled with gravity modeling, is giving some insight on pre-basalt sequences (Corfield, 2010, Calvès et al, 2011, Scaife, 2012, Nathaniel, 2013).

Drilling information in public domain from the deep water (e.g. DSDP Site 219 and IODP Site 1457, Shipboard Scientific Party, 2007 and Pandey et al., 2016, respectively, Fig. 4) does not help much in correlating the shelf stratigraphy to the deep margin. Site 219 is located in the rift zone of the Laccadive ridge and has received primarily pelagic sediments, the deepest penetration being of Late Palaeocene age (Shipboard Scientific Party, 2007, Fig 4). The IODP Site 1457 is located in more than 3,500m of water depth at the western edge of Laxmi Basin and the oldest sediments penetrated were of Early Palaeocene age (Pandey et al., 2016, Fig 4).

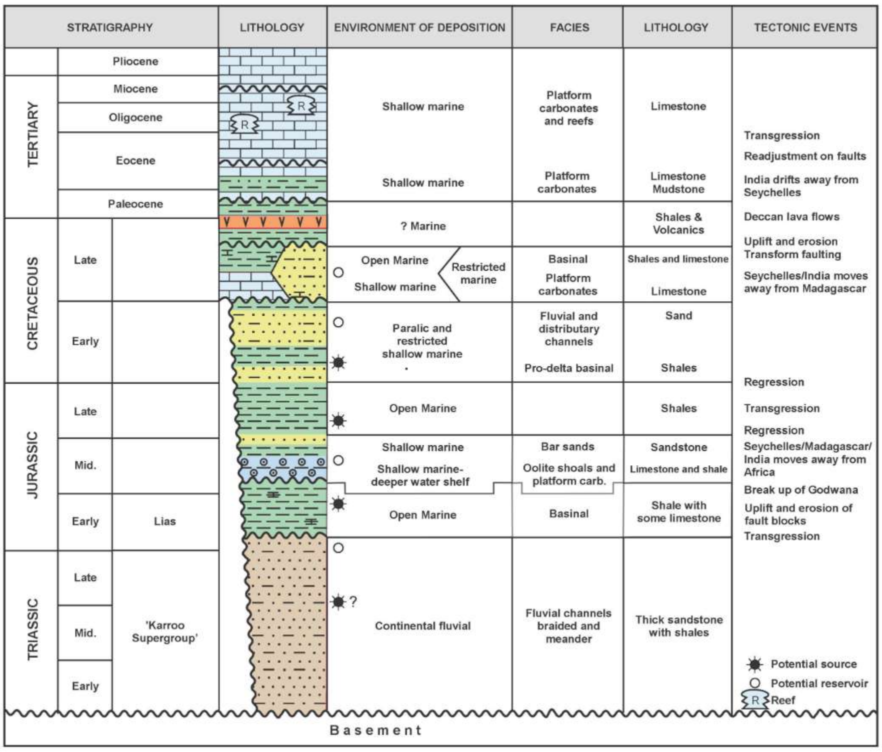

Figure 7. Simplified lithostratigraphy of western margin basins offshore India (from Roberts et al. 2010, and Scaife, 2012). The chart also identifies sequences that could be potential source beds and potential reservoir beds. Further details in text. However, with the existing data it is not possible to correlate this stratigraphy to the deep water (Figures 5 and 6).

As described later, the potential source rocks present on the shelf of Late Jurassic/Early Cretaceous age would be expected to be present in the deep water while the early-rift basin had restricted circulation. The potential reservoir rocks of Early/Late Cretaceous might be present as early sediment-gravity flows in deep water. The Late Cretaceous/Early Tertiary carbonates possibly extend into deep water. During sea-level drops these carbonates probabably generated secondary porosity that could have been preserved (Pande et al., 2008). With very limited drilling data, the offshore stratigraphy in deep water is yet to be firmly established.

Model for Petroleum Generation during the Synrift stage of Passive Margins

In recent years, petroleum formation and migration during the early stages of "Atlantic-type Margins" has received a lot of attention because of very large Pre-salt discoveries in the Brazilian marginal basins (Mohriak, 2015). This stage is especially favourable for source-rock generation as the ocean is narrow with restricted circulation. Following the early lacustrine stage, there were ample opportunities for carbonate and clastic reservoir rocks to be deposited. The overlying salt creates a very efficient seal for the early synrift petroleum system. Mohriak (2015) has identified this model not only for Cretaceous-age Brazilian accumulations but also for the north Caspian Carboniferous accumulations. In addition, potential analogues are also present in the Gulf of Mexico, North Atlantic, West Africa, and Red Sea (see also Martin et al., 2009). However, in the absence of a salt layer, the early syn- rift, fluvial/lacustrine system may be sealed by fine-grained clastic sediments. Beglinger et al (2012) have described a model for conjugate basins along both sides of the South Atlantic and have predicted various facies that should be present during each stage of the basins formation: Prerift, Synrift, Transitional, and Postrift. Presence of salt as a seal, while helpful, is not required.

Recently, Hodgson et al. (2016) , on the basis of extensive dataset of long-offset seismic data, have proposed a model for hydrocarbon generation and trapping for the *entire* South Atlantic. Although, the northern South Atlantic has a salt layer that acts as a seal, in their model, it is not necessary for trapping as the southern part of South Atlantic (offshore Uruguay/Argentina and Namibia/South Africa) does not have a salt layer. In this model, the source rocks were deposited during the early rifting in a restricted-circulation basin. The reservoir rocks consist of basin-floor fans deposited in deep water directly after the source rocks were deposited. The geometry of the sediments provides opportunities for trapping and the depth of burial is sufficient in their model to generate hydrocarbons (Hodgson et al. 2016).

In the equatorial Atlantic, in the Guyana-Suriname basin, recent exploration activity and discoveries have also established a petroleum system with large commercial accumulations (CGX, 2015). The source rocks are proposed to be of Mid-Jurassic age, and the reservoirs are of Albian age (Griffith, 2017). This model proposes the seals to be transgressive shales with migration taking place through faults (Griffith, 2017).

Recent discoveries along the east coast of Africa (Mozambique, Tanzania) have confirmed that the syn-rift segments of these margins (Brownfield, 2016b) have the requisite source, reservoir, and seal components to form significant gas accumulations. Although an extensive salt layer is not present, minor deposits of salt are present in the late Jurassic-age rocks of Mozambique, coastal Tanzania, and Seychelles (Brownfield, 2016b). However, the primary seals are formed by marls and shales. In addition, syn-rift sections in conjugate western Madagascar basins also appear to have well-developed petroleum systems (Tyrrell et al., 2014). The possibility of syn-rift petroleum systems in the deep parts of Saurashtra offshore and Mumbai offshore basins need to be investigated in the context of the early opening history of this part of the western Indian margin.

Early Opening History of the Kutch to Mumbai Offshore Segment

At 67.6Ma, the Laccadive Basin "axis-of-divergence" had initiated its northward propagation from the Laccadive Ridge and the southern part of the Indian continental block (Bhattacharya and Yatheesh, 2015) (Figure 8). According to these authors, this propagation formed the Laxmi Basin between the southern India block and the NW-SE trending Laxmi Ridge. These authors suggest that the divergence in this basin reached the seafloor-spreading stage. However, as mentioned earlier in the paper, on the basis of gravity data and the crustal thickness in the basin, it appears that the crust in the Laxmi Basin did not reach that stage but remained a thinned continental crust (see also Nemčok and Rybár ,2016).

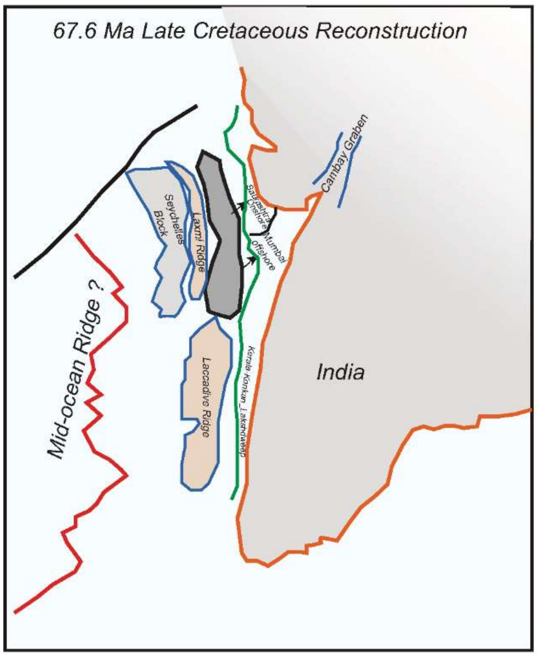

Figure 8. 67.6Ma, Late Maastrichtian, reconstruction of the Western Margin of India (modified from Bhattacharya and Yatheesh, 2015). Green line is the COB, as shown in Figure 3 and others. The basin outlines are the same as shown in Figure 2 and others. The initial extent of Laxmi Basin is shown as the shaded area between the Laxmi Ridge and the Indian continent-ocean-boundary (COB). Arrows show the proposed direction of regional hydrocarbons migration from the early syn-rift basin. Further details in text.

We can visualize a relatively narrow north-south trending basin, bordering the Indian block adjacent to the present day Kutch, Saurashtra, and Mumbai offshore basins (Fig 8). This basin had a restricted circulation created by a possible fracture zone in the mid-ocean ridge to the north, and a lack of space between the Indian margin and the Laccadive Ridge to the south (Figure 8).. Under such circumstances, early sedimentary environments would produce organic-rich lagoonal and fluvial- lacustrine environments, a setting analogous to that proposed by Hodgson et al (2016) for the southern South Atlantic and other locations, such as Guyana-Suriname basin (Griffith, 2017). In the Western Indian continental margin, the seal should have been provided by either fine-grained clastics, or by the lava flows that covered the margin at the end of the Cretaceous (Figure 7).

The model proposed here allows for migration of hydrocarbons generated in the Late Cretaceous/Early Tertiary sequences in the continental margin along Kutch, Saurashtra and Mumbai-offshore basins. Although the commercial production in the Cambay Graben and in the Mumbai offshore is from the Tertiary reservoirs (Figure 4, DGH, 2016), it is quite possible that some of this oil is sourced from the older Late Cretaceous/Early Tertiary source rocks. Migratory path along faults and unconformities would allow hydrocarbons to migrate in Palaeocene/Eocene-age traps as well as in younger reservoirs of late Tertiary age on the shelf (Figure 4). This implies that deeper sequences in water depths of 400-2000m would have a higher probability of capturing these hydrocarbons. Unfortunately, hardly any exploration activity has taken place in the deep waters of Kutch, Saurashtra, and Mumbai-offshore basins (Figure 4).

Evolution of the Kerala Konkan Lakshadweep Basin

In contrast to the basins farther north, the southernmost of the basins, the KKL basin, remained relatively open during the initial opening of the western margin of India (Fig 8). Although the Laccadive Ridge formed the western boundary of the basin, the basin was open to oceanic circulation at least in the south. Therefore, more than likely it probably did not develop the lacustrine source rock suggested to have formed offshore from the Kutch, Saurashtra, and Mumbai offshore basins. However, black shale occurrence has been reported south of Sri Lanka in one of the Deep Sea drilling sites (Munroe and Gill, 2008) As described below, the KKL basin contains sufficient sediment thickness to generate hydrocarbons. The potential source rocks might be primarily terrigeneous or terrigenous mixed with marine carbonates, and thus being gas prone (McCarthy et al., 2011).

Figure 9A shows the total sediment thickness in the KKL basin and also the maximum sediment thickness along the outer shelf and slope, which probably ranges from 3 to 4 km . Besides using the worldwide sediment thickness data, as used by Whittaker et al. (2013), and gravity data of Arora et al. (2012), Campanile et al. (2008) also modeled the total sediment eroded from the margin since the initial rifting and balanced it with the estimated sediment in the margin. Campanile et al. (2008) proposed an "elevated rift flank" model to account for most of the sediment deposited along the margin. Thus most of the potential source rocks in this basin would be expected to be of terrigeneous origin and would probably be gas prone.

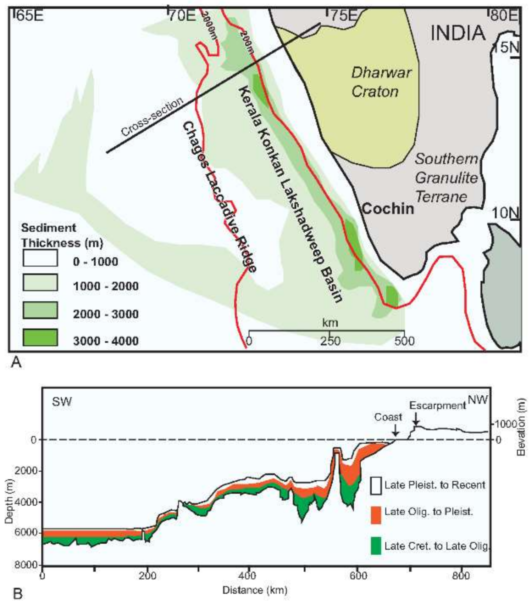

Figure 9. (A) Total sediment thickness in the margin off the KKL basin (modified from Campanile et al.., 2008). The 200- and 2,000m isobaths are also shown. These isopachs are slightly different from those shown in Figure 4. (B) Line drawing interpretation of a seismic record (location in A) showing a cross-section across the KKL basin interpreted from seismic data (modified from Campanile et al., 2008). Although some subsurface data in the area are available, the ages of the three sequences are mostly interpretive. Further details in text.

In the cross section in Figure 9B, the older sequences (in green) are interpreted to represent sediments deposited immediately after rifting. The youngest sequence (not coloured) represents sediments deposited since Pleistocene. According to Campanile et al. (2008), these sequences represent the greatest volume along the margin and consist of terrigeneous material derived from the denudation of the Indian shield. The intervening sequence (in orange) represents a period of lowered elevations on land, and hence, lowered rates of erosion. This sequence might contain mostly carbonates and hence could contain oil-prone source rocks. But this sequence might not have been sufficiently buried to generate hydrocarbons. Hence, at this time the most plausible source for hydrocarbons in the KKL basin appears to be terrigeneous (or mixed) source rocks in the oldest, Late Cretaceous to Late Oligocene, sequence, which would tend to be gas prone. Thus, the early evolution of Kutch, Saurashtra, and Mumbai offshore basins (closed, lacustrine) appears to be different from the KKL basin (open, marine). This difference in geological setting controls their hydrocarbon potential.

Summary and Conclusions

The model as discussed here is summarized in a schematic diagram show as Figure 10. The stratigraphy shown is approximately modeled after the interpretation shown in Figure 5B. The two unconformities Rift-onset Unconformity (ROU) and the Break-up Unconformity (BU) are also marked. The early synrift lacustrine source rock is shown in purple and potential migratory pathways from oldest sequences in the deep water to deep-water traps and onto the traps on the shelf are shown with arrows. The postulated traps are expected to be fault-block traps, unconformity traps and porosity-pinchout stratigraphic traps. However, at this time the data to verify and support this model is not available because of lack of drilling in deep water (Figure 4).

Biswas (2012) and Dwivedi (2016) have recently published summaries of status of exploration in all the Indian basins. While they have discussed the deep-water potential, generation of hydrocarbons in the early syn-rift and long-distance migration from there has not been discussed in any detail. Mishra (2008) has also discussed the potential of deeper plays in the Bombay (Mumbai) offshore basin as the current production is from the shallower post-rift sequence. According to Mishra (2008), the focus has shifted to the exploration in deeper plays within the syn-rift sequence in the basin. Although he has focused only on the Mumbai offshore basin, the basic structural and stratigraphic framework in Kutch and Saurashtra offshore basins is also quite similar. These basins have been partitioned by a series of basement highs which are controlled by NW-SE to N-S trending faults, creating opportunities for structural as well as stratigraphic trapping in the syn-rift sequences in these basins.

Mishra (2008) specifically mentions a Palaeocene-lower Eocene clastic play, Palaeocene-lower Eocene carbonate play, and a fractured basalt play, as well as possible basin-centered gas accumulations. The syn-rift history of the Western Indian margin indicates deposition of oil-generating source rocks in this part of the Indian margin. These source rocks were buried to maturity by further burial under the post-rift sequence. Because of the lack of geophysical and drilling data, even in the existing exploration areas the outermost parts of the margins have not been tested. This paper suggests that while Mishra (2008) recommended focus on *stratigraphically deeper* plays in the current exploration blocks, even higher potential exists in the deep- and ultra-deep water parts of the basin in those *same stratigraphically deeper* plays.

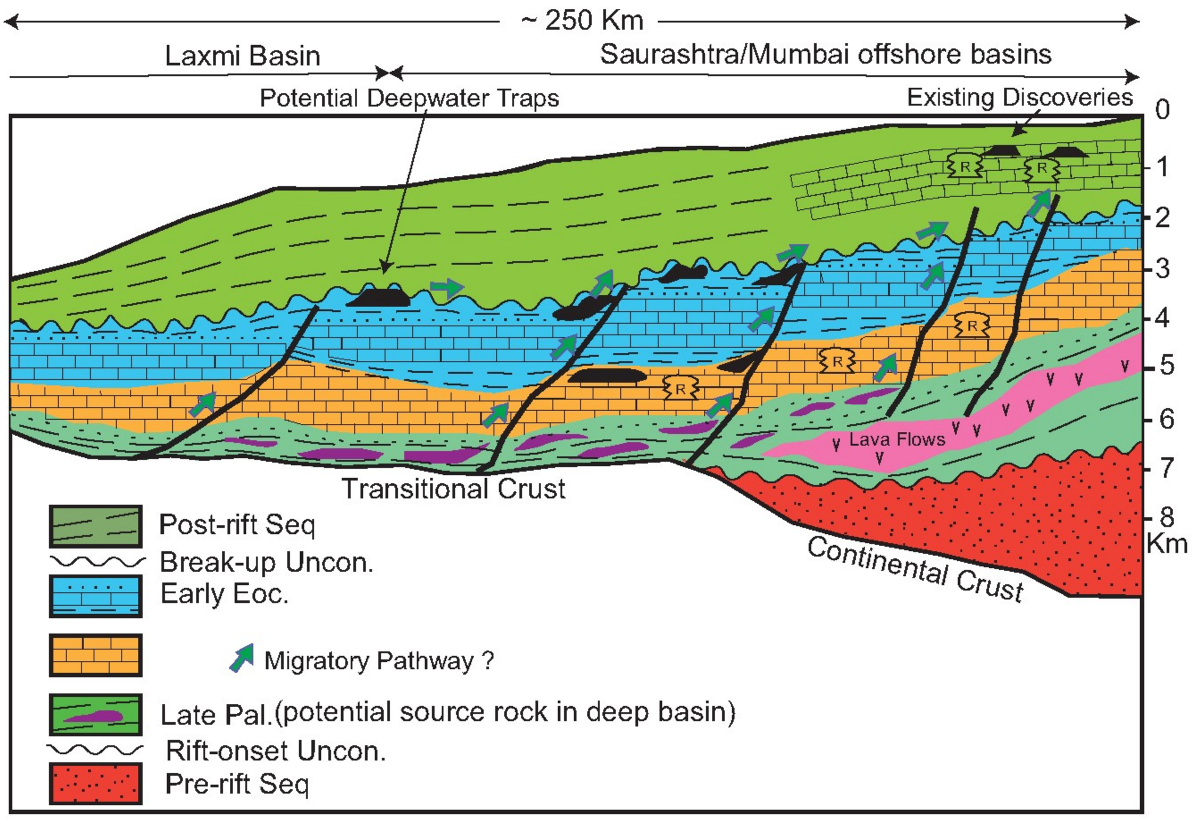

Figure 10. Schematic model for generation, migration and accumulation of hydrocarbons in the early syn-rift stage of northern basins (Kutch, Saurashtra, and Mumbai offshore) along the western margin of India. The model suggests potential for large accumulations in deep and ultra deep waters in the syn-rift sequences of these basins. The extent of basalt flows and their potential as a seal is speculative.

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Diagenetic evolution of onshore Campanian Sandstone, Ariyalur-Cauvery Basin

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Abstract: The onshore Campanian (Sillakkudi Fm.) sandstone consists of sub-angular to angular grains which composed of quartz (97%), feldspar (2.5%) and lithic fragments (0.5%) of continental block provenance derived by the rapid rate of erosion under hot and humid climate. The fabric signifies the free-floating (33%), point (46%), long (17%), sutured (2.5%) and concavo-convex contacts (1.5%). The relative high percentage of free-floating grains and point contacts by calcite cements suggesting early cementation process and diminutive compaction. Whereas the 63% of point and long contact and 4% of sutured and concavo-convex contact symptomatic of the early calcite cementation and mechanical compaction in excess of the chemical compaction.

The sandstone diagenesis is controlled by texture, detrital composition, environment of deposition and associated lithology (Burley et al., 1985; Morad et al., 2000). On a regional scale, tectonic setting of the basin, geothermal gradient, rate and extent of deposition and basin subsidence shows a role in diagenetic process. Lately, deposited sand is a porous, non-equilibrium mixture of detrital minerals and diagenetic processes tend to bring them towards equilibrium with the prevailing physical and chemical conditions, which is achieved by reduction of porosity through compaction and precipitation of stable authigenic cements or grains. The physical and chemical processes are operating simultaneously in response to the surrounding stress field to achieve equilibrium. The process of compaction and cementation results in loss of porosity as it decreases the pore space by squeezing and occluding the pore spaces present within the detrital grains, which is irreversible process. The process of diagenesis is significant in determining the reservoir quality of the rock. The Sillakkudi Sandstone has subjected to diagenetic processes such as compaction, cementation, dissolution of feldspar and clay mineral authigenesis. This study is focused in understanding the diagenetic evolution of onshore Campanian sandstone of Cauvery Basin.

Geology and stratigraphy

The Cretaceous succession of Cauvery Basin consists of a shallow marine sequence with rich faunal succession of Albian-Maastrichtian age. The Cauvery Basin is a rift basin (Rangaraju et al., 1993), developed by extension during the Mesozoic breakup of the Gondwana land (Prabhakar and Zutshi, 1993). Blandford (1862) reports this succession as Uttatur, Trichinopoly and Ariyalur Groups on the basis of lithology. Sastry et al. (1972) refers the Ariyalur Group comprises the Sillakkudi, Kallankurichchi, Ottakovil and Kallamedu Formations in upward succession. The Ariyalur Group conformably rests over the Trichinopoly Group (Table.1). The sediments of this basin are exposed on the coastal plain of Tamil Nadu, along the Ariyalur, Vridhachalam and Pondicherry. Of these, the Ariyalur area provides the complete representation of the Mesozoic succession and afforded contributions on stratigraphy, paleontology, paleoclimate and tectonic evolution of the succession (Banerji, 1979; Ramanathan, 1979; Sundaram and Rao, 1986; Ramasamy and Banerji, 1991; Ramasamy et al., 1995; Govindan et al., 1996; Madhavaraju and Ramasamy, 1999a, b; 2001; Madhavaraju et al. 2002; Ayyasamy, 2006, Nagendra et al., 2003, 2010, 2011, 2017). Except Kallamedu Formation, all the formations of the Ariyalur Group were deposited in the marginal marine environments (Sundaram and Rao, 1986; Madhavaraju and

Ramasamy, 1999b; Madhavaraju and Lee, 2009).

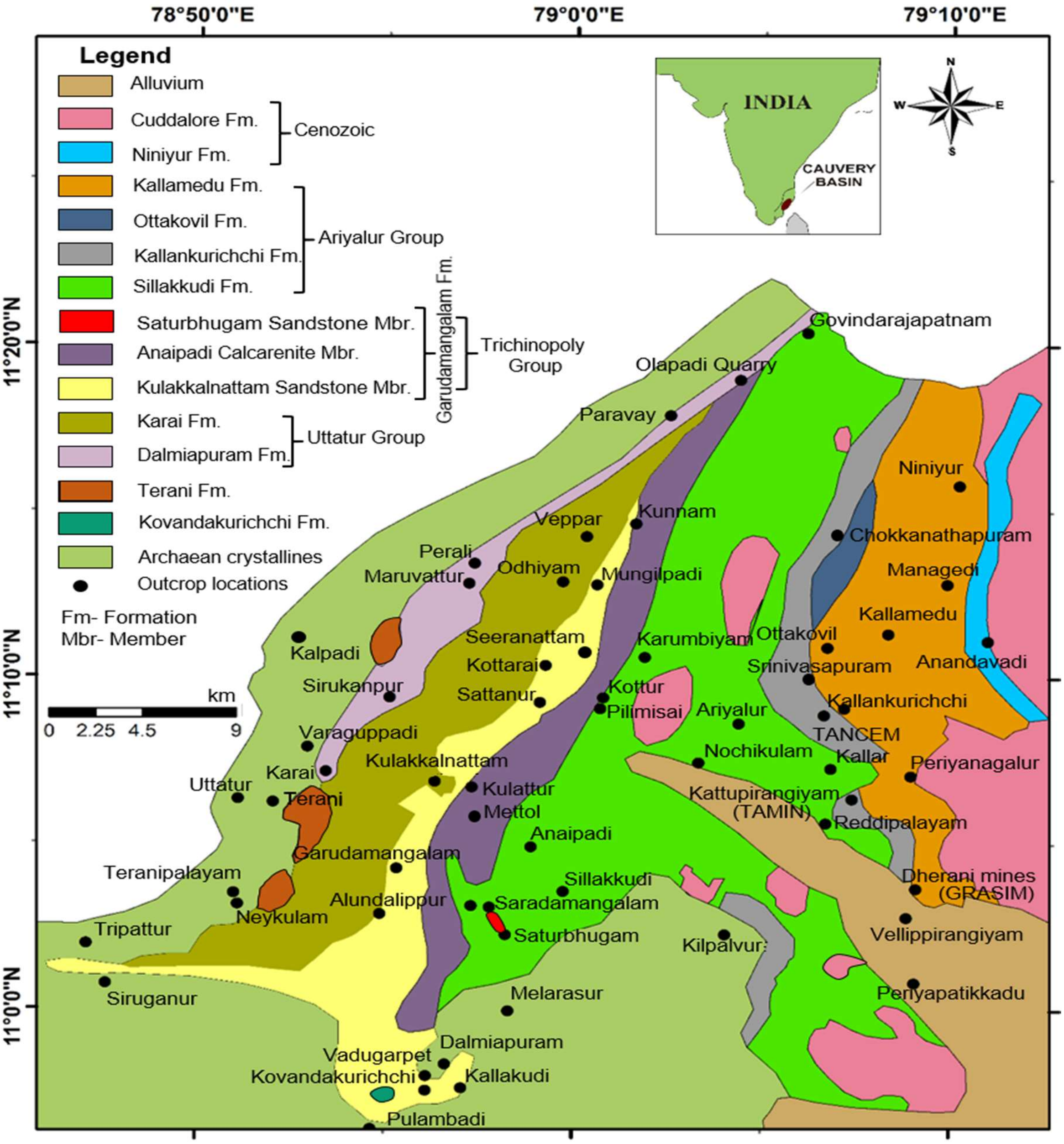


Fig.1 Geological map of Cretaceous successions, Ariyalur- Cauvery Basin

Sillakkudi Formation

The Sillakkudi Formation of Campanian age is exposed at the base of the Kallankurichchi Formation of Ariyalur Group, is addressed in this study to understand the diagenetic evolution of Campanian sandstone. (Fig.1). This formation comprises of fossiliferous calcareous gritty sandstone, calcareous sandstone and interbedded arenaceous limestone with sandy clay. The Sillakkudi Formation (Fig.1) is well-exposed in and around Mettol railway cutting (11°04'54.9"N:79°02'3.1"E),Nochikkulam 11°07'55.8"N:79°03'01"E),and Vayalpadi (11°20'2.5"N: 79°07'9.1"E) areas.

Materials and methodology

Ten sandstone samples (10m interval) sampled at Mettol railway cutting section near Sillakkudi with GPS coordinates. The macroscopic description of sandstone was evaluated qualitatively and quantitatively in the field by using 10X magnified lens. Twenty sandstone thin sections were stained for determining the type of cementation. The multiple grains were measured to its size, shape and angularity to attribute the sphericity and roundness of grains. The grain geometry, authigenic minerals, patterns, habits, pore spaces between the grains, partially filled pores, partly dissolved grains, and an abundance of mineral suites were accounted. The grid spacing method is used in point counting exceeded the grain size to avoid the individual grain to be counted more than once (Van der Plas and Tobi, 1965). The 300 numbers of gains are counted and tabulated for calculation of percentages of quartz, feldspar, and lithic fragments in identification of type of sandstone using QFL plot. To reconstruct the original detrital composition of sandstone, the effect of diagenesis was considered during the counting of QFL grains.

Group	Formation	Lithology	Age
Niniyur Formation			Danian
ARIYALUR	Kallamedu	Unfossiliferous fine to coarse grained sandstones interbedded with siltstone, sandy clay, ferruginous clay and marl	Maastrichtian
	Ottakovil	Fossiliferous calcareous sandstone interbedded with sandy clay	
	Kallankurichchi	Fossiliferous calcareous conglomeratic sandstone interbedded with sandy clay, sandy fossiliferous limestone, fossiliferous limestone and marl	
	Sillakkudi	Unfossiliferous calcareous sandstone, Fossiliferous calcareous gritty sandstone, Fossiliferous calcareous sandstones interbedded with sandy clay and thin band of sandy limestone	Campanian
Trichinopoly Group			

Table 1. Lithostratigraphy of Ariyalur Group (after Sastry et al., 1972)

Results and discussions

The diagenetic characteristics of the sandstones are briefly discussed below;

Mineral composition

The mineralogy of Campanian sandstones was studied to its physical and optical properties. The point counting method is used for describing the mineral grains and its population. The grid spacing method is cast-off in point-counting, to avoid the individual grain count more than once (Van der Plas and Tobi, 1965). The average composition of the detrital minerals of Sillakkudi Sandstone are quartz (97.45%), feldspar (2.41%), and lithic fragment (0.14%) including biotite mica, opaque minerals and heavy minerals (Table.2). Sillakkudi sandstone is fine to medium grained arenaceous, sub-rounded-rounded, angular and moderate to poorly sorted and is classified as quartz arenite.

Sample No	Quartz	Feldspar	Lithic fragments	Total	Quartz%	Feldspar%	Lithic Fragments %
MRC-1	287	11	2	300	95.6	3.7	0.7
MRC-2	293	7	0	300	97.7	2.2	0.1
MRC-3	296	4	0	300	98.7	1.3	0
MRC-5	291	9	0	300	97	3	0
MRC-8	295	5	0	300	98.6	1.4	0
MRC-10	297	3	0	300	99	1	0
SRC-1	291	7	2	300	97	2.7	0.3
SRC-2	289	11	0	300	96	4	0

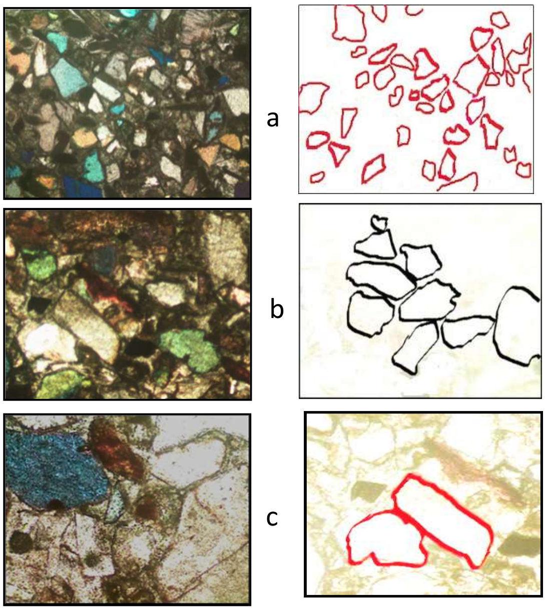
Table. 2. Sandstone composition of Sillakkudi Formation.

Compaction

Compaction process is responsible for closer packing of the detrital grains due to the pressure exerted by the load of overlying sediments (Chilingar et al., 1983). The compaction affects the well-cemented detrital grains directed by the concavo-convex and sutured contact. The inter-granular pore spaces of clastic sediments are eliminated by closer packing, crushing deformation, expulsion of fluids and dissolving of grains. The grain contact in Sillakkudi sandstone was accounted to decipher the compaction history. The detrital grains are signifying, the free-floating (33%), point contact (46%), long contact (17%), sutured contact (2.5%) and concavo-convex contact (1.5%). The 33% of floating grains indicates the early cementation of the detrital sandstone grains (Fig.2). The point contact is formed in the early stages of compaction due to mechanical process, whereas the long contact is developed because of rotation and tuning of grains to the adjoining grain boundaries whereas the sutured and concavo-convex contacts are formed owing to the dissolution of the grains along the boundaries of long contact. The Sillakkudi sandstone illustrates the effect of both mechanical and chemical compactions. The detrital grains of Sillakkudi sandstone are having contact index of 0-4. The free-floating grains, contact index are zero. The average contact index is 1.8 (Fig.3). The contact index is owed to the presence of significant number of free-floating grains which are due to early cementation process and dominance of point and long contact of the detrital sedimentary grains.

Cementation

Cementation is a diagenetic process by which new mineral is precipitated as syntaxial overgrowth in the pore spaces of the detrital sandstone grains from the intraformational saturated fluid which are circulating in the pore space. The authigenic cementing mineral identified in Sillakkudi sandstone are calcite cement ($CaCO_3$) and ferruginous cement (Fe_2O_3). 95% of the total cement is calcite precipitate in sandstone. Calcite cement distributed as oversized pore space filling and rarely in the form of patchy distribution. Calcitic cement was identified by staining the thin sections, where calcite is pinkish orange colour (Fig.4). The process of calcitic cementation might have been formed after considerable burial by



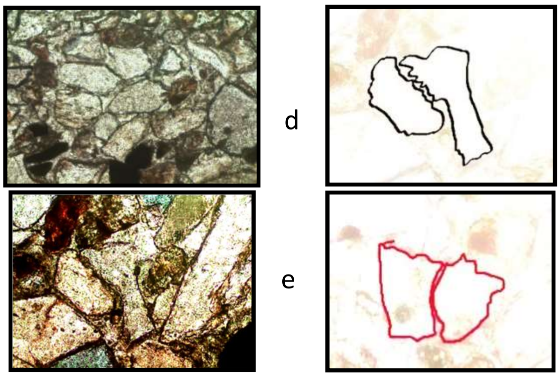
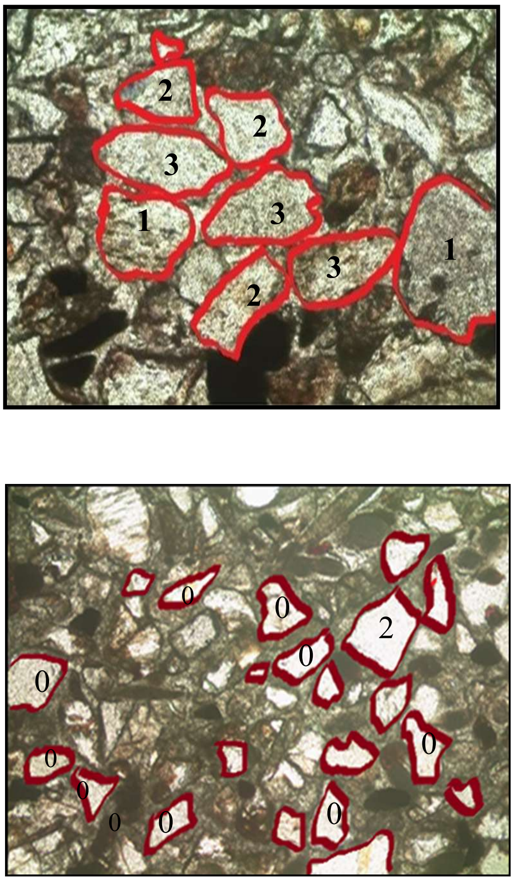


Fig 2. Sandstone fabric; (a) Free floating contact (b) Point contact (c) Long contact (d) Sutured contact (e) Concavo-convex contact

ground water saturated with calcium carbonate moving through the pore spaces. The presence of calcite cement in oversized pore spaces along with the significant number of free floating detrital grain suggests towards the early cementation of the detrital grains in Sillakkudi Sandstone, indicating that the calcite cement was hitherto deposited in a shallow water condition. It is established that the early precipitation of the carbonate cement occurs at niche water column below the sediment water interface (Bjorlykke, 1989).



Average no. of grain contacts a grain has with its neighboring grains.

Maximum value of Contact Index (C.I) was 3 whereas minimum value of Contact Index (CI) was 0.

The overall average contact index was found to be about 1.8 indicating moderate tight packing due to mechanical compaction and early cementation.

Fig 3. Grain contact index of Sillakkudi sandstone

The detrital quartz grain cemented by the calcitic cement is corroded along boundaries, characterized by ferruginous-calcitic cement. The corroded quartz grain exhibits calcite cement infilling, suggesting the presence of syn-depositional calcitic cement, which might have been replaced by the ferruginous cement during deeper burial of the detrital. The calcitic cement was responsible for reducing the porosity and permeability, affecting the reservoir property of the Campanian Sillakkudi Sandstone in Cauvery Basin.

The ferruginous cement occurs in the form of pervasive pore space filling. This is characterized by the ferruginous and calcite cement, the detrital grains are demonstrating the free floating contact, which are cemented by the calcitic cement suggesting the syn-depositional cement, which is later replaced by the calcite cement. However, the inclusion of calcitic cement in the quartz grain suggests the presence of syn-depositional calcitic cement. The ferruginous cement is characterized by the reddish brown colour in both PPL and crossed Nichols. The oversized pore spaces might have been resulted from destruction and leaching of labile framework, possibly feldspar. The total ferruginous cement in the sandstone is about 10%, derived from the weathering and leaching of ferromagnesian silicate minerals in the source area. The precipitation of ferruginous mineral from the iron saturated solution is governed both by the hydrogen ion concentration, pH and the redox potential of the environment. Drever (1974) suggested the precipitation of iron from marine water because of upwelling of the bottom water into oxidizing environment.

Porosity reduction

The original porosity of the sandstone is reduced during the diagenetic process due to the process of compaction and cementation. Here, assumed the initial porosity for the Sillakkudi Sandstone to model the porosity evolution and relative role of cementation and compaction for porosity reduction. The Sillakkudi Sandstone are medium to fine grained, moderate to poorly sorted and have dominance of quartz (96%) in QFL framework composition which, qualifies to have an initial porosity of 45% (Atkins & Mcbride,1992). This is calculated by using the following formula and variation diagram of Lundegard (1992).

Compaction porosity loss (COPL): IP – [(100-Ip) X (MCP)}/ (100-MCP)]…. (1)
Cementation porosity loss (CEPL): IP – COPL X (T_c/MCP) ….. (2)

Where, COPL- Porosity Loss due to Compaction,
CEPL- Porosity Loss due to Cementation,
IP-Initial Porosity of sandstone (ie.45%),
T_c -Total volume of cement; 25%
MCP- Minus Cement Porosity (30%).
The relative values for COPL is 21.5 whereas CEPL is 27.

This infers that cementation was the major cause for the reduction in porosity and hence compaction is the secondary factor for porosity reduction. The process of early cementation may have reduced the porosity and established a stable framework of sand grains which has decreased the effect of compaction in later stages of diagenesis. Hence, the cementation enactment in the diagenesis, when compared to compaction in sandstone compared to compaction.

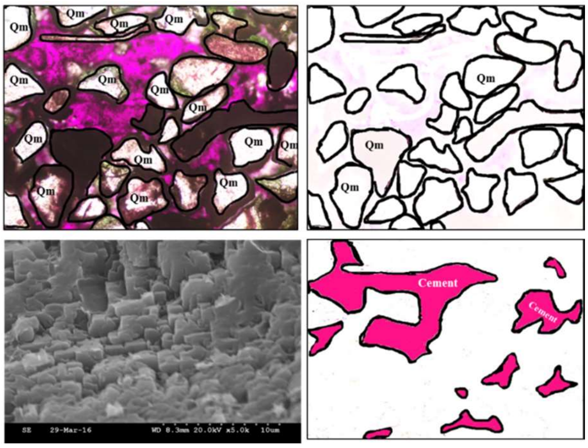


Fig 4. Calcite cementation in sandstone fabric

Discussion

Diagenetic features in Sillakkudi sandstone has different stages of compaction and cementation. The relative percentage of different petro-fabric contacts are free-floating, point, long, sutured and concavo-convex contacts. The relative high percentage of free-floating grains and point contact cemented by calcitic cement suggests that the sandstone were subjected to early cementation process and consequently little compaction effects. The relative high percentage of long contact advocates that the mechanical compaction was more dominant than the chemical compaction which is indicated by relative low percentage of sutured and concavo-convex contact. Two types of cement have been identified in the Sillakkudi sandstone; calcitic cement and ferruginous cement in which calcite is the dominating cement (90 %) than that of the ferruginous cement (10%) of the total cement in Sillakkudi sandstone. Calcite was the first cement precipitated in the pore spaces of sandstone, which is indicated by the free-floating grain (33%) and by the detrital grains showing point contact (46%) were cemented by calcitic cement and was replaced by the ferruginous cement which was precipitated in the later stages of diagenesis. Loss in porosity was due to early cementation process in comparison to compaction process. Hence compaction is the secondary process in porosity reduction. The detrital sandstone grains endured early cementation process, indicated by 33% of free-floating grains cemented by calcite. Calcite cementation is followed by compaction which is indicated by different type of petro-fabric contact in sandstone. Ferruginous cement is precipitated at the later stages of diagenesis which is due to dissolution of the ferromagnesian minerals and replacement of calcitic cement.

Conclusions

- Sillakkudi Sandstone is fine to medium grained arenaceous, sub-rounded-rounded, angular and moderate to poorly sorted and is classified as quartz arenite ($Q_{97.45\%}$ $F_{2.41\%}$ $L_{0.14\%}$)
- Monocrystalline quartz>Polycrystalline quartz, plagioclase feldspar are dominant. Biotite, opaque mineral and zircon forms the accessory mineralogy of Sillakkudi Sandstone.
- The modal composition of the Sillakkudi Sandstone reveals a continental block provenance where orogenic forces were absent and rapid erosion under hot and humid conditions which lead to dissolution of feldspar and lithic fragments.
- The relative percentage of free-floating grains (33%) and point contact (46%) cemented by calcite suggests that the sandstone were subjected to early cementation process, consequently petite compaction effects. The long contact (17%) suggests that the mechanical compaction was more dominant than the chemical compaction, indicated by relative low percentage of sutured and concavo-convex contacts.

- Calcitic cement (90%) and ferruginous cement (10%) were identified in the Sillakkudi Sandstone. Calcite was the first cement precipitated in the pore spaces of sandstone, which is deciphered by the 33% free-floating and 46% point contact grains were cemented by calcitic cement and was replaced by the ferruginous cement which was precipitated in the later stages of diagenesis.
- Loss in porosity was due to early cementation process in comparison to compaction process hence, the compaction is the secondary process in porosity reduction.

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Sources and transport of the heavy minerals in some Gondwana basins of extra-peninsular eastern India

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Abstract: The present endeavor is concerned with analyses of heavy mineral distributions entombed within the sandstones of some extra-peninsular Gondwana basins located in Singrimari, Meghalaya; Elephant Flat, Arunachal Pradesh and Kalijhora, West Bengal. Around 60% of the heavy minerals are similar in all the study areas with the common mineral species being zircon, garnet, opaque minerals, tourmaline, rutile, epidote, kyanite, staurolite and titanite. Compared to Singrimari and Kalijhora, Elephant Flat suite hosts more varieties. Heavy mineral indices indicate the sandstones of the study areas to be somewhat mineralogically mature. Hydraulic separation and transportation length influenced variation in the physical attributes of heavy minerals between Singrimari and that of Kalijhora and Elephant Flat. The heavy minerals were contributed from a southern Precambrian terrain and accumulated in a mature continental passive margin setting. Source rocks of the study areas were closely associated in space ± time and were a mélange of ultrastable and metastable minerals. It is considerably probable that contributions of detritus from the denuded Precambrian Eastern Ghats Supergroup were very high. The fluviatile Singrimari Gondwanas were closer to the provenance and the drainage network extended further north wherein the Kalijhora and Elephant Flat Gondwana rocks were deposited under marine shoreline influence.

Keywords: Heavy minerals, Gondwana sandstones, Extra-peninsular India, provenance, statistical tests

Introduction

Clastic sedimentary rocks are windows to myriad facts of the geological past. Their analyses help one to have an understanding of the pre-depositional setup, nature of provenance, influence of relief and climate, weathering, tectonic setting of depositional basins, diagenetic stages etc (Dickinson, 1985; Suttner and Dutta, 1986; Boggs, 2009). Although sparse, heavy minerals which are a key component of siliciclastic sedimentary rocks play a discriminatory role in this regard.

Heavy mineral study is one of the oldest fields of endeavour in sedimentary petrology (Hubert, 1962; Mange and Maurer, 1992; Ramasamy and Karikalan, 2010). Quantitative treatment of heavy minerals was pioneered by Artini in 1898 and 1950s onward heavy minerals in sands and sandstones were mostly studied in detail (Von Andel, 1959). Application of advanced analytical techniques and mathematical treatment of data attracted a lot of workers towards heavy mineral studies. Although certain heavy mineral species can be selectively destroyed during transportation and diagenesis, the remaining ones carry a lot of ingredients to reflect their source as well as let one know about the tectonic history of provenance, erosion, weathering, transport path, dispersal pattern, deposition and post-depositional changes (Morton, 1985a; Lindholm, 1987; Silva and Vital, 2000; Mishra and Tiwari, 2005; Hota and Maejima, 2009) thereby contributing a lot towards basin analysis, delineation of sedimentary petrologic province and correlation.

Formation of Gondwanaland south of the supercontinent Pangaea, deposition of Gondwana rocks with the onset of Permo-Carboniferous along rifts (palaeo-sutures) were some of the most important events that took place in the geological past of our Earth. Continued rifting and subsequent breakup of Gondwanaland along the pre-existing tracks of weaknesses influenced land-sea distribution on Earth as what we see today. Gondwana Supergroup today can be found in many now separated locales. Making efforts towards understanding tectono-sedimentary evolution of Gondwana Supergroup and correlation studies as such have been a global obsession amongst geologists since long.

In the present endeavour heavy minerals from three extra-peninsular Gondwana locales exposed in and around Singrimari, Meghalaya; Elephant Flat, Arunachal Pradesh and Kalijhora in West Bengal of India have been considered for detailed petrographic investigations and subsequent statistical analyses. Objectives of the present attempt revolve around elucidation of the heavy mineral suites and their variations apart from determination of provenance in particular and correlation in general.

Geology of the study areas

The geological setup of Singrimari exudes a litho-association similar to the ones found in and around many Gondwana exposures of peninsular India, the Elephant Flat and Kalijhora exposures reflect the influence of Himalayan geodynamism (Fig. 1).

The Singrimari area lies at the western most tip of the Assam-Meghalaya Plateau where a Gondwanide sedimentary blanket of roughly 20 sq. km. (Table 1, Fig. 2) spreads over an eroded Precambrian basement, (Baruah and Das, 2001). Sedimentation here started with a southerly pinching basal coarser sandstone having pebbles towards the base. This buff-brown, friable-compact fining upward unit shows pinching and swelling and minor westerly slipping step faults apart from hosting carbonaceous shale. This unit shows two truncated cyclothems and a northward palaeocurrent direction, (Baruah and Das, 2012). Carbonaceous shales bear

Figure 1: Location of the three study areas in and around Singrimari, Meghalaya; Elephant Flat, Arunachal Pradesh and Kalijhora in West Bengal of India; Source: Google Earth image.

AGE	LITHOTYPES
Recent	Alluvium ~~~~~~~Unconformity~~~~~
Jurassic?	Basic Intrusives - Dolerite ~~~~~~~Unconformity~~~~~~ Fine grained sandstones bearing sedimentary pebbles at the base towards north, laystone, siltstone.
Permo-Carboniferous	~~~~~~~~~~hiatus~~~~~~~~~ Pebbly sandstones with layers of carbonaceous shale having specks of coal - Jhama (?). Shales bear palaeofloral remnants and are mylonitised at certain patches ~~~~~~~Unconformity~~~~~
Precambrian	Quartzofeldspathic gneiss - granite gneiss, calc-silicate gneiss, amphibolite, migmatite, granite, vein rocks - quartzofeldspathic (pegmatite in certain cases) and quartz vein.

Table 1: Lithostratigraphy of Singrimari area

palaeofloral remnants of Gondwanide affinity. Following a hiatus from here, the next sedimentation resulted in northerly pinching sandstone. Hosting sedimentary pebbles of the nature of the basal sandstones towards the base (Fig. 5A), this upper unit is buff-pink, friable-compact and fine-very fine grained. It entombs minor claystones and Fe-laminations which exudes a seasonal increment like look. The whole sedimentary column is intruded by dolerite intrusives. A highly extensive drainage network shed recent alluvium to sporadically cap the older lithounits. Overall, the sedimentary exposures which trends N10°E-N30°E with low dip towards west looks to be the easternmost fringe of a Gondwana basin where intermittent channel shifting, subsidence partially aided by tectonic play took place.

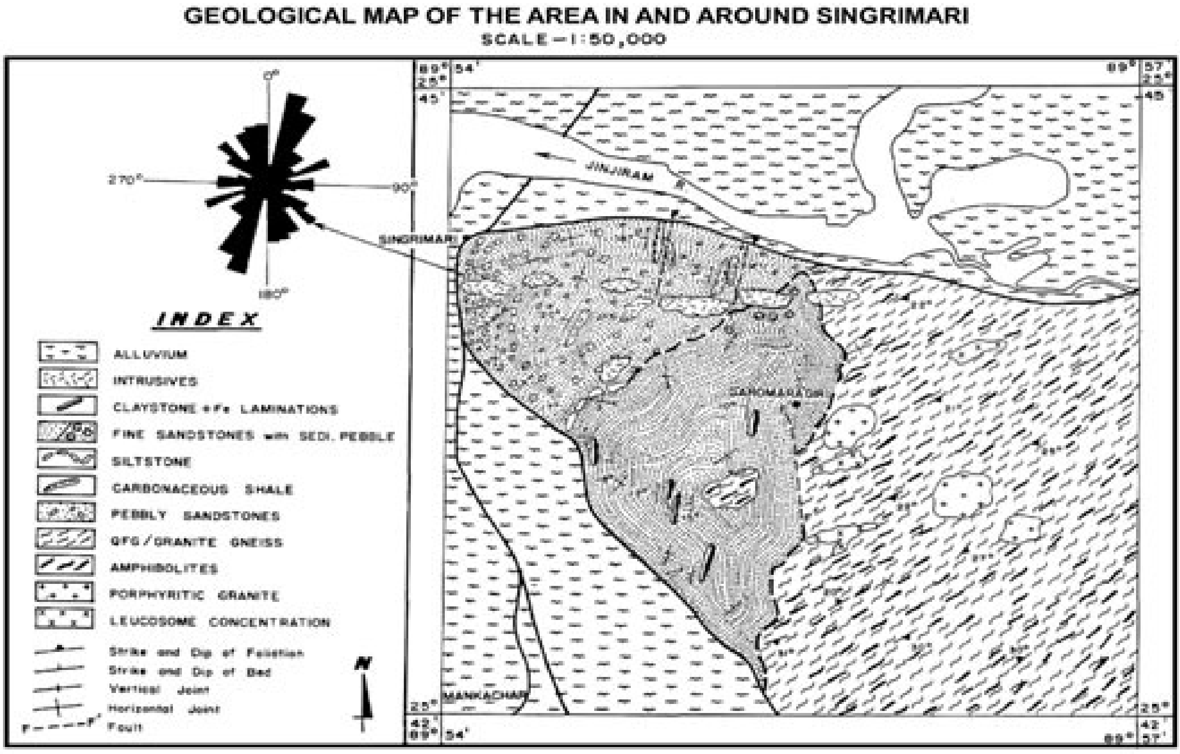


Figure 2: Geological map of the areas in and around Singrimari, Meghalaya (after Baruah and Das,

AGE		**LITHOTYPES**
Tertiary		Fine grained, white and ferrugenous sandstones
		~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ unconformity ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
↓ North	Upper Unit	Massive micaceous sandstone interbedded with carbonaceous shale, shale, shaly sandstone, ferrugenous sandstones, Coarse and gritty sandstone shale and coal, Plant fossils: Vertibraria, Schizoneura, Taenopteris
Permo-Carboniferous	Lower Unit	Hard, massive, coarse grained sandstones criss crossed by quartz veins; Black sandstones and shale (interlayered). Shales host plant fossils; Black, buff fine grained sandstones
		~ °~ °~ ° ~ ° ~ ° ~ ° ~ ° ~ ° Crushed zone ° ~ ° ~ ° ~ ° ~ ° ~ ° ~ °
		Hard shale Crushed coal quartzitic sandstone
		~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ unconformity ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
Precambrian		Slate, Phyllite, Quartzite.

Table 2: Synthesised lithostratigraphy of Elephant Flat area

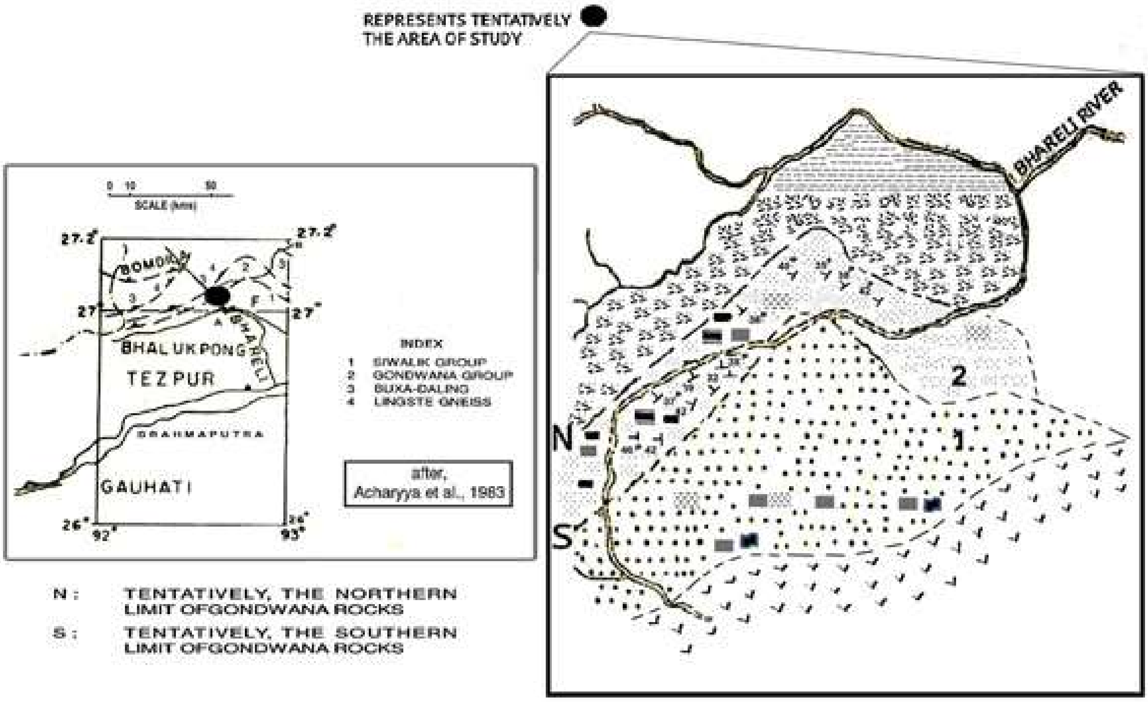


Figure 3: Geological map of the areas in and around Elephant Flat, Arunachal Pradesh (modified after Acharyya et al., 1983)

About 14 kms. North of Bhalukpung point on way to Bomdila, Gondwana rocks are exposed in and around Elephant Flat area between Pinjuli Nala and Sessa Nala from south to north (Baruah, 2007). Tertiary (Siwalik Group of rocks) and Precambrian rocks mark the southern and northern limits. E-W trending Himalayan thrusts (MBT) traverse the area consequently affecting the normal stratigraphic sequence (Table 2, Fig. 3). The area is sandstone dominated with varieties being buff-, grey- and black coloured, gritty-, and medium to fine grained. These arkosic to quartzitic arenaceous varieties are inter-layered with minor shaly sandstones, silty shale, shale, carbonaceous shale, lenses of coal (Fig.5B).

Coal in particular is crushed and shows high reflectance owing to tectonic jerks. Repetition of the litho assemblage: sandstone - shale - coal, colour variations are indicative of either seasonal influence or tectonic control. Dominance of black, recrystallised, fine and massive sandstones increases towards north. Plant fossils like Vertibraria, Glossopteris and Schizoneura confirm their age to be Lower Gondwana. The rock units dip towards north with the amount of dip varying between 30° to 60°. Occasionally vertical beds are also seen in these rocks which strike ENE-WSW to NE-SW. Kalijhora in Darjeeling Himalayas hosts Gondwana rocks (known as Rishi Group here) sandwiched between Precambrian Dalings towards north and Siwalik rocks towards south in a roughly ENE-WSW to WNW-ESE trend in the vicinity of the MBT (Table 3, Fig. 4). The exposed rocks mostly comprise of sandstones which are relatively more compact than the Siwalik sandstones. The arenaceous units are found as buff, grey, dark grey coloured and a little bit recrystallised. Grey sandstones along the river bed hosts variable calcareous ingredients. Carbonaceous shale, sandy shale, coal are some of the other litho units (Fig. 5C). At places coal exudes an anthracitic look owing to thrusting. Unlike Elephant Flat area which is also a part of the Himalayan framework, Kalijhora is devoid of fossils.

At least two prominent deformational phases are evident. Across the Kalijhora on its either bank, sandstone beds are dipping oppositely (Fig. 5D). The beds on the northern bank show a moderate north-westerly dip while those on the southern bank show a moderate southerly dip reflecting the existence of a larger antiform with east-west axial planar trend and a moderately westerly plunging fold axis. Consequent to D_1 a weak bedding parallel foliation developed in the sandstones. Subsequent to formation of F_1 folds, NE-SW trending F_2 folds developed. The area is also affected by dextral shearing reflected best by the carbonaceous shale and coal. This whole sequence underwent brittle deformation later (Basu, 2013; Kar et al., 2017).

AGE	**GROUP**	**LITHOTYPES**
Recent		Alluvium
		~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~unconformity~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
Tertiary	Siwalik	Medium grained sandstone, carbonaceous shale intercalated with sandy shale, silt, minor marl and pebbly sandstones, conglomerate: Repetitive sequence
	↓ North	~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ thrusted ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
		Fine to medium sandstone, sandy shale, shale, minor coal, pebbly sandstones, conglomerate
		~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ unconformity ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
		Fine to medium grained buff coloured sandstones
Permo-Carboniferous	Gondwana (Rishi)	Grey coloured intercalated with slaty Shale, carbonaceous shale and coal; minor gritty sandstones; few sandstones exude a calcareous look Grey to dark grey recrystallised sandstone
		~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ unconformity ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~ ~
Precambrian	Daling	Massive quartzites Intercalations of foliated quartzites and phyllites

Table 3: Synthesised lithostratigraphy of Kalijhora area

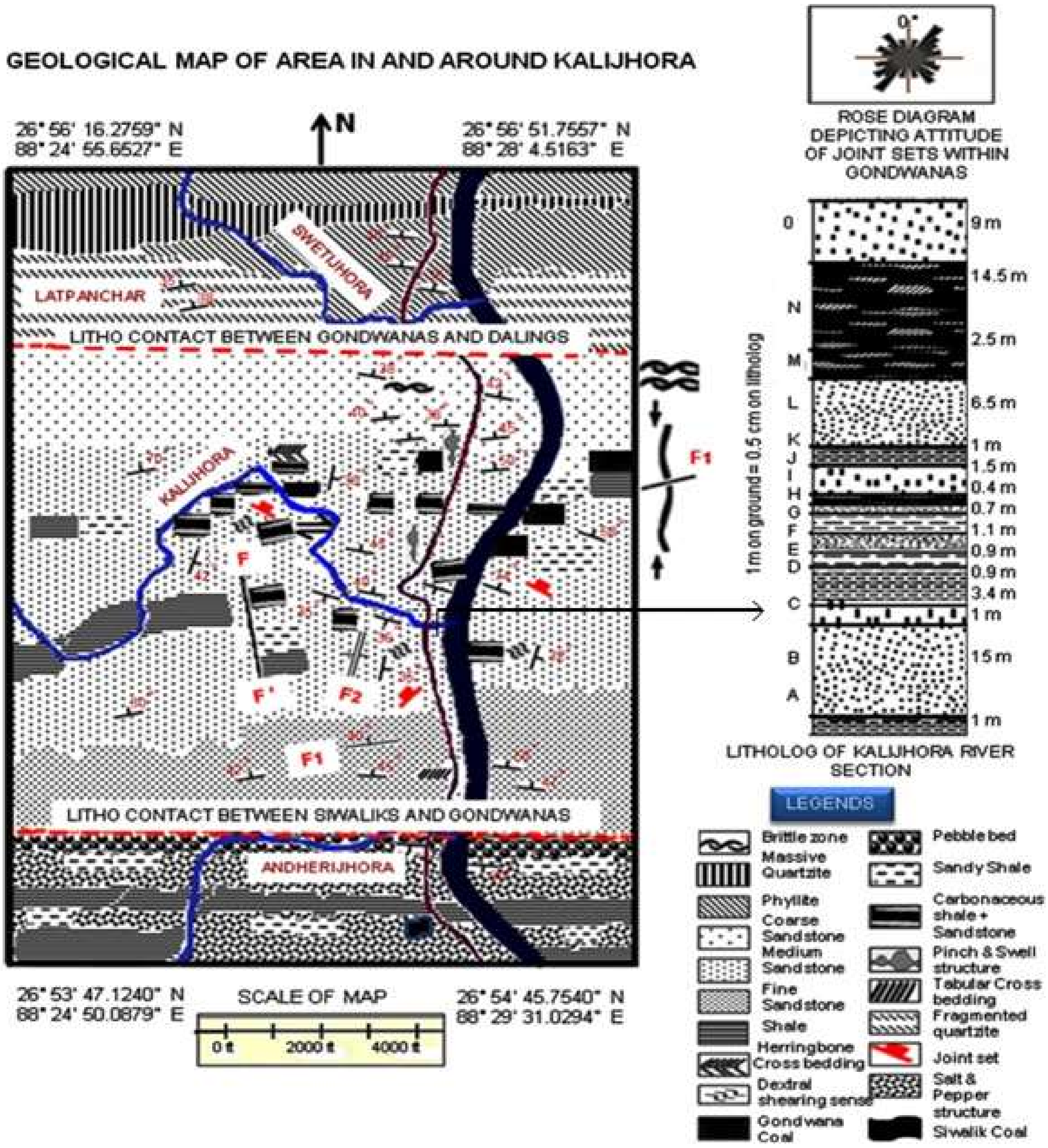


Figure 4: Geological map of the areas in and around Kalijhora, West Bengal (after Kar et al., 2017)

5a

5B

5C 5D

Figure 5: (A) Photograph shows traces of a current-bedding within the basal pebbly sandstone; Locality: south-east of BSF Camp, Singrimari; (B) Photograph shows alternations of fine grey sandstone, carbonaceous shale and coal; Locality: south of Elephant Flat proper, (Baruah, 2007); (C) Photograph shows alternations of sandstone and coal; Locality: Kalijhora; (D) Photograph shows sandstones being warped into an antiform with lensoidal presence of coaly matter at the core; Locality: North bank of Kalijhora river, (Kar et al., 2017).

Methodology

Sand fractions from 0.250 mm to 0.0625 mm (medium to very fine grained) have been considered for analyses. Representative samples have been put to “Funnel Separation” method (Krumbein and Pettijohn, 1938). 84 representative thin-sections were considered for petrographic studies. Based on field findings Singrimari sandstones were classified as upper and lower (basal). Around 100 counts were made per section to substantiate the suite characteristics of the heavy minerals following Lindholm (1987). Common heavy mineral parameters like ZTR, shape index and density index were calculated following Hubert, 1962 and Flores and Schideler, 1978 apart from analysing reciprocal relationships of selected ultrastable – metastable heavy minerals.

The multivariate data of the heavy minerals were put to some statistical tests like correlation matrix analyses, principal component analyses and cluster analyses (Davis, 2002). Mutual sympathetic and antipathetic relationships amongst the heavy minerals were figured out by correlation coefficients. All statistical analyses have been performed to have a better understanding of the heavy mineral assemblages, inter-relationship amongst different mineral species and the source rocks. SPSS-20 was used for all statistical analyses.

Results

Heavy minerals and their variability not only indicate the nature of source rocks but also the influences of sedimentary cycle processes. The heavy mineral assemblage of the study areas comprise of both transparent and opaque varieties (Table 4, Fig. 6) as listed below:

The Singrimari suite comprise of zircon + garnet + opaque minerals + tourmaline + rutile + chloritoid + epidote + kyanite + staurolite + titanite + apatite. Transparent heavy minerals constitute 32.12% of Upper Sandstones and 60.27% of the Basal Sandstones.

The Elephant Flat suite hosts zircon + rutile + garnet + opaque minerals + tourmaline + epidote + titanite + cordierite + actinolite + staurolite + kyanite + brookite + biotite. Both actinolite and biotite exudes strong leaching. Transparent heavy minerals constitute 39.75% of the total.

The Kalijhora suite comprise of zircon + tourmaline + rutile + kyanite + staurolite + epidote + garnet + chloritoid +

opaques + titanite + apatite. Transparent heavy minerals have a 93.18% share of the lot.

Although spatially separated, the heavy mineral finds in the study areas have a lot of similarity amidst minor perceptible differences and a comparative account of observations is stated herewith:

Zircon grains in all the study areas occur in a variety of forms right from prismatic, subhedral to euhedral types with well defined crystal faces through sub-rounded forms to rounded forms. The grains are colourless, gray to pale brownish, show straight extinction and pale high order interference colour and contain opaque and non-opaque inclusions. The brownish varieties sometimes show ferruginous encrustations while the gray varieties show more of minute opaque inclusions. Primary growth forms like parallel (with common base) and twinned crystals are rare compared to secondary growth which includes overgrowth, outgrowth and multiple growths. Overgrowths are seen on prismatic ('sawfish' type) as well as pyramidal faces. Necked zircons and those showing geniculate twinning are rare. Zircons with zircon inclusions are also seen. Size wise zircons from the Upper Sandstones (7.3% to 24.3%) of Singrimari are finer and unimodal compared to the Basal Sandstones (10.1% to 27.03%) which show extreme bimodality. Zircons of Elephant Flat area (12.12% to 29.16%) show unimodality similar to Upper Sandstones of Singrimari. Zircons from Kalijhora area (32.28% to 45.54%) are mostly medium grained and bimodal.

Tourmaline grains in all the study areas are prismatic and angular to sub-rounded. Tourmalines are identified by their characteristic pleochroism from light brown to dark brown and light green to dark green. The varieties are dominantly brown followed by some colourless ones and a few in Singrimari and Kalijhora are with bluish tinge. Tourmalines in Elephant Flat show partings. The abundance of tourmalines varies from 1.04% to 5.19% in case of Upper Sandstones and 1.35% to 3.25% in case of the Basal Sandstones of Singrimari. In Elephant Flat tourmaline grains vary from 0% to 6.4%. Tourmalines are most abundant in Kalijhora after zircon and they vary from 30.54% to 44.81.

Rutiles are identified by their peculiar ‘blood red’ colouration. The grains are mostly sub-angular to sub-rounded in form and distinct prismatic and pyramidal terminations are seen in some cases. Under reflectance, the grains show vitreous lustre. Faint striations slightly oblique to the prismatic faces are seen in all the study areas. The percentage of rutiles varies from 1.1% to 5.04% in case of the Upper Sandstones and 1.1% to 3.28% in case of the Basal Sandstones of Singrimari. Rutiles are most abundant in the Elephant Flat suite after zircon and it varies from 2.08% to 18.25%. Rutiles in Kalijhora range from 0% to 6.66%.

Garnets are sub-angular to sub-rounded, reddish brown and mostly anhedral in all the areas. The grains are isotropic to feebly anisotropic and show small opaque inclusions. Garnets are most abundant in the Singrimari suite after zircon and pitted surfaces in certain grains are seen. Pitted surfaces are common in Singrimari and Kalijhora. In Elephant Flat and Kalijhora garnets are relatively less. The percentage of garnets varies from 1.7% to 19.5% in case of the Upper Sandstones and 18.2% to 35.2% in case of the Basal Sandstones. In Elephant Flat percentage of garnets vary from 0% to 8.2% while in Singrimari it ranges from 0% to 9.18%.

Kyanites Characterized by transverse fractures kyanites are seen as bladed, platy and elongated grains with irregular terminations in all the study areas. They occur as colourless to pale green colour. The grains show inclined (~30°) extinction angle and a higher order interference colour of blue, pink and yellow. The percentage of kyanites vary from 1.4% to 3.4% in case of the Upper Sandstones while it case of the Basal Sandstones of Singrimari it is found only in one sample showing a quantity of 2.1%. In Elephant Flat the percentage of kyanites vary from 0% to 1.5%. Kyanites are rare in Kalijhora. Only two samples mark their presence and abundance varies from 0% to 1.63%.

Epidotes range from colourless ones to those with the characteristic pistachio green colour and shiny surfaces. The grains have mostly irregular boundaries and are sub-angular in form. The grains show straight extinction and, brilliant green to purplish and red interference colours. The percentage of epidotes varies from 0.9% to 15.5% in case of the Upper Sandstones and 1.75% to 6.5% in case of the Basal Sandstones in Singrimari. Epidotes in Elephant Flat exhibit themselves as small chips and vary from 0% to 6.02%. In Kalijhora percentage of epidote varies from 0% to 12.85%.

Staurolites in all the study areas are light yellow to straw yellow in colour, angular to sub-angular, shows parallel extinction and low birefringence. The grains mark themselves as irregular with hackly fracture. The percentage of staurolites in Singrimari varies from 1.25% to 3.25% in case of the Upper Sandstones while in case of the Basal Sandstones it ranges from 1.03% to 2.04%. In Elephant Flat a few staurolites with inclusions of quartz and opaque minerals are seen. The percentage of staurolite here varies from 0% to 2.01%. In Kalijhora the percentage of staurolites varies from 0% to 9.54%.

Opaques are sub-rounded to anhedral in all the study areas and are most dominant of all the minerals stated above. Under reflected setup, certain grains show black, reddish and rarely bluish reflectance. EPMA studies of heavy opaques of Singrimari and Elephant Flat were done. Magnetite is found to be dominant in Singrimari while it is poor in Elephant Flat. In Singrimari the percentage of opaque minerals varies from 50.1% to 80.2% in case of the Upper Sandstones and, 24.1% to 49.25% in case of the Basal Sandstones. Opaques average 58.43% in Elephant Flat while it is lowest in Kalijhora amounting to only 6.64% on average.

Titanites Although low in abundance, titanites are encountered in all the study areas. The grains are identified by their rhombohedral nature, very high relief, dark marginal rim, light yellow colour with dusky tinge and symmetrical extinction. The grains show white to light yellow interference colour. In Singrimari the percentage of titanites varies from 0.6% to 2.4% in case of the Upper Sandstones, while in Basal Sandstones it ranges from 1.01% to 4.02%. Titanites vary from 0% to 2.5% in Elephant Flat while it ranges from 0% to 13.97% in Kalijhora.

Apatites grains are found only in Singrimari and Kalijhora. These grains are colourless to straw green in colour, sub-angular, show parallel extinction and low birefringence. The colourless grains show prismatic habit more clearly than the straw green type grains which mark themselves as sub-angular. Overall, these grains are not so common. The percentage of apatite in Singrimari varies from 1.03% to 1.2% in case of the Upper Sandstones while in case of the Basal Sandstones it ranges from 2% to 2.2%. The percentage of apatite in Kalijhora varies from 0% to 2.57%.

Chloritoids are identified by features like dark greenish to black colour, sub-angular to sub-rounded forms and a translucent border surrounding an opaque core. The typical scaly flakes or wisps are not clearly visible. The grains show nearly straight extinction when aligned along its longer dimension. Pleochroism is strong. However, the dark body colour of the grains blanket the clarity of these characteristics. In Singrimari the percentage of chloritoid varies from 1.09% to 6.1% in case of the Upper Sandstones whereas in case of the Basal Sandstones it ranges from 1.05% to 4.9%. In Kalijhora it varies from 0% to 6.27%. Chloritoids are not found in Elephant Flat.

A few minerals like cordierite, actinolite, brookite and biotite have been found only in Elephant Flat area.

Cordierite is sparse in terms of abundance and is marked by its subhedral, sub-rounded, slightly prismatic nature, light yellow colour with dusky tinge, and straight extinction when oriented parallel to their prismatic and longer dimension. The grains show white to light yellow interference colour. Sub-conchoidal fracture is seen. The percentage of cordierites varies from 0% to 2.84%.

Actinolite expresses itself as fibrous green elongated, subhedral to anhedral grains. Their cleavages are distinct. They are lower in abundance compared to the other minerals. The grains show inclined extinction of around 7° and exhibit green interference colour. Leaching is clearly seen in the actinolites and as a result, specks of iron are seen to be smeared in and around the actinolite grains. In fact, a few actinolites are themselves seen to be secondary after pyroxenes. The pyroxenes in this case are distinguished by their deeper green colour, higher relief and distinct cleavages. Evidences of transition from pyroxene to actinolite are seen. In this case, the two phases can be distinguished by the differences in relief and colour contrast. The percentage of actinolites varies from 0% to 4.56%.

Brookite is a rare entity and is identified by its high relief, light yellowish brown, slightly translucent, prismatic and tabular expression. Faint striations are seen parallel to the longer dimension of the grain and partial extinction is seen parallel to the striations. Many small opaques specks are seen as inclusions. The percentage of brookite varies from 0% to 1.5%.

Biotites are characterised by their brown colour, hexagonal and flaky habit. The biotites are marked by opaque minerals and rutile as inclusions. Biotite exhibits leaching and evidences of their secondary origin after amphiboles. The percentage of biotites varies from 0% to 5.39%.

Heavy Minerals and few Indices	**Singrimari (Upper)**	**Singrimari (Basal)**	**Elephant Flat**	**Kalijhora**
	Average of **19** Representative Samples	Average of **11** Representative Samples	Average of **30** Representative Samples	Average of **24** Representative Samples
Zircon	14.34	29.18	21.26	38.95
Tourmaline	1.23	0.95	2.19	38.1
Rutile	1.26	1.38	8.27	1.41
Kyanite	0.38	0.31	0.13	0.04
Staurolite	0.36	0.86	0.19	1.69
Epidote	4.12	4.3	1.72	6.65
Garnet	7.19	18.57	4.09	1.56
Chloritoid	2.75	2.46	Abs.	0.34
Opaque	68.48	39.8	58.43	6.64
Titanite	0.45	1.82	0.49	3.93
Apatite	0.05	0.45	Abs.	0.5

Cordierite	Abs.	Abs.	0.54	Abs.
Actinolite	Abs.	Abs.	0.78	Abs.
Brookite	Abs.	Abs.	0.08	Abs.
Biotite	Abs.	Abs.	1.84	Abs.
ZTR Index	59.45	55.8	44.1	84.18
Bl+El	20.46	36.54	33.22	83.27
Sm. Equant	11.66	23.74	6.53	9.9
Shape Index	2.07	1.74	5.92	8.41
Sm. Transparent	32.12	60.27	39.75	93.18
Density Index (O/NO)	2.28	0.68	1.55	0.07

Table 4: Average abundance and few indices of heavy minerals in the three study areas

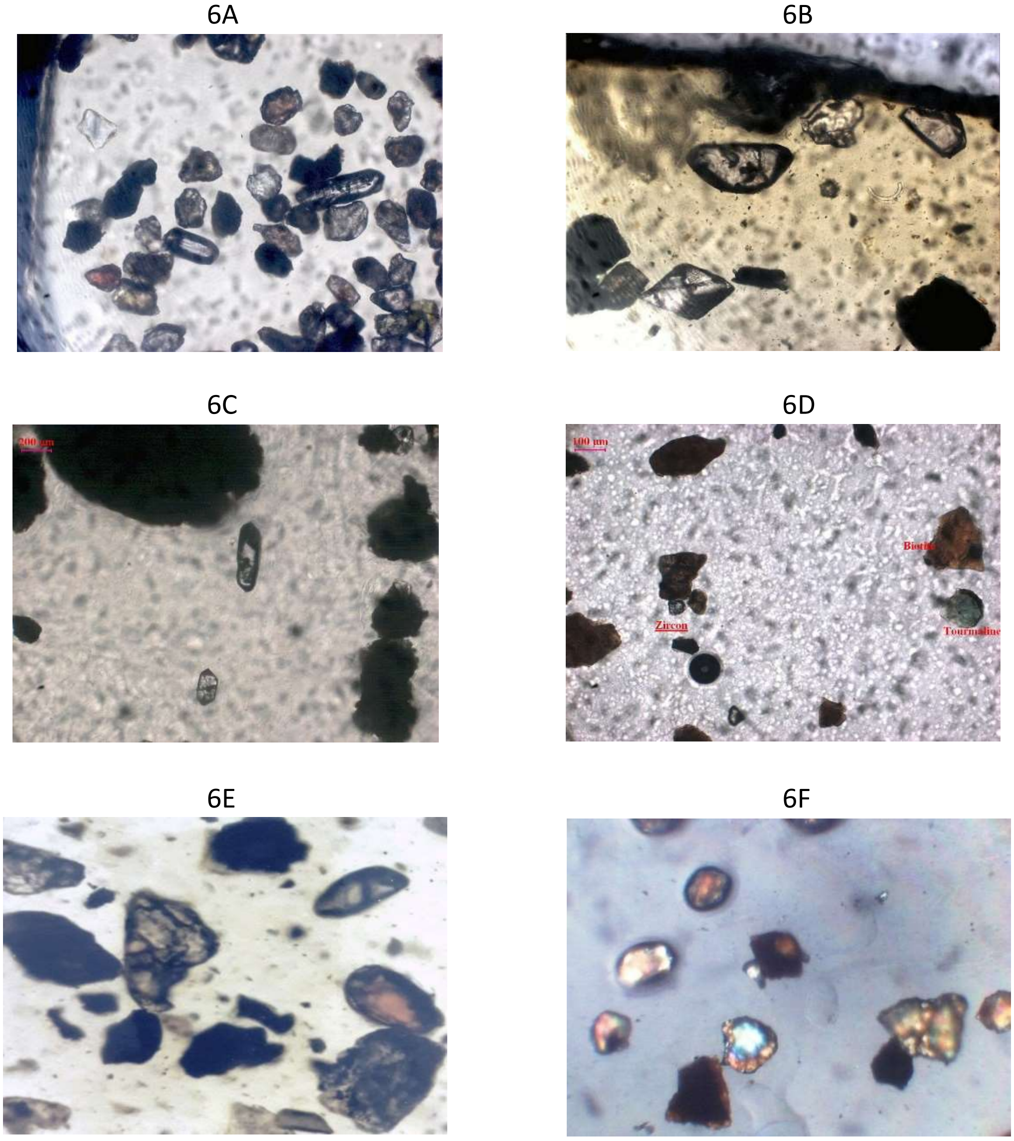


Figure 6: Photomicrographs showing (A) euhedral zircon, rutile, garnet , epidote and opaque grains in Singrimari sandstones; (B) Zircon, sphene and garnet grains in Singrimari sandstones. Magnification: 100X; (C) Two varieties of zircon: authigenic and nearly euhedral in Elephant Flat sandstones; (D) Garnet, biotite (leached), tourmaline, zircon in Elephant Flat sandstones; (E) Nearly euhedral zircon, sub-rounded tourmaline, garnet and opaque minerals in Kalijhora sandstones and (F) Zircon, epidote and rutile in Kalijhora sandstones. Magnification: 100X.

Heavy mineral indices: a few implications

While source rocks contribute the heavy minerals, their concentration are influenced by factors like nature of terrain, sediment influx from hinterland, energy conditions, weathering, length and nature of transportation, geomorphology as well as tectonic setup. Even marine action and coastal geomorphology influences heavy mineral concentration, (Cheepurupalli et al., 2012). Certain heavy mineral indices like ZTR, Shape index, Density index, reciprocal relationships between selected heavy minerals helps one to have a better understanding on many afore mentioned factors.

The summation of quantitative percentage of zircon, tourmaline, and rutile amongst the transparent, non-micaceous and detrital heavy minerals is an indication of mineralogical maturity of the sediments (Hubert, 1962). In the present case ZTR index is moderately high in Singrimari and Elephant Flat while it is extremely high in Kalijhora. ZTR index is commonly found to be high in beach or littoral zone depositional environments mostly due to long transportation distances from provenance and the prevailing high energy environment.

Shape Index is the ratio of bladed and elongated minerals like zircon, tourmaline, rutile, kyanite, actinolite etc to equant minerals like garnet and epidote while density index is the ratio of opaque heavy minerals to transparent heavy minerals. Analyses of shape index results show the values to be relatively higher in Elephant Flat and Kalijhora compared to Singrimari indicating dominance of bladed and elongated minerals in these two areas. Density index values do not vary much. However contribution from opaque sources was more in Singrimari towards the later stages of the sedimentation process. Hydraulic separation by density may have played some role in enhancement of bladed and elongated minerals in the Kalijhora and Elephant Flat areas as high density minerals settle more rapidly than the low density ones, (Prothero and Schwab, 2004). Selective decomposition of heavy minerals had taken place during transportation or in post depositional stages.

With an objective to have an idea about the nature of source rocks and their stability, reciprocal relationships between six selected minerals namely zircon, tourmaline, rutile, garnet, epidote and staurolite (Table 5) were calculated and analysed. Amongst the ultrastable minerals the dominance of zircon is high to very high in all the study areas. Tourmaline / garnet and tourmaline / epidote ratios is Elephant Flat and Kalijhora areas reveal the dominance of ultrastable minerals over metastable ones. The ratio metastable / ultrastable heavy minerals also reveal similar features. Relatively the share of ultrastable minerals is more in the Kalijhora and Elephant Flat compared to Singrimari. This may be due to the influence of provenance, recycling or changes coming into effect during transportation or post-depositional events. Proximity to the

Study areas	**Zircon / Rutile**	**Zircon / Tourmaline**	**Tourmaline / Garnet**	**Staurolite / Garnet**	**Tourmaline / Epidote**	**Metastable / Ultrastable**
Singrimari (Upper)	11.38	11.66	0.17	0.05	0.30	0.69
Singrimari (Basal)	21.14	30.72	0.05	0.05	0.22	0.75
Elephant Flat	2.57	9.71	0.54	0.05	1.27	0.19
Kalijhora	27.62	1.02	24.42	1.08	5.73	0.13

Table 5: Reciprocal relationships of selected heavy minerals in the three study areas

provenance has influenced the presence of more metastable grains in Singrimari compared to Elephant Flat and Kalijhora areas, (Fig. 7).

Compositions of clastic sedimentary rocks have been used as a tool to decipher tectonic setting in various ways, (Bhatia, 1983; Roser and Korsch 1986, Nechaev and Isphording, 1993). The discrimination diagram of Nechaev and Isphording (1993) used in the present case (Fig. 8) is a right angled triangle with the apices being coded as MF, MT and GM. MF represents heavy minerals like pyroxene, hornblende and olivine derived from mafic magmatic rocks. MT denotes common constituents of basic metamorphic rocks like amphiboles, garnet and epidote while GM stand for accessory minerals of granite and sialic metamorphic rocks like zircon, tourmaline, staurolite, kyanite, andalusite, monazite and sillimanite. Plots from all the study areas are found to cluster within the field of mature continental passive margin, a feature also corroborated by petrographic and geochemical findings, (Kar et al., 2017). Such settings are characterised by minerals which are dominantly derived from granites and sialic metamorphic rocks, reworked zones as well as deeply weathered zones which are tectonically less perturbed.

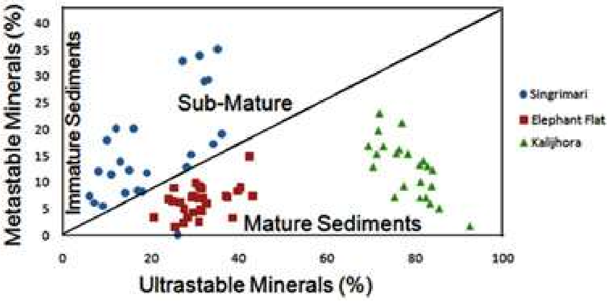


Figure 7: Relationship between ultrastable and metastable heavy minerals of the study areas, (after Pettijohn, 1957).

Statistical Analyses

Geological endeavours depend to a large extent on observations in which there is a large portion of uncertainty, (Davis, 2002). Application of statistics scales down the levels of uncertainty to an appreciable extent. A few statistical analytical procedures like bivariate correlation, principal component analysis and cluster analysis have been applied in the present case to arrive at a logical conclusion. It may be mentioned that although in petrographic procedures Singrimari heavy minerals were grouped into two: upper and basal, the groups have been merged into one for statistical analysis as it was found that there is more than 90% similarity in the nature of both the distributions.

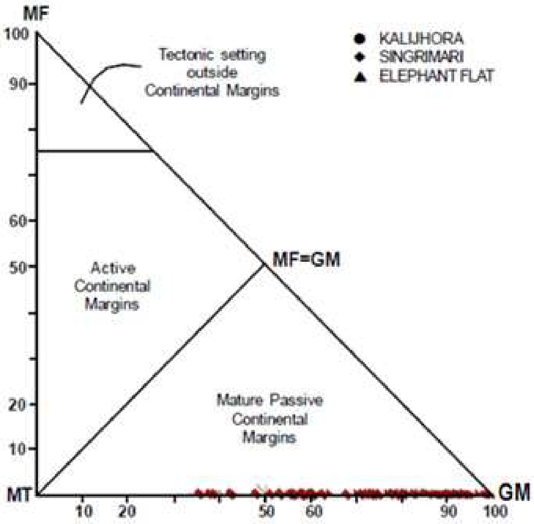


Figure 8: Tectonic discrimination diagram showing inter-relationship of the MF-MT-GM suites of heavy minerals from the study areas, (after Nechaev and Isphording, 1993).

Correlation Matrix Analysis

Detailed analyses of correlation matrix of the Singrimari heavy mineral assemblage (Table 6A) at 5% significance level show that the bivariate relationship between zircon-staurolite, zircon-garnet, zircon-apatite, zircon-sphene, staurolite-apatite and garnet-sphene are strongly significant. In Elephant Flat (Table 6B) epidote-brookite relationship is strongly significant while rutile-epidote, rutile-garnet and staurolite-cordierite relationships are moderately significant. Similarly in Kalijhora (Table 6C), bivariate relationship between rutile-kyanite and chloritoid-sphene are strongly significant while those between tourmaline-opaque and zircon-kyanite are moderately significant. Such relationships could be due to the fact that the source rocks responsible for contributing these minerals as found in the three study areas were closely associated in space ± time.

Furthermore, a strong to moderate retrogressive relationship exists between zircon-opaques, garnet-opaques and sphene-opaques in all the study areas suggesting that supply of opaque minerals were from sources that had very less zircon, garnet and sphene. Correlation analyses considering | r | >0.5 (c.f., Hota et al., 2002) also supports these observations.

		ZIR.	TOUR	RUT.	KYA.	STAU.	EPI.	GAR.	CHLO	APA.	OPAQ	SPH.
Correlation	ZIRCON	1.000	.027	-.046	-.152	.350	-.043	.556	-.012	.393	-.895	.498
	TOUR	.027	1.000	-.183	.027	.184	-.135	-.239	-.298	.028	.128	-.182
	RUTILE	-.046	-.183	1.000	-.110	-.154	-.097	.145	-.065	-.210	-.070	.111
	KYANITE	-.152	.027	-.110	1.000	-.213	-.032	-.144	-.009	-.127	.134	-.160
	STAUR	.350	.184	-.154	-.213	1.000	-.073	.239	-.077	.533	-.367	-.037
	EPIDOTE	-.043	-.135	-.097	-.032	-.073	1.000	-.060	-.168	.031	-.079	.045
	GARNET	.556	-.239	.145	-.144	.239	-.060	1.000	.053	.022	-.828	.628
	CHLO	-.012	-.298	-.065	-.009	-.077	-.168	.053	1.000	.023	-.055	-.133
	APATITE	.393	.028	-.210	-.127	.533	.031	.022	.023	1.000	-.271	-.177
	OPAQUES	-.895	.128	-.070	.134	-.367	-.079	-.828	-.055	-.271	1.000	-.606
	SPHENE	.498	-.182	.111	-.160	-.037	.045	.628	-.133	-.177	-.606	1.000
Sig. (1-tailed)	ZIRCON		.444	.404	.212	.029	.411	.001	.476	.016	.000	.003
	TOUR	.444		.167	.443	.165	.239	.102	.055	.441	.251	.167
	RUTILE	.404	.167		.281	.208	.304	.222	.367	.133	.356	.279
	KYANITE	.212	.443	.281		.129	.433	.224	.482	.252	.240	.199
	STAUR	.029	.165	.208	.129		.351	.102	.344	.001	.023	.424
	EPIDOTE	.411	.239	.304	.433	.351		.376	.187	.436	.338	.406
	GARNET	.001	.102	.222	.224	.102	.376		.391	.455	.000	.000
	CHLO	.476	.055	.367	.482	.344	.187	.391		.451	.386	.243
	APATITE	.016	.441	.133	.252	.001	.436	.455	.451		.074	.174
	OPAQUES	.000	.251	.356	.240	.023	.338	.000	.386	.074		.000
	SPHENE	.003	.167	.279	.199	.424	.406	.000	.243	.174	.000	

Table 6A: Matrix of correlation between heavy minerals of Singrimari Gondwana

		ZIR	TOU	RUT	KYA	STA	EPI	GAR	COR	ACT	BRO	OPA	SPH	BIO
Correlation	ZIR	1.000	.040	.096	-.050	.059	-.225	.237	.037	-.013	-.004	-.605	.224	-.108
	TOU	.040	1.000	-.297	.061	.021	-.340	-.142	.249	-.041	-.072	.009	-.131	-.067
	RUT	.096	-.297	1.000	.024	-.296	.428	.477	-.132	-.291	.308	-.701	.125	.212
	KYA	-.050	.061	.024	1.000	.313	-.108	.076	.153	-.192	-.087	-.055	.112	-.057
	STA	.059	.021	-.296	.313	1.000	-.275	-.138	.447	.025	-.099	.088	-.009	-.047
	EPI	-.225	-.340	.428	-.108	-.275	1.000	-.237	-.418	-.149	.521	-.126	.098	.199
	GAR	.237	-.142	.477	.076	-.138	-.237	1.000	.169	-.157	-.185	-.613	.323	.138
	COR	.037	.249	-.132	.153	.447	-.418	.169	1.000	-.036	-.171	-.122	-.122	.099
	ACT	-.013	-.041	-.291	-.192	.025	-.149	-.157	-.036	1.000	-.151	.064	.169	-.014
	BRO	-.004	-.072	.308	-.087	-.099	.521	-.185	-.171	-.151	1.000	-.190	-.168	.156
	OPA	-.605	.009	-.701	-.055	.088	-.126	-.613	-.122	.064	-.190	1.000	-.437	-.362
	SPH	.224	-.131	.125	.112	-.009	.098	.323	-.122	.169	-.168	-.437	1.000	.298
	BIO	-.108	-.067	.212	-.057	-.047	.199	.138	.099	-.014	.156	-.362	.298	1.000
Sig. (1-tailed)	ZIR		.416	.306	.396	.378	.116	.104	.423	.472	.491	.000	.117	.284
	TOU	.416		.055	.375	.457	.033	.226	.093	.414	.352	.482	.246	.363
	RUT	.306	.055		.449	.056	.009	.004	.243	.060	.049	.000	.255	.130
	KYA	.396	.375	.449		.046	.286	.345	.210	.155	.324	.386	.278	.382
	STA	.378	.457	.056	.046		.071	.233	.007	.447	.301	.323	.482	.403
	EPI	.116	.033	.009	.286	.071		.103	.011	.216	.002	.254	.303	.145
	GAR	.104	.226	.004	.345	.233	.103		.186	.203	.164	.000	.041	.233
	COR	.423	.093	.243	.210	.007	.011	.186		.426	.184	.260	.261	.302
	ACT	.472	.414	.060	.155	.447	.216	.203	.426		.213	.368	.187	.471
	BRO	.491	.352	.049	.324	.301	.002	.164	.184	.213		.157	.187	.205
	OPA	.000	.482	.000	.386	.323	.254	.000	.260	.368	.157		.008	.025
	SPH	.117	.246	.255	.278	.482	.303	.041	.261	.187	.187	.008		.055
	BIO	.284	.363	.130	.382	.403	.145	.233	.302	.471	.205	.025	.055	

Table 6B: Matrix of correlation between heavy minerals of Elephant Flat Gondwana sandstones

		ZIR	TOU	RUT	KYA	STA	EPI	GAR	CHL	OPA	SPH	APA
Correlation	ZIR	1.000	.086	-.016	.398	-.214	-.475	-.040	.031	-.380	.146	-.124
	TOU	.086	1.000	-.068	.111	-.411	-.273	.003	-.289	.382	-.493	.113
	RUT	-.016	-.068	1.000	.574	-.012	.188	-.341	-.195	.022	-.256	-.222
	KYA	.398	.111	.574	1.000	-.106	-.286	-.063	-.055	-.039	-.185	-.159
	STA	-.214	-.411	-.012	-.106	1.000	-.065	-.255	-.134	-.192	.199	-.114
	EPI	-.475	-.273	.188	-.286	-.065	1.000	-.118	-.175	-.165	-.326	.275
	GAR	-.040	.003	-.341	-.063	-.255	-.118	1.000	-.104	.100	-.194	-.164
	CHL	.031	-.289	-.195	-.055	-.134	-.175	-.104	1.000	-.150	.520	-.137
	OPA	-.380	.382	.022	-.039	-.192	-.165	.100	-.150	1.000	-.472	-.038
	SPH	.146	-.493	-.256	-.185	.199	-.326	-.194	.520	-.472	1.000	-.082
	APA	-.124	.113	-.222	-.159	-.114	.275	-.164	-.137	-.038	-.082	1.000
Sig. (1-tailed)	ZIR		.344	.470	.027	.157	.010	.427	.443	.033	.248	.282
	TOU	.344		.376	.303	.023	.099	.494	.085	.033	.007	.300
	RUT	.470	.376		.002	.479	.190	.051	.180	.459	.113	.148
	KYA	.027	.303	.002		.312	.088	.386	.399	.428	.194	.228
	STA	.157	.023	.479	.312		.382	.115	.266	.184	.175	.298
	EPI	.010	.099	.190	.088	.382		.291	.207	.220	.060	.096
	GAR	.427	.494	.051	.386	.115	.291		.314	.321	.182	.222
	CHL	.443	.085	.180	.399	.266	.207	.314		.242	.005	.262
	OPA	.033	.033	.459	.428	.184	.220	.321	.242		.010	.431
	SPH	.248	.007	.113	.194	.175	.060	.182	.005	.010		.352
	APA	.282	.300	.148	.228	.298	.096	.222	.262	.431	.352	

Table 6C: Matrix of correlation between heavy minerals of Kalijhora Gondwana sandstone.

Principal Component Analysis (PCA)

Principal Component Analysis is a sophisticated multivariate statistical technique which transforms a number of possibly correlated variables into a smaller number of variables called principal components. PCA helps to analyse interrelationships between several variables concurrently. It is a way of identifying patterns in data and expressing the data in such a way as to highlight their similarities and differences without much loss of information (Davis, 2002). Only those principal components which are statistically significant and greater than unity (1) are used for geological interpretation.

Heavy Minerals	**Component**				
	1	2	3	4	5
Eigenvalues	3.284	1.856	1.287	1.128	1.060
Percentage of total variance	29.852	16.872	11.696	10.257	9.636
Cumulative percentage of total variance	29.852	46.724	58.420	68.677	78.313
ZIRCON	**.873**	.165	-.035	-.030	.164
TOURMALINE	-.155	**.517**	-.539	-.384	.175
RUTILE	**.063**	-.507	-.066	-.358	-.492
KYANITE	-.281	-.077	-.014	.066	**.796**
STAUROLITE	.453	**.675**	.045	-.108	-.179
EPIDOTE	.009	-.045	-.263	**.892**	-.167
GARNET	**.838**	-.290	.026	-.082	.086
CHLORITOID	.006	-.123	**.877**	-.034	.120
APATITE	.334	**.721**	.264	.170	-.137
OPAQUES	-.966	**.040**	-.006	-.051	-.128
SPHENE	**.679**	-.469	-.282	.018	.104

Extraction Method: Principal Component Analysis; 5 components extracted.

Table 7A: Matrix of five components for the 11 heavy minerals of Singrimari Gondwana sandstones

In case of Singrimari (Table 6A) five principal components which are greater than unity account for a cumulative percentage of total variance of 78.313. The principal component – 1 includes minerals like zircon, rutile, garnet and sphene while principal component – 2 includes tourmaline, staurolite, apatite and opaques. Chloritoid, epidote and kyanite make up lone representations as principal components – 3, 4 and 5.

In case of Elephant Flat (Table 6B) six principal components which are greater than unity account for a cumulative percentage of total variance of 78.213. The principal component – 1 includes minerals like rutile, epidote and garnet while principal component – 2 includes staurolite and cordierite. While principal component – 3 is marked by kyanite, principal component – 4 is represented by actinolite, opaques, sphene and biotite. Tourmaline and brookite marks principal component – 5 while zircon marks principal component – 6.

In case of Kalijhora (Table 6C) six principal components which are greater than unity account for a cumulative percentage of total variance of 86.825. The principal component – 1 includes minerals like tourmaline, garnet and opaque while principal component – 2 includes zircon and kyanite. While principal component – 3 is marked by rutile, staurolite and epidote, principal components – 4, – 5 and – 6 are marked by apatite, sphene and chloritoid respectively.

It is interesting to note that in Elephant Flat and Kalijhora areas, staurolite is almost equally loaded to two principal components and the association of staurolite and sphene is common in both the areas.

Heavy Minerals	**Component**					
	1	2	3	4	5	6
Eigenvalues	2.946	2.339	1.462	1.250	1.135	1.035
Percentage of total variance	22.662	17.996	11.249	9.614	8.729	7.964
Cumulative percentage of total variance	22.662	40.658	51.906	61.521	70.249	78.213
ZIRCON	.330	.486	-.196	-.404	.221	**.548**
TOURMALINE	-.336	.288	.159	-.329	**.455**	-.211
RUTILE	**.849**	-.085	.226	-.121	-.149	-.084
KYANITE	-.042	.321	**.482**	.322	-.416	.246
STAUROLITE	-.355	**.427**	.359	**.426**	.090	.404
EPIDOTE	**.466**	-.720	.140	.221	.047	.144
GARNET	**.579**	.541	-.064	-.139	-.311	-.301
CORDIERITE	-.209	**.623**	.395	.116	.272	-.233
ACTINOLITE	-.220	.041	-.677	**.288**	**.280**	.122
BROOKITE	.349	-.502	.399	-.054	**.443**	.265
OPAQUE	-.847	-.427	-.018	**.080**	-.229	-.106
SPHENE	.454	.303	-.432	**.464**	-.065	.131
BIOTITE	.430	.023	.047	**.539**	.413	-.425

Extraction Method: Principal Component Analysis; 6 components extracted.

Table 7B: Matrix of six components for the 13 heavy minerals of Elephant Flat Gondwana sandstones

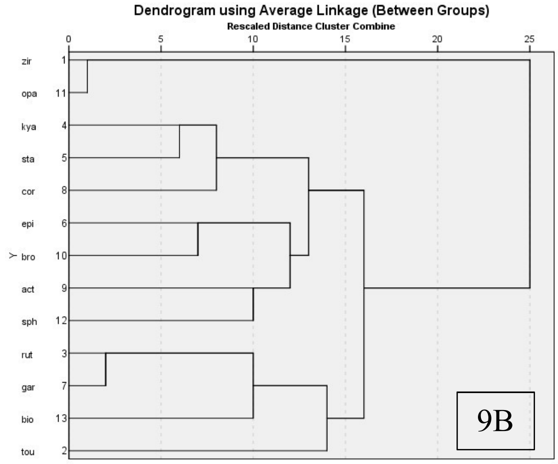
Heavy Minerals	**Component**					
	1	2	3	4	5	6
Eigenvalues	2.417	2.040	1.754	1.240	1.063	1.037
Percentage of total variance	21.975	18.549	15.947	11.269	9.661	9.424
Cumulative percentage of total variance	21.975	40.524	56.471	67.739	77.400	86.825
ZIRCON	-.192	**.761**	-.123	.386	-.098	-.271
TOURMALINE	**.692**	.250	-.350	.206	.343	-.008
RUTILE	.260	.325	**.813**	-.100	-.079	.243
KYANITE	.200	**.758**	.396	.030	-.090	.044
STAUROLITE	-.397	-.226	**.380**	-.413	**<u>.379</u>**	-.513
EPIDOTE	.158	-.683	**.461**	.248	-.398	.149
GARNET	**.188**	-.014	-.547	-.304	-.661	-.231
CHLORITOID	-.593	.102	-.248	-.015	.000	**.677**
OPAQUE	**.641**	-.091	-.243	-.432	.339	.303
SPHENE	-.891	.072	-.140	.032	**.143**	.095
APATITE	.141	-.419	-.054	**.724**	.219	-.071

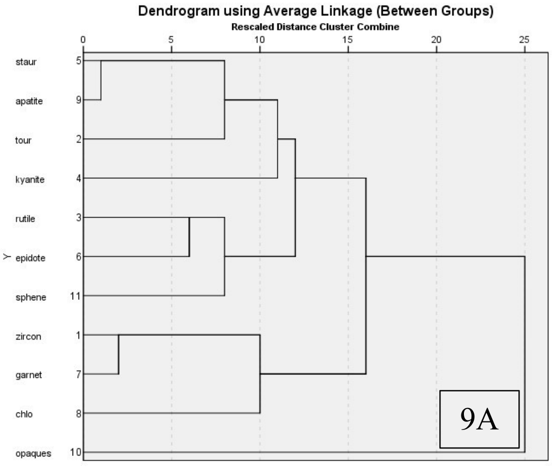
Extraction Method: Principal Component Analysis; 6 components extracted.

Table 7C: Matrix of six components for the 11 heavy minerals of Kalijhora Gondwana sandstones

Cluster Analysis

Cluster analysis is a sort of baffling assortment technique designed to create groups, clusters or associations which are homogenous and distinct from other groups, (Davis, 2002). The process attempts to deduce lineage amongst components of a distribution and it is regarded as an efficient way of displaying complex relationships among many objects. In the present case dendograms





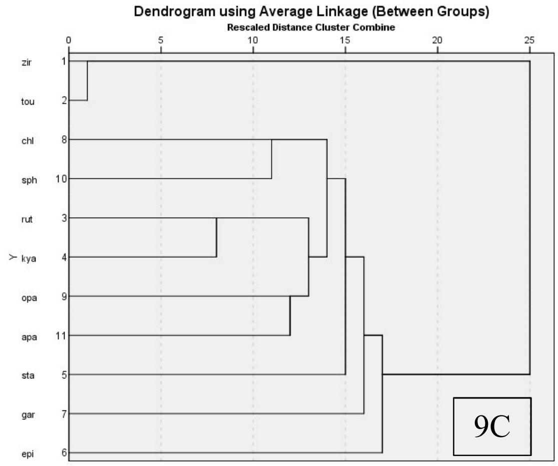


Figure 9A-C: Dendogram of heavy minerals from Gondwana sandstones of Singrimari, Elephant Flat and Kalijhora.

(Figures 9A, B and C) of distance matrix clustered by average linkage between groups were prepared)

Analyses of the dendograms reveal clusters which are found to match to a large extent with the principal component analysis findings. The major groups which can be related to provenance are enlisted herewith. In Singrimari three major clusters in the form of staurolite-apatite-tourmaline, rutile-epidote-sphene and zircon-garnet-chlorite are reflected from the dendogram. Elephant Flat is marked by clusters like kyanite-staurolite-cordierite and rutile-garnet-biotite. Chloritoid-sphene-rutile-kyanite and rutile-kyanite-opaques make up the two significant heavy mineral clusters in Kalijhora.

Discussion

Heavy minerals from all the three study areas bear both opaque and non-opaque varieties. While garnets are more dominant after opaques and zircons in the Singrimari suite, rutile occupies the similar status in the Elephant Flat suite. Zircon and tourmaline are very high in Kalijhora where opaque minerals are least compared to the other two areas of study. The overall composition may however be affected by allied processes during various phases of a sedimentary cycle like palaeoweathering, transportation, deposition and diagenesis (Morton and Johnsson, 1993).

Parallel growths in zircon indicate igneous genesis and is attributed to their survival during mechanical transportation. These grains are also considered as characteristic of anatectic, autocthonous or, metasomatic granitic rocks, (Poldervaart, 1955). The presence of sub-rounded zircons indicates a reworked source while tectonic impacts are reflected by the broken grains. Authigenic overgrowths seen are mostly due to post-depositional changes. Overgrowths and authigenesis is more in Singrimari and Kalijhora suites compared to the Elephant Flat assemblage. Zircons of basal sandstones of Singrimari and Kalijhora exhibit bimodality while upper sandstones of Singrimari and Elephant Flat shows distinct unimodality and these may be related to nature of source rocks. Further, it is seen that the abundance of opaque and transparent heavy mineral components of Upper Singrimari unit and Elephant Flat does not differ much from each other. The higher presence of garnets in the Singrimari suite and rutile in the Elephant Flat indicate influx from crystalline gneisses and schists and acid igneous rocks. Rutile and garnet are indicative of metamorphosed argillaceous sediments too, (Force, 1980). Garnets may be a product of breakdown of chlorites in the lower grade and mica in the higher grade as well as contributions from garnet rich metasedimentary rocks. The existence of etched garnets suggests etching during burial, (Grzebyk and Leszczynski, 2006). The presence of larger grains of rutile particularly in the Elephant Flat indicates contributions from granitic pegmatites. The presence of brown variety of tourmaline is indicative of metamorphic provenance, (Blatt et al., 1972) while epidote may be derived from acid igneous rocks, (Heinrich, 1956). Bluish tourmaline is generally contributed from pegmatites. Titanite is an indicator of gneissic and schistose provenance as well as late stage igneous derivatives. The association of garnet, staurolite and epidote also hints about a metamorphic source in the same way as does garnet, chloritoid, staurolite and titanite. Contribution of opaque sources was more in Singrimari deposits towards the later stages of the sedimentation process. Hydraulic separation by density may have influenced distribution of opaques in the Kalijhora and Elephant Flat compared to Singrimari. The presence of actinolites, rutile, opaque oxides hint at the presence of some basic / mafic source rocks. Overall, these heavy minerals may be linked to reworked sediments, low and high rank metamorphic rocks, sialic and minor mafic igneous rocks typically seen in a Precambrian terrain. Post depositional diagenetic as well as stress related changes are also seen.

ZTR index in the present case is moderately high in Singrimari and Elephant Flat while it is extremely high in Kalijhora and hints at relatively higher mineralogical maturity. High ZTR values in Kalijhora support its nearness to shoreline. Higher proportions of opaque minerals and the presence of more heavy mineral species have masked the ZTR values of Elephant Flat area. Analyses of shape index indicate dominance of bladed and elongated minerals in Elephant Flat and Kalijhora compared to Singrimari. This could have been possible due to hydraulic separation and longer distance of Elephant Flat and Kalijhora from the provenance. Study of reciprocal relationships show dominance of ultrastable minerals in Kalijhora and Elephant Flat compared to Singrimari and this was due to proximity of Singrimari area to the provenance as well as recycling or changes coming into effect during transportation as well as due to post-depositional events.

Analysis of plate tectonic settings following Nechaev and Isphording (1993) shows affinity towards mature continental passive margin. This finding is further corroborated by petrographic and geochemical findings. Such settings are characterised by minerals which are dominantly derived from granites and sialic metamorphic rocks, reworked zones as well as deeply weathered zones. Effects of uplift were probably more in the Elephant Flat suite compared to the Singrimari and Kalijhora areas. This is reflected by the presence of vulnerable species within the Elephant Flat sandstones.

Correlation matrix analyses of progressive and retrogressive relationships between different heavy minerals indicated that source rocks of the three study areas were closely associated in space □ time. Principal component analyses have helped to understand the different statistically significant heavy mineral assemblages in each of the study areas in order of their dominance and the same could be linked up with the possible source rocks. While five principal components dominate Singrimari assemblage, six components dominate Elephant Flat and Kalijhora. Cluster analyses with the help of dendograms reveal clusters that match to a large extent with the principal component analysis findings. In Singrimari three major clusters have been found while Elephant Flat and Kalijhora are marked by two significant heavy mineral clusters. Scrutiny of PCA and cluster analyses results show the heavy mineral suites to comprise of ultrastable and metastable minerals. This suggests derivation of the sediments from different lithologies. Close association of ultrastable and metastable minerals may be due to high stability and preservation potential of certain species and equal degree of mineral stability for others (Pettijohn, 1984). Garnet is seen to be a part of the Principal Component-1 in all the three study areas. It is possible that khondalites which are integral components of the East Ghats Supergroup and where garnet is a major constituent contributed these minerals.

On a regional scale, western part of the present day region of the Bay of Bengal was a landmass before the breakup of the Pangea. The Ninety-east Ridge which formed a water divide between India and Australia and the adjacent landward regions that now lie in the Bay of Bengal and west Australia basins, like the Wharton Basin, formed the catchment regions. These areas flourished with thick growth of vegetations and contributed to the main source of Gondwana coal deposits found in India and Australia, now preserved in fault bounded grabens, (Desikachar, 1977). Continued tensional stress during Permian times caused criss-cross rift basins like the Eastern Lesser Himalayan rift, Purnea-Rajmahal-Galsi rift, Kuchma rift etc in Eastern India which were connected to each other and also important depocentres for Gondwana sedimentation, (Biswas, 1999). These Permo-Triassic formations occur extensively in all the basins and show uniformity in many attributes, (Chakraborty et al., 2003). Many studies also emphasize the existence of Pan-African sutures in Australia and Antarctica with implications that the different crustal blocks of eastern Gondwanaland had closer co-existence around 500 m.a. ago, (Chatterjee et al., 2007). The Eastern Ghats belt exhibits strong Pan-African imprints. It is certain that the Gondwana sedimentation was a global tectono-sedimentation phenomenon and the initial tectonic instability of the whole setup was later ameliorated by crustal maturity. Judging by the occurrences of Lower Gondwana rocks in the Peninsula, it appears that these isolated outcrops were deposited in valleys of sluggish rivers which drained the land to the south and discharged the same into the Tethys at north, (Dutta, 1976). In context with the present study it may be stated that the fluviatile Singrimari Gondwanas (Baruah, 2007) were closer to the provenance and the drainage network extended further north wherein the Kalijhora and Elephant Flat Gondwana rocks were found deposited under marine shoreline influence. Under these circumstances it is highly probable that contributions of detritus from adjacent denuded Precambrian terrains particularly the Eastern Ghats Supergroup were very high.

Conclusions

Based on afore stated findings and discussion, the following points may be forwarded as conclusions:

1. Heavy minerals from all the three study areas bear both opaque and non-opaque varieties. The Singrimari suite comprise of heavy minerals like zircon + garnet + opaque minerals + tourmaline + rutile + chloritoid + epidote + kyanite + staurolite + titanite + apatite. The Elephant Flat suite hosts zircon + rutile + garnet + opaque minerals + tourmaline + epidote + titanite + cordierite + actinolite + staurolite + kyanite + brookite + biotite while the Kalijhora suite entombs zircon + tourmaline + rutile + kyanite + staurolite + epidote + garnet + chloritoid + opaques + titanite + apatite.
2. Elevated ZTR values indicate the presently analysed sandstones to be somewhat mineralogically mature. High ZTR values in Kalijhora support its nearness to shoreline.
3. Bladed, elongated and ultrastable minerals are dominant in Elephant Flat and Kalijhora compared to Singrimari. This could have been possible due to hydraulic separation and longer distance of transportation of Elephant Flat and Kalijhora sediments from the provenance.
4. The heavy minerals show affinity towards mature continental passive margin and may be linked to source rock types like reworked sediments; low and high rank metamorphic rocks, sialic and minor mafic igneous rocks which are typically seen in a Precambrian terrain.
5. Statistical tests like correlation matrix analyses, principal component analyses and cluster analyses indicate the source rocks of the three study areas to be closely associated in space □ time and a mélange of ultrastable and metastable minerals.
6. Prior to breakup of Pangea, the Ninety-east Ridge formed a catchment region which flourished with thick growth of vegetations and contributed to the main source of Gondwana coal deposits found in India and Australia. It is highly probable that contributions of detritus from the adjacent denuded Precambrian terrains particularly Eastern Ghats Supergroup were very high. Some contributions may also have been from distant sources located in the Trans-Antarctican mountains,
7. The fluviatile Singrimari Gondwanas with a northward palaeocurrent direction, (Baruah and Das, 2012) were closer to the provenance and the

drainage network extended further north wherein the Kalijhora (Kar et al., 2017) and Elephant Flat Gondwana rocks were deposited under marine shoreline influence.

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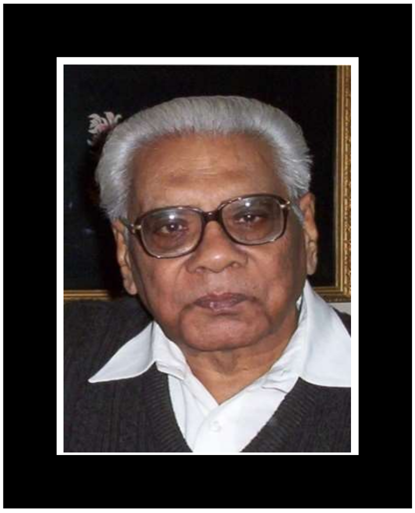
OBITUARY



Professor Virendra Kumar Srivastava (1930 – 2018)

Professor Virendra K. Srivastava was born on 7th September, 1930 at Bikaner (Rajasthan) to Justice Lakshmi Narayan of the Allahabad High Court. He spent most of his childhood and received early education till 1946 at Allahabad. Thereafter he moved to Banaras (now Varanasi) and obtained the Degrees of B.Sc. and M.Sc. in Geology from the Banaras Hindu University in 1948 and 1950 respectively, securing First Class and First Position. He commenced his professional career as Lecturer in Geology at University of Rajasthan, Udaipur in October, 1950, and shifted to join the newly established Department of Geology, Aligarh Muslim University, Aligarh in 1953 where he established himself as a friendly colleague and an excellent teacher, ever ready to help students. In view of brilliant academic record, he was awarded Smith-Mundt Fellowship and Fulbright Travel Grant for higher studies in U.S.A. in 1956. He obtained the M.S. Degree from the prestigious Johns Hopkins University, Baltimore in 1957, having completed advanced courses in Igneous and Metamorphic Petrology, Crystallography, and most importantly in Sedimentary Petrology, the latter under the guidance of Professor F. J. Pettijohn, a world-renowned authority of the subject. He was also admitted to Maryland Chapter of Sigma XI, U.S.A.

On his return to AMU he initiated his research programme by undertaking a detailed field and laboratory study of Talchir glacial deposits of the Damodar Valley Coalfields, and worked out a paleo-glacial transport model of Talcher tillites based on extensive data of embedded clast fabric and associated sedimentary structures, for which he was awarded the Degree of Doctor of Philosophy (Ph.D.) in Geology from AMU in 1961. Prof. Srivastava had been a great asset to sedimentology, actively engaged in various research projects on Aravalli, Vindhyan and Gondwana basins of peninsular India and Tertiary rocks of Himachal Pradesh. He supervised ten M.Phil and Ph.D. programmes, and published some 55 research papers in various national and international journals of repute. As a distinguished sedimentologist, he was invited occasionally by various universities and institutes to deliver lectures on varied aspects of sedimentary geology. He was elected as President of the Indian Association of Sedimentologists in 1984 and was nominated to the National Committee of International Union of Geological Sciences by INSA. He was selected by INSA to visit erstwhile Soviet Union in October 1988.

Professor Srivastava retired as Chairman, Department of Geology, AMU in 1990. He passed away in the night of October 23, 2018, having recovered from repeated chest infection. His passing away was peaceful at his residence in NOIDA in the presence of his sons Rajiv and Shantanu, daughter Nalini, and daughters-in-law, Jayashree and Nishi. His wife Hemlata Srivastava passed away 10 years back in 2008.

All of us at AMU and elsewhere, working and retired, and a large number of friends and former students, many of whom occupied top positions in various universities and national institutes like ONGC, GSI, NGRI, Coal India and private concerns, deeply mourn the loss of Prof. V. K. Srivastava, and extend heartfelt condolences to the bereaved family. May his Soul Rest in Peace.

Professor of Geology (Retd) **S M Casshyap**
Formerly: Chairman, Department of Geology &
Dean Faculty of Science, AMU

Professor and Chairman, Dept. of Geology, AMU (Retd) **M. Raza**

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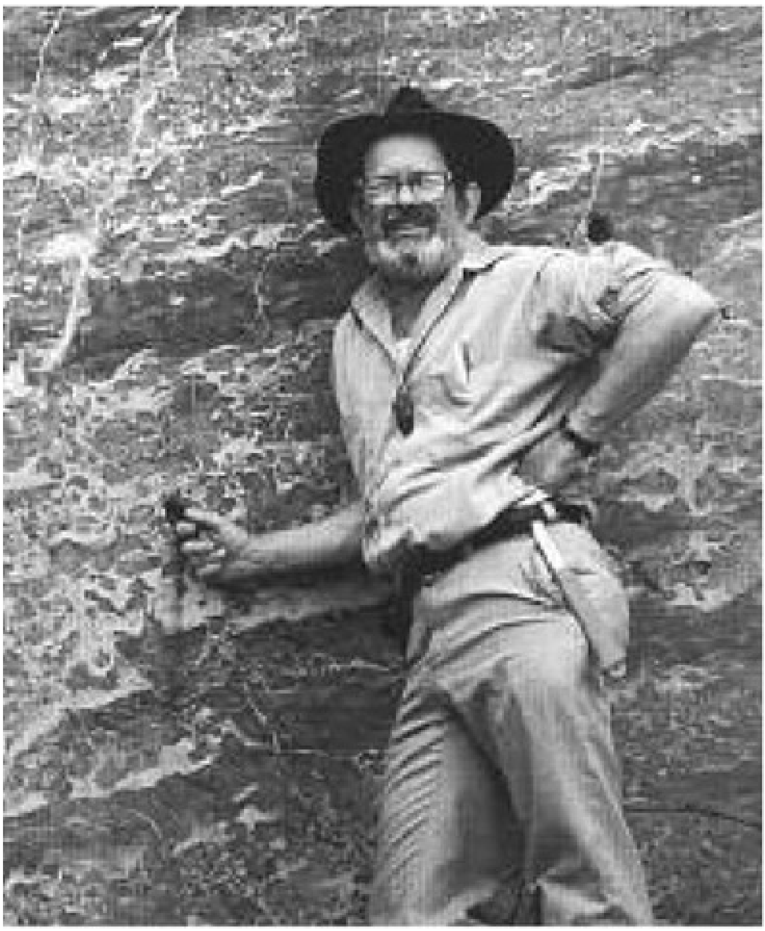

Robert Louis Folk

On June 4, 2018 the sedimentary geology community lost one of its heroes (www.jsg.utexas.edu/news/2018/06/remembering-bob-folk/). Robert Louis Folk's international reputation was founded on his classifications for limestones and sandstones but also on an ebullient personality that allowed him to build friendships and collaborations with colleagues all over the world. His entertaining presentation style always drew a happy crowd. He was popularly known as Bob Folk, although at times he would introduce himself as "Luigi", an Italian version of his middle name.

Bob authored over 100 research papers in international scientific journals and professional volumes. The value of his written and oral contributions earned him the W.H. Twenhofel Gold Medal from the SEPM (1979), the H.C. Sorby Medal from the IAS (1990), and the Penrose Gold Medal from the GSA (2000). In addition, he was awarded the Neil Miner Outstanding Teacher Award from the National Association of Geology Teachers (1989).

Bob Folk was born September 30, 1925, in Cleveland, Ohio. His father, George Billmyer Folk, grew up on a farm in the Shenandoah Valley and became a lawyer in Cleveland. His mother, Marjorie Kinkead Folk of Columbus, Ohio, was an accomplished pianist and painter. Bob became interested in rocks and minerals around age five.because of all the pretty pebbles in the moraines that had been carried down from the Canadian shield. He became attracted to sedimentary rock classification because there existed exotic names for igneous rocks like andesite or gabbro, but sedimentary rocks were just sandstone, limestone or shale; he thought there must be a better way. Later, he found the better way and his classification of sedimentary rocks is still the gold standard and established him as one of the founders of “Soft Rock Geology.”

Bob entered Penn State as one of only three geology majors that year. The turning-point in his career was in 4th semester when he took hand specimen petrology under the incomparable Paul D. Krynine, a titan of sedimentology who instilled into students the need for detailed observation and classification, and showed them how to think critically. In college Bob was a long-time member of the Nittany Co-op, where 20 meals were $5.25 a week. In 1946, while working as a waiter in the dining hall of the co-op, Bob met, Marjorie Thomas of Kennett Square, Pennsylvania. They were engaged three weeks later and married in six months.

After getting a Ph.D. in 1952, Bob worked briefly for Gulf Research & Development Company in Houston, Texas and Pascagoula, Mississippi, examining marine sediments and river sands of the eastern Gulf Coast. At that time, textural analysis was thought to be the “key to finding oil fields”. But Bob decided that his future lay in teaching, and in February, 1952, while driving through Austin, Texas, Bob walked in off the street to the Geology Department and asked if they had any jobs. Luckily, their sedimentologist was about to retire, so the department chair virtually hired him on the spot for $4,200 a year.

In those days, before the pressure of grant-driven science, the department allowed him to work on anything he pleased – dune sands, pebble shapes in Tahiti, modern carbonate sediments of Yucatan, the petrology of avian urine, the petrography of roofing tiles, enhanced stereo vision using two hands, black phytokarst from Hell, a unit of scuffle abrasion on stone steps, vitrified rat feces of aragonite, and a challenge to the concept that the pyramids of Egypt are made of epoxy-cemented crushed stone. He did this research without having to squander science-time writing proposals. Wherever he traveled Bob sought out the local culture and cuisine, using bits of languages he quickly acquired and applied with abandon. He was passably fluent in Czech and Italian, but never hesitated to make exclamations in Chinese. He liked to grade graduate student papers in Egyptian hieroglyphics, leaving it up to them to translate his marking system.

Teaching field camp in the Marathon Basin, Trans-Pecos Texas, Bob became involved in the problem of radiolarian/spicule cherts and the deep vs. shallow controversy he carried on with Earle McBride for over 3 decades. In 1973, at the invitation of Riccardo Assereto, Marge, Bob, and daughter Jenny spent six months at the University of Milano and fell in love with the Italian life style. As a result, in 1974-75, Bob and Earle expanded their interests in chert to Sicily, the Appenines, and the Alps. Thanks to the support from the University of Texas, Bob spent many summers working in bell’ Italia, usually with a student (preferably a “schiava” rather than a “schiavo”) or a colleague in tow.

From the introductory course he taught for many years to now well-established colleagues who revered him as a master, Bob’s impact as a teacher was tremendous. “Transformative” and “life-changing” are common descriptions from students speaking of their time in his classes. Perhaps unthinkable in modern classrooms, flying chalk bits regularly punctuated his lectures. Woe to a student who’s attention drifted! In graduate level lab sessions he went from microscope to microscope with his favorite wood-carved Australian snake stick; all of his students recall that poke in the ribs and the command to “Speak! What do you see?”. He had a near-magical ability to make people see more. Stories collected from his students on the occasion of his 90th birthday give an impression of what it was like to study and do research with Bob Folk: http://www.jsg.utexas.edu/alumni/files/folktales_book.pdf

His *Petrology of Sedimentary Rocks*, known as the Orange Book, a soft-bound locally published semi-text that grew from his course notes, first appeared in 1957 and was revised periodically until 1980. It was used as a reference for his graduate petrography courses and sold for little more than production costs. The 1980 version is available in a searchable pdf format: http://hdl.handle.net/2152/22930. Although dated and lacking references, it remains a fundamental resource for sedimentary petrologists and enjoyable reading. This humble-looking book is held by libraries world-wide and is a treasured volume on the personal shelves of many geologists.

In 1979 Bob's career took an abrupt turn. Always looking for another excuse to continue fieldwork in Italy, he hit on the idea of working on Roman travertines with his colleague Hank Chafetz. There he discovered that bacteria had played a major role in the formation of these carbonates. Bob retired from teaching in 1988 and that summer another scientific ("great leap forward, or catastrophic fiasco, your choice" – Bob's words) occurred when he and student Paula Noble studied the aragonite-forming hot springs at Viterbo, near Roma. Examining the samples with the SEM, Bob realized that he was seeing minute 0.1 micron ovoids that he interpreted as — NANNOBACTERIA! Few paid much attention to his 1992 GSA talk on this discovery, until four years later, a team from NASA shocked the world by their claim to have found nanno bacteria of similar size and shape in a Martian meteorite. Bob wondered "Do you think I could have ever gotten funding for a grant entitled 'Search for extraterrestrial life starting with hot-water Italian travertines'? No way!" Forms resembling nanno bacteria have since been found in mammal blood, dental plaque, kidney stones, clogged human arteries and arthritic joints. L.S. Land (as well as nearly all biologists) thought this was a career-busting fiasco. Regardless of one's preferred interpretation it is, however, undeniable that at small scales, many crystals do not display the expected euhedral shapes, as you can see in Folk's 2005 contribution to *Journal of Earth System Science* (Proceedings. Earth and Planetary Sciences /Indian Academy of Sciences), v. 114, no. 3, p. 369-374.

He had many hobbies, including a very complicated dice baseball game that he started in 1944 and maintained until last year. He enjoyed history, particularly about the Civil War (both of his great-grandfathers were in that war), non-realistic painting (several people have his acrylics), and collecting rocks, stamps and coins, as well as amateur astronomy.

Bob liked to dance with his wife and/or students at the iconic Austin bar and music hall the Broken Spoke, and loved country music as well as Grand Opera, symphony, and popular melodious music. Marge and he were members of the Wedding Ring class at First Methodist Church from 1954 on. They enjoyed almost every weekend at their log cabin overlooking Lake Travis. Bob was also an accomplished pasta chef (sauces only). The last item in his recipe for carbonara is "add a smattering of fireplace ashes."

We continue to collect stories and remembrances of Bob Folk. We are working together with Folk students Murray Felsher, Gus Cotera, and Miles O. Hayes to compile these materials for a web posting that documents the impact Bob Folk had on our community, to augment those already available. Please feel free to send us your contributions. Materials will be published as submitted, with no editing (except in a case of poor taste and/or bad spelling).

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Robert Henry Dott, Jr. (June 2, 1929 – February 27, 2018)

The geologic community sadly lost one of the giants of sedimentology and the history of geology of the 20th century- a renowned teacher, scholar, author, mentor, and humanist. Robert (Bob) H. Dott, Jr. died February 27, 2018 in Madison, WI after battling lymphoma for 11 years. Bob was born on June 2, 1929 in Tulsa, Oklahoma, son of prominent petroleum geologist Robert H. Dott, Sr. after attending elementary through high school in Norman, OK, Bob graduated from the University of Michigan with a B.S. in 1950 and an M.S. in 1951. He and his wife, Nancy (who died on January 13, 2018), were married on February 1, 1951. Bob completed a Ph.D. working under Professor Marshall Kay at Columbia University (1955), an early proponent of continental drift.

During two years of active duty in the U.S. Air Force, Bob participated in several Arctic research projects. After the Air Force, he worked in the petroleum industry in Oregon and California for three years. In 1958 he accepted a faculty position at the University of Wisconsin from which he retired in 1994 as an Emeritus Professor. Bob's academic career focused primarily on sedimentology, tectonics, and the evolution of the Earth. He conducted research in southwestern Wisconsin on Cambrian and Ordovician siliciclastic successions, around Wisconsin's famous Baraboo Hills, in southwestern Oregon, Tierra del Fuego, South Georgia Island, and Antarctica.

The Dott classification of sandstones (1964) is still widely used today. In 1971 Bob co-authored, with Roger Batten, a classic textbook of earth history, ***Evolution of the Earth***, (now co-authored with D.R. Prothero in more recent editions). Bob was very active in professional societies, including SEPM, GSA, and IAS, and served as President of SEPM from 1981-1982. He was co-convener of the First SEPM Research Conference held in 1980 in the Baraboo Hills of Wisconsin, which was entitled "Cratonic Shelf Sedimentation: The Orthoquartzite-Carbonate Suite Revisited". Bob was awarded Honorary Membership by SEPM in 1987, as well as the Twenhofel medal from SEPM in 1993, and in 2001 he received the Laurence L. Sloss Award in Sedimentary Geology from the Sedimentary Geology Division of the GSA. Bob was also the national chair of the History of Geology Division of the GSA, and in 1995 received the Division's Mary C. Rabbit Award for exceptional scholarly contributions of fundamental importance to our understanding of the history of the geological sciences. In April 2011 he received the American Geological Institute's Marcus Milling Legendary Geologist Medal and was named a Wisconsin Academy of Sciences, Arts and Letters Fellow in 2011.

During his career, Bob also developed a deep interest in the history of geology. He created a course in the subject and published studies of several important geologists, including James Hutton, father of modern geology. After retiring from teaching Bob continued to contribute to the history of geology and to the knowledge of Wisconsin geology. In 2004 he and co-author John W. Attig published the Roadside Geology of Wisconsin.

Over his 36 years on the faculty at the University of Wisconsin, Bob worked with 60 MS and PhD students, and post-doctoral fellows. Bob and his graduate students studied sediments deposited in nearly every environment from ancient Sahara sands to deep seas. It was common for Bob to keep up with, or even stride past the graduate students in the field, especially climbing up hills, earning him the title of "mountain goat". Bob was the ideal mentor; he continued close relationships with many of his former students up until his death. He was a model that many of his former students and their academic progeny have tried to emulate. He left a lasting legacy in sedimentary and historical geology and is deeply missed

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