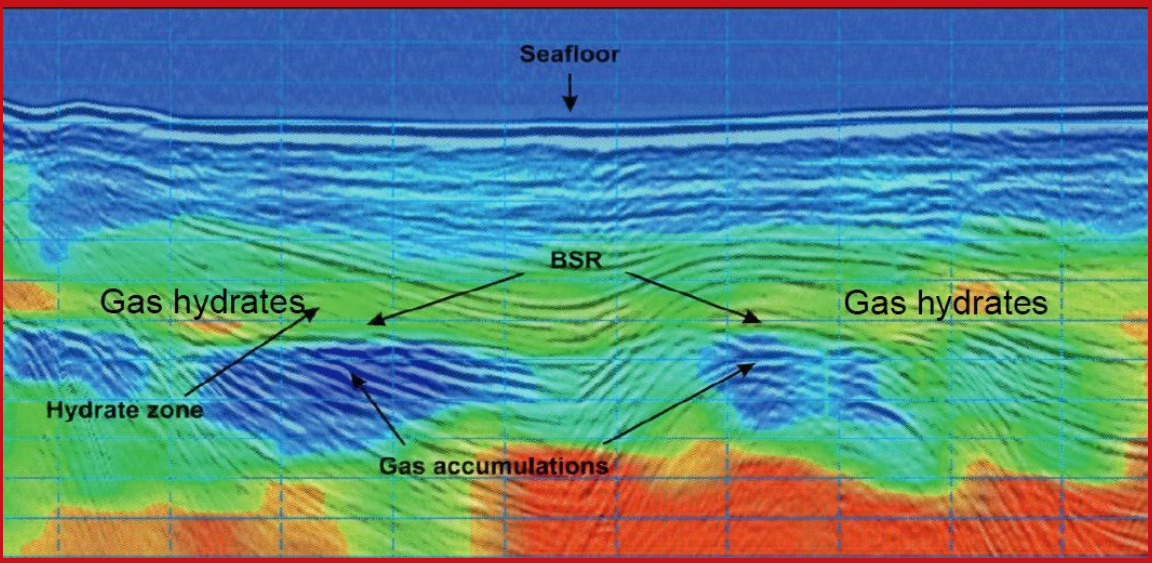
**ASTC Communications**
*Enlightening Minds for Transformation*

# GAS HYDRATES: A POTENTIAL, CLEAN ENERGY SOURCE FOR INDIA




**Dr. KALACHAND SAIN**

**Academy for Science, Technology and Communication**
*A Platform to Share Knowledge & Insights*

**Academy for Science, Technology and Communication**

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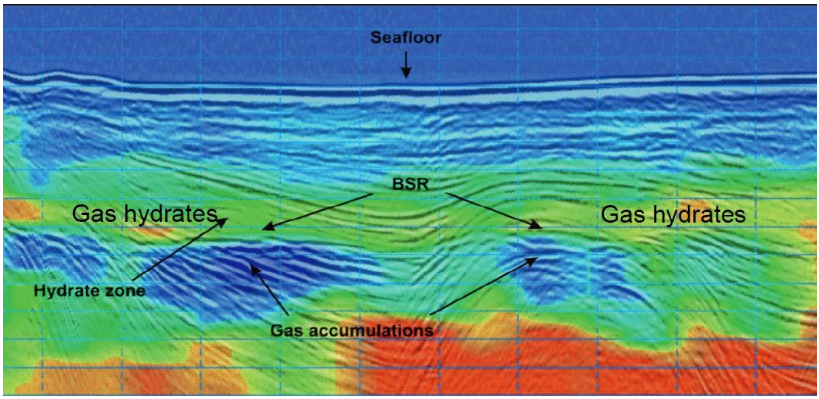
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## Dr Kalachand Sain



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# Preface



The burning of dried wood was likely the first controlled use of fuel by early humans. Since then, humanity has steadily expanded its energy repertoire, first coal, then other fossil fuels such as petrol, diesel, and natural gas; later electricity generated from these fuels, and more recently, renewable sources like solar, wind, and tidal power. The quality of human life has always been closely tied to the accessibility of energy, and today the level of development of a society is often measured by its per capita energy consumption.

For centuries, we have relied heavily on fossil fuels, but this dependence has led to both resource depletion and severe environmental consequences. The world is now urgently seeking alternative energy sources that are cleaner and more sustainable. “Gas hydrate” is one such promising option.

Water molecules can join hands, link and form cages. These cages, can imprison, or host another substance. Such cages, entrapping a host substance, are called “clathrates”. Warfarin Sodium, a blood thinner drug taken to prevent clots hence strokes is an example of clathrate structure. If a clathrate hosts gas molecule, we call them gas-hydrates; gas in water cage. A simple everyday example is carbonated ice cream, made by rapidly cooling a mixture of ice cream base and carbon dioxide under high pressure. The result is a product containing $CO_2$hydrates, which release a tingling sensation in the mouth. In nature, however, gas hydrates most often contain methane, a potent fuel.

Deep beneath the ocean floor, animal waste and microbial activity generate methane gas. Under conditions of high pressure and low temperature, typical of ocean depths, this methane becomes trapped within water cages, forming vast deposits of ‘gas hydrates’. These could potentially meet our energy needs for centuries.

Dr. Kalachand Sain, a leading expert on gas hydrates, explains this untapped source of fuel for our country. He gives us an in depth understanding of the source, science and technology of harvesting this massive energy source. The small booklet in your hands deals with a large energy source under water

**Dr. Ch. Mohan Rao**
Chairman-Scientific Advisory Council, ASTC

* Former Director CCMB, Hyderabad and Professor & Head, Department of Biological Sciences, BITS Pilani, Hyderabad.

# Editor's Vision



The Academy of Science, Technology, and Communication (ASTC) has released a series of booklets under the title "ASTC COMMUNICATIONS," which present contemporary scientific topics to a wide audience. This publication is the fourth in the series. "Gas-Hydrates: A Clean and Huge Potential Energy Source for India" was authored by Dr. Kalachand Sain, former Chief Scientist and Head of the Seismic Group at CSIR-NGRI, Hyderabad. Dr. Sain brings extensive expertise in seismotectonics, geodynamics, basin evolution, conventional hydrocarbons, non-conventional gas hydrates and geothermal energy resources, as well as sub-volcanic imaging and geo-hazards mitigation.

Dr. Kalachand Sain, a leading authority in this field, provided valuable insights from his research and recent scientific publications in this Communication. Methane stored in gas-hydrate reserves is estimated to be more than 1,500 times greater than India's current natural gas supply, suggesting the potential to satisfy energy demands for centuries. Developing gas-hydrate resources could enhance India's energy security while reducing dependence on coal and oil. While India holds significant promise for utilizing gas hydrates as an energy source, there are technical, economic, and policy obstacles to overcome. Dr. Sain presents a thorough summary of the latest advancements and future opportunities in gas-hydrate technologies. He concludes that integrating gas hydrates with renewable sources such as ocean currents, tidal waves, or wind power offers considerable promise for diversified energy production. Embracing low-carbon and gas-based innovations can support India's pursuit of energy independence and contribute to achieving UN clean energy objectives.

The ASTC remains dedicated to advancing scientific literacy and understanding through the publication of the "ASTC Communications" series at frequent intervals covering a wide range of contemporary scientific subjects, ensuring that readers from various backgrounds have access to current developments and insights in science and technology. Your feedback and suggestions are invaluable to help us continually improve the quality and relevance of the "ASTC Communications" series.

**RBN Prasad**
Chief Editor - ASTC Publications

*Former Chief Scientist & Head, Centre for Lipid Research, CSIR-Indian Institute of Chemical Technology, & Former President, Oil Technologists' Society of India.

# Pesident's Voice



Energy is essential to modern life. While the world continues to rely largely on coal, oil, and natural gas, these resources are finite and contribute significantly to climate change. This makes it imperative to explore cleaner, safer, and more sustainable energy alternatives.

Gas hydrates represent one such promising option. They are a naturally occurring form of energy found deep beneath the ocean floor and in polar regions, where methane gas is securely trapped within ice-like crystalline structures. Scientific studies conducted worldwide have demonstrated that gas hydrates contain an enormous amount of energy—potentially exceeding all known conventional fossil fuel reserves combined—while offering a comparatively cleaner alternative.

As the global energy system transitions toward sustainability, gas hydrates may serve as a vital bridge between present energy demands and long-term climate and environmental goals. India, with its extensive coastline and offshore sedimentary basins, is among the countries known to host significant gas-hydrate resources. For a nation with limited conventional hydrocarbon reserves but vast hydrate-bearing regions, understanding this resource is crucial for informed public discourse and long-term policy planning.

Beyond their energy potential, gas hydrates play an important role in Earth's natural systems. They are closely linked to the global carbon cycle, ocean–climate interactions, and the mechanical stability of seabed sediments. Studying gas hydrates therefore contributes not only to future energy security but also to environmental protection and a deeper understanding of the planet's dynamic processes.

This booklet is authored by Dr. Kalachand Sain, a distinguished geoscientist who has made significant contributions to the understanding of Earth's subsurface, energy resources, and natural hazards. He has served in leading Earth science institutions, advised national programmes on energy and climate, and contributed extensively to research on clean and emerging energy resources, including gas hydrates. His work effectively bridges advanced scientific research and policy-oriented solutions for India's sustainable future.

This booklet has been prepared as an outreach effort to introduce gas hydrates in a simple, accessible, and engaging manner. It aims to spark curiosity among students, inform the general public, and encourage young minds to explore careers in earth sciences, energy research, and environmental studies. It is hoped that this work will inspire informed discussion, responsible thinking, and a deeper appreciation of the hidden energy systems beneath our oceans and polar regions.

**Dr. C. Manikyamba**
President, ASTC and DAE-Raja Ramanna Chair (RRC), CSIR-NGRI

Chief Scientist & Head, Geochemistry Division and Former CSIR- Emeritus Scientist,
CSIR-National Geophysical Research Institute

# From Secretary's Desk

The Academy for Science, Technology and Communication (ASTC) is a premier institution committed to promoting scientific temper, strengthening science communication, and advancing the dissemination of scientific knowledge to society. It brings together professors, scientists, technologists, and medical professionals from diverse disciplines dedicated to research excellence and societal impact.

The Scientific Advisory Council (SAC) guides ASTC's academic vision and strategic direction. For over two decades, ASTC has thrived through voluntary support and collaboration from distinguished individuals and leading scientific organizations, with all major initiatives conducted without government funding—reflecting its strong community-driven and mission-oriented ethos.

ASTC organizes public lectures, seminars, symposia, refresher courses, and panel discussions, publishes scholarly works, nurtures young scientific talent, and recognizes excellence through fellowships and awards. Membership opportunities include Life, Annual, NRI, and Institutional memberships, recognizing outstanding contributions to science and technology. ASTC invites academicians, researchers and industry professionals to join as Fellows to strengthen the growing academic network, promote meaningful academia–industry interaction, and contribute ideas that inspire, engage, and innovate for the benefit of society.

To strengthen science communication, ASTC has launched a concise publication series titled ASTC Communications, presenting contemporary scientific topics in an accessible format for a wider audience. This fourth booklet, "Gas Hydrates: A Potential Clean Energy Source for India" by Dr. Kalachand Sain, explains what gas hydrates are, their significance, and their potential role in India's future energy security with a lower environmental footprint. Written in clear language, it aims to build public awareness and informed perspectives on clean energy.

Dr. Kalachand Sain, one of India's most cited Earth scientists, has extensive experience in Earth systems, energy resources, and climate-related research, and has advised the Government of India on energy initiatives. His work has been instrumental in connecting advanced scientific research with public understanding and national sustainability goals.

**Sri C.L. Narasimha Rao**
Secretary, ASTC

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# Gas Hydrates: A Potential, Clean Energy Source For India

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# Introduction

Energy is the prime engine for any country's socioeconomic growth and strategic advancement. However, the gigantic energy requirement of the world is mostly met by fossil fuels (coal, oil and natural gas), which have been ascribed to global warming and climate change (CC). The coal produces the maximum amount of $CO_2$ followed by oil and the least amount by natural gas. This has necessitated for a breakthrough in the green and/or renewable energy sectors such as hydrogen, hydro, solar, wind, geothermal, nuclear, ocean currents, tidal waves, biofuels, plastic to aviation fuels, agricultural residues to ethanol, EVs or batteries on wheels etc. as a remedial measure of climate changeability, specifically to reduce the emission of $CO_2$ and control further rise of temperature by 1.5-2.0°C. Nevertheless, no renaissance has occurred in the renewable/green energy sectors that can replace the fossil fuels. The 2021 report of International Energy Agency has predicted that fossil fuels will remain as main energy supplier. Therefore, we need to foster low-carbon energy supply and strengthen gas-based technology to meet cleaner energy requirement (SDG-7) at one hand and have much reduced impact to the CC (SDG-13) on the other hand. This can be achieved through gasification of coals and oils. As no major oil and natural gas fields have been discovered in the last many decades, and the era of exploration of oil and natural gas at ease is almost over, different kinds of unconventional and renewable energy resources are sought for India that has limited reserves of conventional energy resources. Gas- hydrates, which are ice-like crystalline compound (Fig.1 (a)) of methane (99.9%) and water, are envisaged as one of the best energy supplier. The energy stored within global gas-hydrates is more than two times the energy reserve of total fossil fuels. Unlike natural gas, oil and minerals, gas-hydrates are not stable at standard temperature and pressure (STP). Upon dissociation, one volume of gas-hydrates releases 164 volumes of methane and 0.8 volume of fresh water at STP (Fig.1 (b)).




**Fig.1: (a) Gas hydrates-bearing sediments, (b) One unit of gas-hydrates is equivalent to 164 units of gas at STP.**

Gas-hydrates are formed at high pressure and low temperature conditions when the methane concentration surpasses the solubility limit. In tropical countries like India, gas-hydrates have been found within a few hundred meters below the sea-bottom where the water depth is more than 500 meters that can exert sufficient pressure and have reduced bottom temperature. Gas-hydrates naturally exist in different morphological forms such as disseminated, nodular, grain coatings, veins, lenses, layered or massive (Fig.2). The common crystalline form of gas-hydrates is Structure-I in which methane is the main constituent (Fig.3). However, presence of higher molecular weight hydrocarbons or other heavier gases may form Structure-II or Structure-H with different properties.

Gas-hydrates have been recognised globally by geophysical, geochemical, geological and microbial surveys, and are recovered by drilling and coring. Fig.4 shows worldwide distribution of gas-hydrates occurrences along the continental margins and permafrost regions. It has been predicted that world's deposits of gas-hydrates contain ~$5 \times 10^{15}$ $m^3$ of methane gas, which is more than 10 times of total conventional natural gas accumulations, and only 15% production from such reservoirs can meet the global energy requirement for about two centuries. Since methane gas is the cleanest of all hydrocarbon fuels, its usage will cause less pollution to the atmosphere and hence play much reduced role to the global warming.

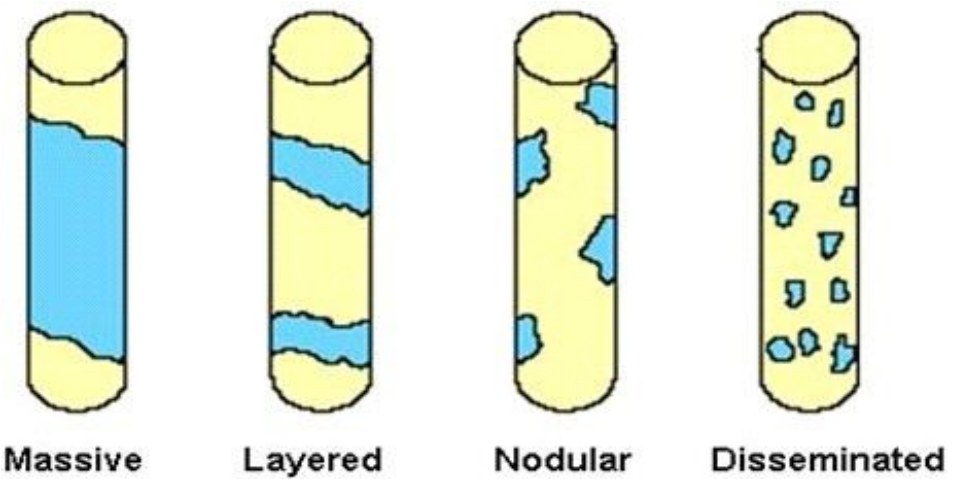



**Fig.2 Different morphologies of natural gas-hydrates (After Sloan, 1998).**

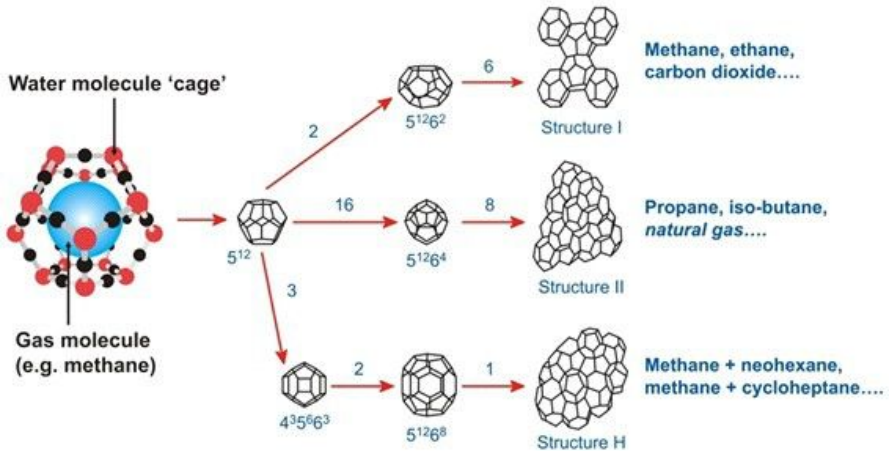



**Fig.3 Unit-cell structure of Gas-hydrate with different composition (After Ripmeester et al., 1987).**

Numerous factors such as bathymetry (500 - 4000 m), sea-bottom temperature (1.2 – 9.0 °C), sediment thicknesses (2 - 16 km), rate of sedimentation (3.5 - 40 cm/kyr), and TOC (0.14 - 6.18%) indicate good prospects of gas-hydrates in the vast offshore of India. The amount of methane frozen as gas-hydrates along the Indian margin is more than 1500 times of country's natural gas reserves. It has been prognosticated that ~10% production can meet India's crushing energy requirement for several decades. Thus, the potential of developing gas-hydrates as an energy resource of India is immense. Methane from marine gas-hydrates could serve as a bridge of India's energy transition from coal and oil to more sustainable gas-based resources for many centuries.

Although no viable production technology is available anywhere in the world, the success of test production at McKenzie delta of Canada in 2007/2008, Alaska of USA in 2012 and Qilian Mountains of China in 2016 over the permafrost regions, and in Nankai Trough off Japan in 2013 and in South China Sea in 2017 provide great hopes for energy security of several Asia-Pacific countries like India, Japan, South Korea and China (Chen et al., 2020). Therefore, delineation, characterization and assessment of gas-hydrates, and estimation of critical parameters such as porosity, permeability and pore pressure have been essential for developing geology-specific extraction technology. It is the laboratory experiments and field simulation studies that provide useful insight in understanding the dissociation kinetics of gas-hydrates for the development of economically-viable and environmentally-safe production technology.

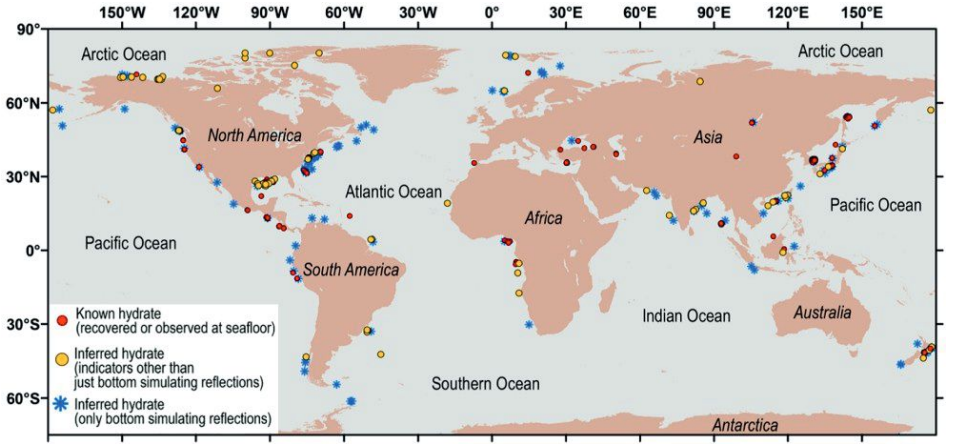



**Fig.4: Global map of gas-hydrates occurrences (After Ruppel and Waite, 2020)**

The present CC scenario, increasing demand of carbon-free energy, inadequate resources of conventional fossil fuels, no breakthrough in renewable/green-energy sectors have necessitated a shift towards gas-based industries or mixed energy resources. This has made gas-hydrates very promising, as its use can have much reduced carbon footprint compared to that produced by oil and coal. The Ministry of Petroleum & Natural Gas and the Ministry of Earth Sciences have formulated national programs of gas-hydrates. The Directorate General of Hydrocarbons (DGH) has been managing the National Gas Hydrates Program (NGHP) with the constituent members: Oil and Natural Gas Corporation Limited, Oil India Limited, Gas Authority of India Limited, CSIR-National Geophysical Research Institute (NGRI), CSIR-National Institute of Oceanography, ESSO- National Institute of Ocean Technology, Indian Institute of Technology at Kharagpur, Kanpur, Delhi and ISM-Dhanbad. These organizations/institutes are actively involved for the exploration and ground truth validation followed by technology advancement for safe production of gas-hydrates.

Some basic aspects related to where gas-hydrates occur, how are they formed, what are their structures and morphology, what is their p-t curve, how can they be explored etc. are available in published literatures. The global status on exploration and exploitation of gas-hydrates, when will they be produced safely, what are the bottlenecks, and feasible production techniques are also available in literatures. Here we present a comprehensive outline of gas-hydrates researches

and development, which include geological settings, exploration methodologies, technological advancements, and environmental impacts. This also stresses upon the international collaboration in harnessing gas-hydrates, underscoring their strategic role in India's transition to sustainable energy future.

## Exploration of Gas-hydrates

Identification of Gas-hydrates: Presence of gas-hydrates has been established mainly by seismic experiment with identifying an anomalous reflector, known as the bottom simulating reflector (BSR) on seismic section. This prime indicator for gas-hydrates is not a geological boundary but a physical interface between gas-hydrates bearing sediments above and water- or gas-bearing sediments underneath. This can be recognised based on certain characteristics like (i) mimicking the shape of seafloor reflector, (ii) cutting across underlying dipping sedimentary strata, and (iii) having opposite polarity with reference to the seafloor event (Fig.5).

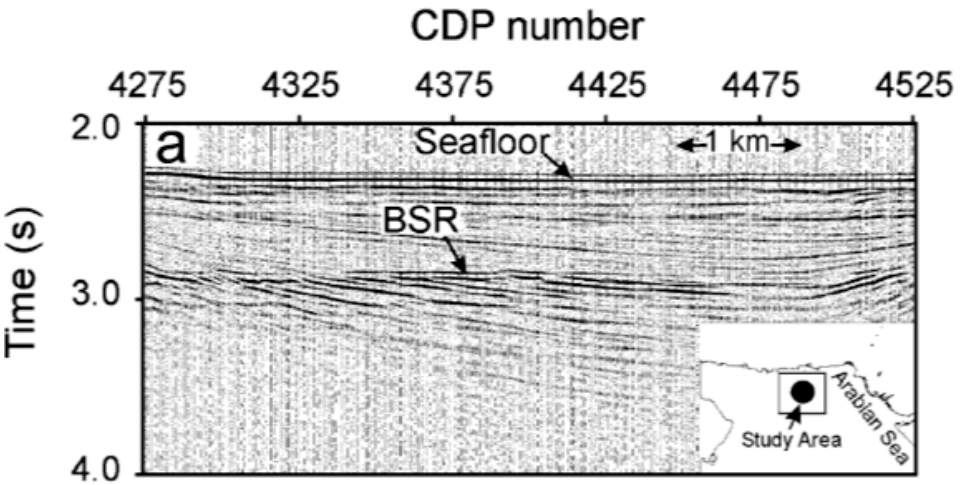



**Fig.5: A seismic section showing BSR, main marker for gas-hydrates, in the Makran accretionary prism (After Sain et al., 2000).**

Gas-hydrates Stability: The BSR is often associated with the base of gas-hydrates stability zone (GHSZ). Thus, it is required to prepare theoretical map of GHSZ that helps in detecting BSR from seismic data. The stability zone mainly depends on bathymetry, seafloor temperature and geothermal gradient in the marine environment, and may also be affected by presence of $CO_2$, $H_2S$ and dissolved

salts. Based on water depth, bottom temperature and geothermal gradient within the exclusive economic zone (EEZ) along the Indian offshore, the GHSZ map (Fig.6) was prepared to illuminate the gas-hydrates scenario in India.

Characterization of Gas-hydrates: The diagenetic processes can also generate BSR-like features. Thus, it is necessary to characterize the hydrate-related BSR for distinguishing it from the diagenetic BSR. It has been observed that hydrate-bearing sediments above the BSR are associated with high seismic velocity, amplitude blanking, low attenuation, and low sweetness. Whereas, gas bearing sediments below the BSR show low velocity, high reflection strength, frequency shadow, high attenuation, and high sweetness. The seismic attributes do not only ascertain the presence of gas-hydrates but also helps in delimiting gas-hydrates and underlying free-gas zones (Fig.7). By adopting appropriate approaches, the attributes, especially the seismic velocity and attenuation can be translated into the amount of gas-hydrates and free-gas across the BSR.

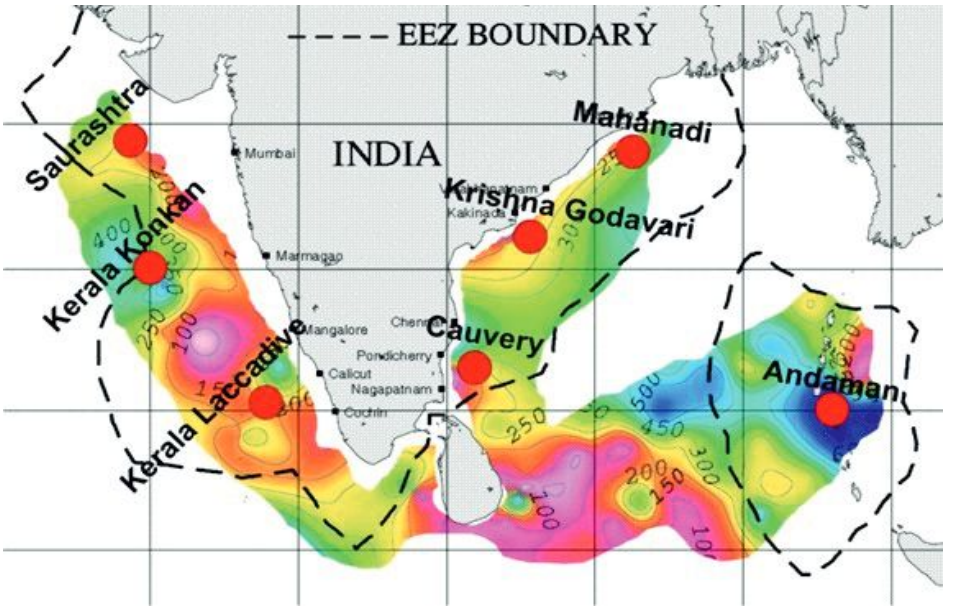



**Fig.6: GHSZ map in meter below sea floor (mbsf) within the Indian EEZ (dashed line). The most prospective basins (Krishna-Godavari, Mahanadi and Andaman) and less-explored but potential basins (Kerala-Konkan, Saurashtra, Kerala-Laccadive and Cauvery) are superimposed. Light pink and dark blue represent the minimum (0) and maximum (700) thickness of GHSZ (After Sain et al., 2011).**

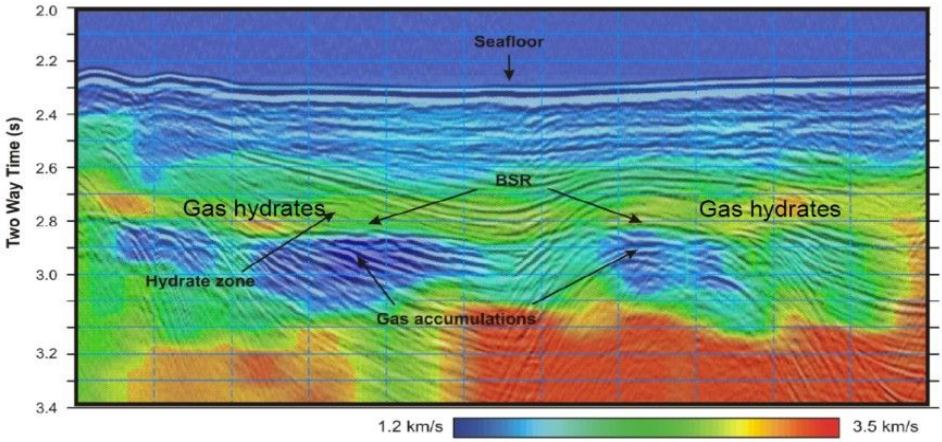



**Fig.7: High and low seismic velocities across the BSR indicate possible zones of gas-hydrates and free-gas (After Ojha and Sain, 2009).**

Quantification of Gas-hydrates: The rock physics modelling has been employed to the seismic velocities for the assessment of gas-hydrates and underlying free- gas. A suit of methods has been developed for the quantification of gas-hydrates from seismic data (Sain 2022 and references therein). A typical example of amplitude versus offset (AVO) data and rock physics modelling shows gas- hydrates as laterally varying between 4 to 15% and free-gas less than 3.5% across a BSR (Fig.8). Based on effective medium modelling, the vertical variation of gas- hydrates saturation has also been estimated from log data in the Krishna-Godavari (KG) basin. The 2D full waveform inversion of seismic data and simultaneous rock physics modelling have been used for the delineation of 2D saturation of gas-hydrates along a seismic line in the Arabian Sea.

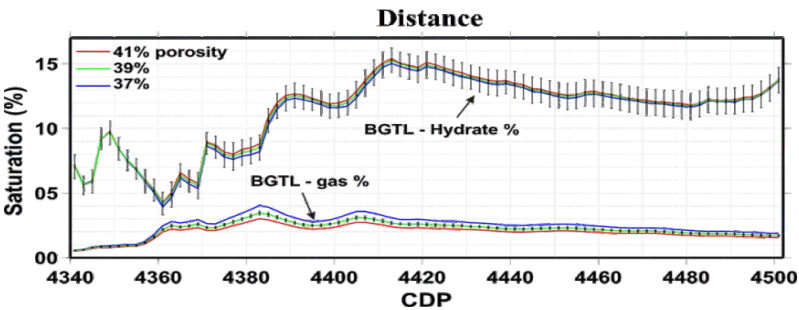



**Fig.8: Quantification of gas-hydrates and free-gas from AVO data and rock physics modeling across the BSR along the seismic line as shown in Fig.5 (After Ojha et al., 2010).**

Critical Parameters: Besides resource potential, it is very much required to estimate the critical parameters, which can be used for designing the geology and area specific exploitation technique for safety and feasibility. The seismic and log data have been analysed for calculating several critical parameters mostly in the eastern Indian margin (Sain, 2022 and references therein), and provide useful inputs.

## KG, The Most Prospective Basin in India

Analysis of available seismic and bathymetry data in KG basin shows evidences of slumping and sliding, fluid/gas paths, gas seepages, faults, fractures and turbidity deposits, etc. All these are important features that can be related to the formation of gas-hydrates. A large volume of multi-channel and ocean bottom seismic data have been acquired in 2010 by CSIR-NGRI between 500 to 2500 m water depths in KG and Mahanadi basins. The data show wide-spread occurrences of BSRs and hence gas-hydrates in both the basins, mainly in the KG basin (Fig.9). Other constituent members of NGHP have also identified gas-hydrates in KG and Mahanadi basins as well as in Cauvery basin and Andaman regions. The KG basin is a deltaic sedimentary basin. The continuous supply of thick sediments by the Krishna and Godavari rivers makes this basin a suitable womb for hydrocarbon accumulation and formation of gas-hydrates (Fig.10).

To validate the results of surface seismic data, to understand the geologic/structural controls on the formation and occurrences of gas-hydrates, to examine the effect of gas-hydrates on the physical properties of host sediments, and to investigate the microbiology and geochemistry of gas-hydrates, numerous holes were drilled and sediment-cores were recovered during the 1st Expedition of NGHP in 2006. The main outcome was the discovery of 120 m thick massive gas-hydrates deposit in fractured clay in the KG basin, one of the richest gas-hydrates deposits in the world. The wells were also drilled in the KG and Mahanadi deep water areas during the 2nd Expedition in 2015 in search of sand reservoirs that are most suitable for production, understanding the nucleation mechanism of gas-hydrates, comprehending lithology control and reservoir characteristics, and to find out suitable locations for future pilot production. This expedition successfully identified gas-hydrates in sand reservoir in KG basin. The log data coupled with seismic data have been used for the assessment of gas-hydrates, estimation of critical parameters, and providing geologic characteristics (Sain 2022 and references therein) in KG and Mahanadi basins and Andaman region. The KG basin (Fig.11) is the most prospective basin in the eastern Indian margin where a test production of gas-hydrates can be planned.

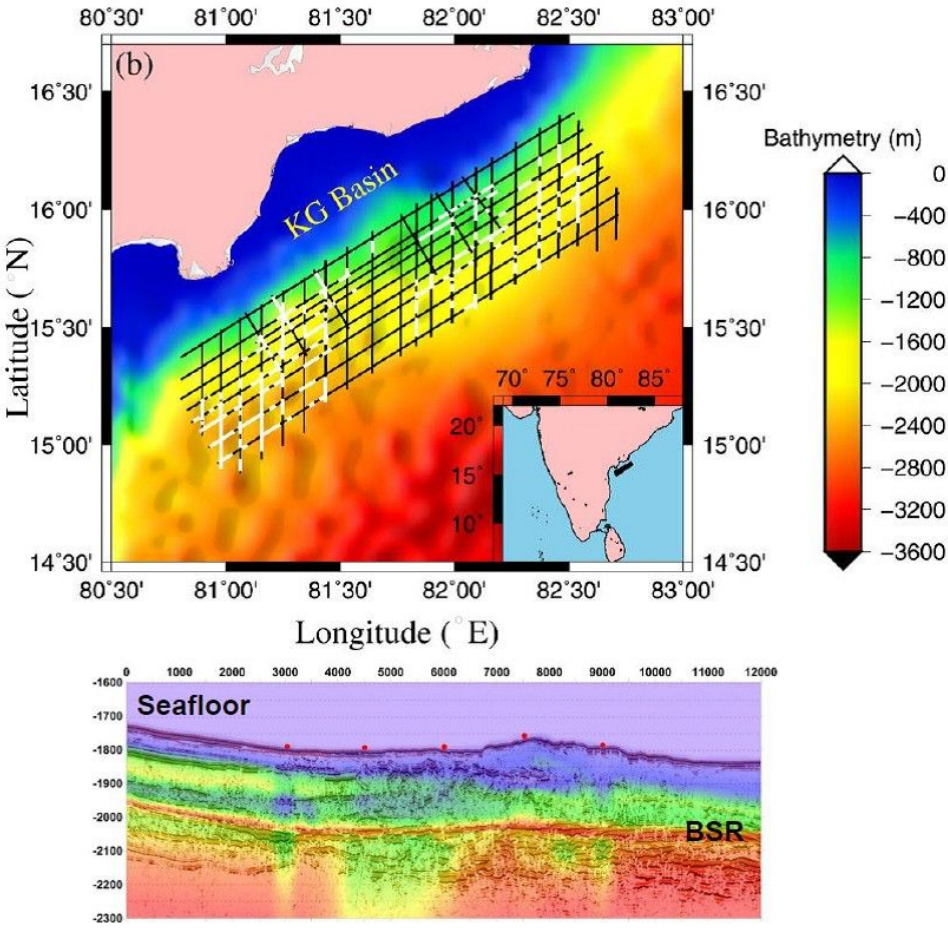



**Fig.9: Seismic line (black) along which data were acquired in KG basin. Wide-spread BSRs (white lines) are observed on seismic section. The bathymetry (m) is also shown. BSR, marker for gas-hydrates, is clearly observed over a typical small section. (After Sain et al., 2012).**

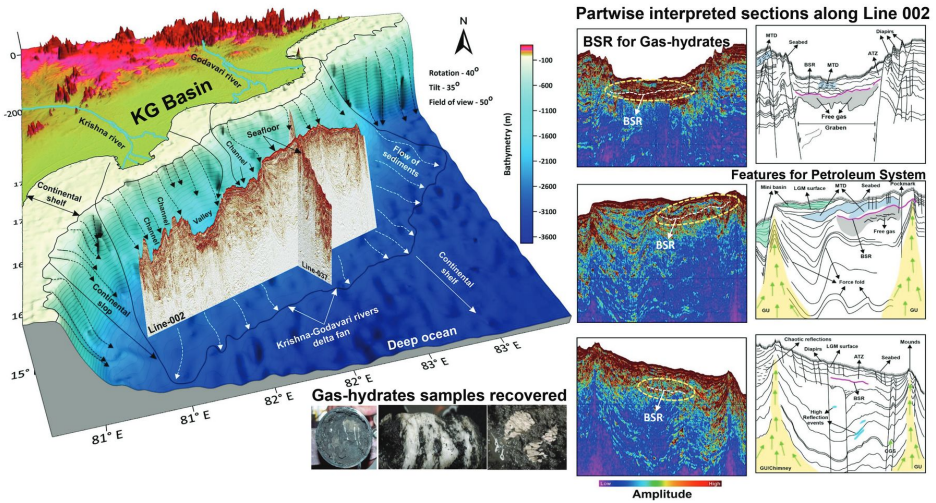



**Fig.10: KG offshore with the Krishna and Godavari rivers, seismic sections showing varied features for conventional hydrocarbons and gas-hydrates, and samples recovered.**

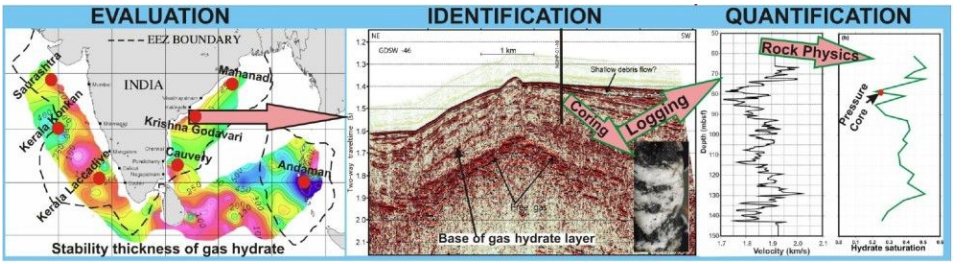



**Fig.11: The best site in KG basin for test production, as proven by seismic data, and validated by drilling and coring.**

## Production Methodologies

Since gas-hydrates are stable at high pressure and low temperature, conventional production methods cannot be used. The depressurization or heating or injection of chemical inhibitors like methanol, di-ethylene glycol (DEG), mono ethylene glycol (MEG) or a combination of these can be considered for suitable production (Fig.12). Extraction of gas-hydrates is also envisaged through molecular substitution by injecting a mixture of $CO_2$ and $N_2$. Such study will also strengthen the Carbon Capture, Utilisation, and Sequestration (CCUS) experiments by geological seizure of $CO_2$ and extraction of methane from marine gas-hydrates reservoirs.

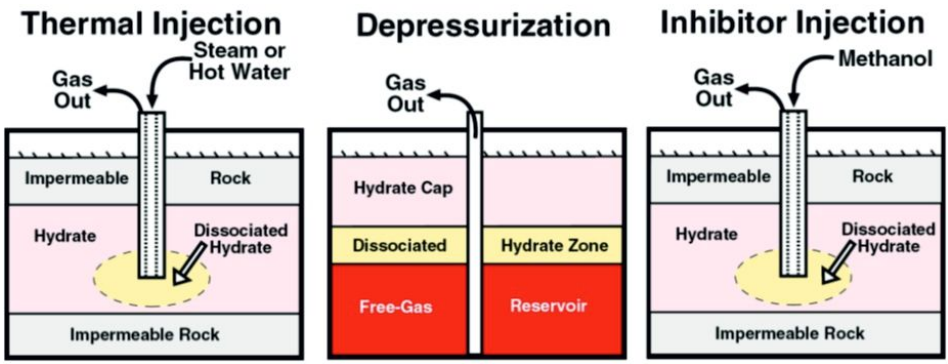



**Fig.12: Plausible methods for the production of gas-hydrates (After Holder et al., 1984).**

Though the technology for possible extraction of methane from gas-hydrates reservoirs does not exist anywhere in the world at present, but a lot of technological advancement has taken place. Based on depressurization method on a test production, Canada has produced ~13000 $m^3$ of cumulative gas for 6 days in the Mackenzie delta in 2007/2008. The United States has also test produced 24085 $m^3$ of cumulative gas for 6 weeks in Ignik Sikumi in 2012 by injecting a mixture of $CO_2$ and $N_2$. Based on depressurization method, Japan has demonstrated a test production of ~120000 $m^3$ of cumulative gas and 200 $m^3$ of water for 6 days in the Nankai Trough. The depressurization method seems to be the cost-effective for production of marine gas-hydrates. In this method, the pressure is lowered into the underlying free-gas zone, which gets transmitted into the overlying hydrate-bearing sediments and dissociates solid gas-hydrates into the gas. China has produced >120000 $m^3$ of cumulative gas in the South China Sea for about 7 days, probably by a combination of depressurization and heating methods.

All these tests were carried out in sand reservoirs and stopped after some days to avoid drilling hazards due to sand production. Singapore has been pursuing research to mitigate the challenges on sand mitigation and water management for sustainability. Germany has also focussed on sequestration of $CO_2$ in methane hydrates reservoir below seafloor through an initiative called SUbmarine GAs hydrate Reservoirs (SUGAR). China has been involved in introducing the fluidization principle of mining, in which uncontrollable gas-hydrates can be changed into manageable gas-hydrates by seabed closed lifting system. Indian drilling and coring programs have established gas-hydrates in fractured clay during the 1st expedition and in sand reservoir during the 2nd expedition in KG basin, and now looks forward for pilot production in the sand reservoirs.

## Environment Issue

It is to be mentioned that gas-hydrates, if not managed properly during the production or get dissociated by tectonic disturbances and/or rise in seabed temperature due to tidal loading and unloading, can not only release methane into the atmosphere for climate change but also lead to marine geo-hazards such as seafloor subsidence, slope failure, landslides, slumps and slides; and damage to oil platforms, coastal installation and fishing networks (Gupta and Sain, 2013). However, it was presented at the 9th International Methane Hydrates R&D Workshop in Hyderabad that the methane emission is unlikely, as the gas gets dissolved in water and hence cannot escape into atmosphere even during a big blowout. The engineering study, during the production test at Nankai Trough, did not exhibit any sign of slope instability also. Though these are positive strides, changes in geotechnical properties and methane emission are to be monitored that may lead to mass failure and play role to climate irregularity.

Gas-hydrates may prevent normal sedimentation and hence compaction, which may build excess pore pressure in the underlying free-gas zone and can cause hazards while drilling. During the $CO_2$-$CH_4$ molecular substitution process, more stable $CO_2$ hydrates are formed and methane are released. However, this may obstruct further contact between $CO_2$ gas and $CH_4$- hydrates and hence impede the substitution process for production. Again leakage of $CO_2$ may cause sea acidification or catastrophe to marine ecosystem. The use of chemical inhibitors to dissociate marine gas-hydrates can harm the living kingdom. We need to understand all these phenomena before producing gas from gas-hydrates. The economic benefit for production of gas-hydrates and protection of marine environment can be addressed by science-technology-innovation interface, and be alleviated by partnership with international organizations that are actively involved.

## Laboratrory Experiments and Simulation Studies

The marine gas-hydrates are quite complex, and it is not so easy to conduct in-situ experiments for comprehending the dissociation kinetics directly. Hence, gas-hydrates have been synthesized at high pressure reactors with varying sizes of clay particles and water saturation at CSIR-NGRI, first time in India, for studying formation and dissociation kinetics of gas-hydrates. The formation cycle reveals possible p-t conditions needed and the degree of sub-cooling, induction time, and gas uptake within the hydrates. The dissociation cycle gives a clear understanding of phase stability and enthalpies necessary for destabilization of

gas-hydrates. The study provided important implications with regard to the development of plausible extraction technology. The laser Raman spectroscopy technique affirms the hydrate formation by showing characteristic peaks of hydrates and gas phases at respective positions. The synthesis of gas-hydrates also provided useful input in understanding the CCUS processes. The laboratory experiments are also significant for understanding socially-relevant technological applications such as gas separation owing to selectivity of guest molecules; water treatment, desalination or potable water due to preferential host lattice; storage and transportation owing to larger volumetric compression; and removing hydrate plugs for flow assurance.

To overcome the environment barriers and to make the production method economically viable, field tests at gas-hydrates reservoirs are mandatory. However, direct field tests are not only cost intensive and risky, but are limited to short duration and constrained by vertical well configuration only. It is the reservoir simulation study that can provide the best possible field plan for production in commercial scale, mitigation of environmental challenges, and reducing the cost involved. Several reservoir simulators and codes are available (Ghosal et al., 2018 and references therein), which can solve governing equations of complex coupled processes that include mass and heat transfer, dissociation kinetics, mechanical deformation, multi-phase fluid flow physics etc. The simulation study helps in understanding the parameter sensitivity to the dissociation of hydrates and gas production for long duration as well as in understanding the efficacy of horizontal versus vertical drilling while depressurization, thermal stimulation, chemical inhibition or $CO_2$ sequestration or a combination of these.

## Scopes for India's Energy Security

As per the 2021 BP Statistical Review, India's import of more than 50% of natural gas in 2020 emphasizes the strategic importance of utilising domestic gas-hydrates for long-term energy security. Through the geophysical experiments and drilling and coring programs, India has established huge reservoirs of gas-hydrates, particularly in the KG offshore basin. The energy potential of gas-hydrates is so huge that only 10% extraction can meet India's overwhelming energy requirement for several decades. However, usage of gas-hydrates relies on technological innovation, international collaboration and government's initiative on regulatory framework. Japan's successful pilot production from marine gas-hydrates in Nankai Trough, the United States' environmental management practices, and

China's initiative of changing uncontrollable gas-hydrates into manageable gas-hydrates by seabed closed lifting system provide models for efficient production of gas from gas-hydrates reservoirs. China's program on pilot production of gas-hydrates from the South China Sea in 2017 highlights the benefits from the government and private partnership. India must encourage research for production of gas-hydrates, environment impact assessment, and public-private partnerships. With continued international collaboration, India can become a leader in developing gas-hydrates technology to drive hugely to sustainable development goals in strengthening India's energy security. To address the technological and environmental challenges, targeted regulations are to be formulated and executed for extraction of gas from gas-hydrates reservoirs.

CSIR-NGRI has established state-of-the-art Gas Hydrate Research Centre, which is fully equipped with the first-rate facilities for processing, modelling inversion, and advanced interpretation of seismic data (Sain, 2022 and references therein; Fig.13) along with laboratory amenities for comprehensive physical studies of gas-hydrates. The simulation studies can also be pursued by utilising the available computational facility.

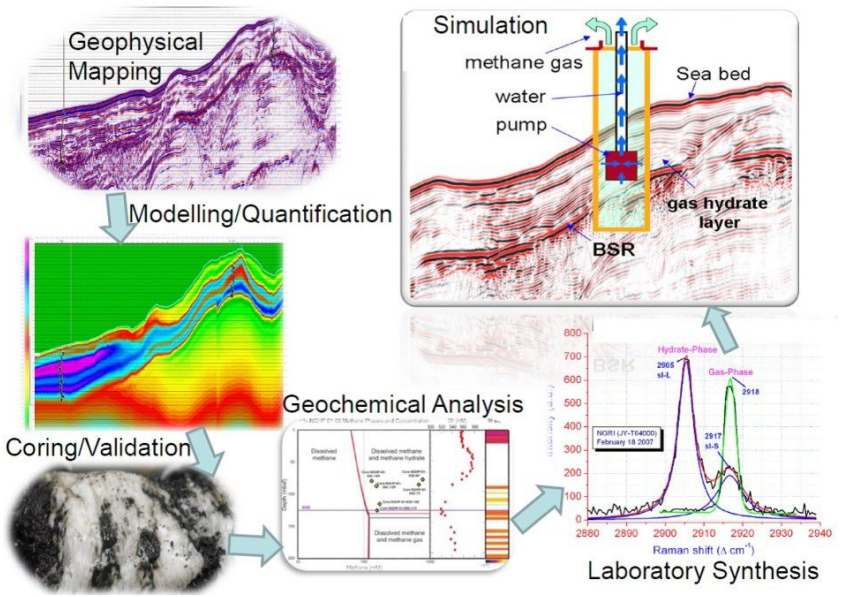



**Fig.13: Facility for comprehensive gas-hydrates R & D studies at CSIR-NGRI, Hyderabad.**

Several approaches based on traveltime tomography, full waveform inversion, AVO modelling, pre-stack depth migration, common reflection surface stack have been developed (Sain, 2022 and references therein). These tools can be improved upon and appropriately employed to available multi-channel and Ocean bottom seismic data for further exploration. The concept of artificial intelligence can be extended for delineating 3D architecture of gas-hydrates and free-gas bearing zones in better understanding the genesis of gas-hydrates. The rock physics modelling can be advanced in translating estimated physical properties into the quantification of gas-hydrates. Additionally, the data can be utilized for the derivation of critical parameters - porosity, permeability, pore pressure and geo-technical properties that are required for planning production test and development of production method suited to geological condition in the Indian offshore. Different simulation strategies are to be tested for comprehending the economic and environment aspects while tapping the huge potential of gas-hydrates. There lies a tremendous scope for the development of hybrid technology for mixed energy production by coupling gas-hydrates production with the ocean currents or tidal waves or wind energy. This will pave the way to meet India's crushing energy requirement for many centuries, as India produces indigenously less than one-third of her energy requirement, and faces elevated tariff by US.

## Conclusions

Gas-hydrates, which consist of mainly (99.9%) methane gas are envisaged as major future clean energy resources due to their huge potential along the Indian margin. It has been prognosticated that methane stored within gas-hydrates reserve is more than 1500 times of country's present natural gas reserve, which can sustain India's energy requirement for several centuries. Therefore, it makes sense to invest for the development and production of gas-hydrates because of their high market prospects to secure India's energy security and reduce direct dependency on coal and oil. Several institutes/organizations under the umbrella of Indian NGHP have generated plethora of information with regard to delineation and assessment of gas-hydrates along with derivation of critical parameters and understanding the petroleum system and dissociation kinetics, which are necessary for developing geology-specific production technology.

As unmanageable dissociation of gas-hydrates may pose threats to seafloor stability, marine ecosystem, and climate change, gas-hydrates are to be exploited in a controlled manner. Based on resource potential and geotechnical properties of gas-hydrates reservoirs, different simulation studies must be encouraged for

development of economically viable and environment-safe production method to exploit the huge energy potential of gas-hydrates. India must collaborate with countries like Japan, United States, and China, which have made major strides for the successful test production and environment related research for strengthening the research and development of gas-hydrates. Since gas-hydrates have been established in sand-dominated reservoirs in KG basin by drilling and coring, a pilot production must be intended at least at one location over there. Hence, we must be ready with the identification of most potential gas-hydrates reservoirs before a feasible production technology is made available.

There lies a tremendous scope for synergy through the development of hybrid technology for mixed energy production by coupling gas-hydrates with the ocean currents or tidal waves or wind energy. As we require to foster the low-carbon energy supply and strengthen the gas-based technology, production of gas-hydrates can make India energy self-reliant and meet the UN initiatives of SDG-7 (affordable and clean energy) and SDG-13 (climate action).

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Kalachand Sain obtained his M.Sc. (Tech) in App. Geophysics from IIT-ISM, Dhanbad, and Ph.D. in Active Seismology from CSIR-NGRI, Hyderabad in 1995. He visited Cambridge University (UK) and Rice University (USA) as a post-doctoral Fellow, and USGS (USA) as a Visiting Scientist. He has been continuing his research as JC Bose National Fellow at CSIR-NGRI. He is an honorary Outstanding Prof. at AcSIR, Ghaziabad and Advisor at DST Centre of Excellence for Climate Information – IIT Delhi. He was Director at Dehradun- based WIHG-DST, and held additional charge as Director of BSIP-DST, Lucknow for a short span, and was Chief Scientist & Head of Seismic Group at CSIR-NGRI.His expertise includes Machine Learning, seismic tomography, attribute characterization and rock physics modelling. His research covers seismotectonics, geodynamics, basin evolution; conventional hydrocarbons, non-conventional gas-hydrates & geothermal energy resources; sub-volcanic imaging; geo-hazards and remediation. He is the Subject Editor ofProceedings of INSA (Earth Sciences), and was in the Editorial Board for'Encyclopaedia of Solid Earth Geophysics' (2011 and 2021) by Springer. He visited many countries, completed several international/national collaborations, delivered more than hundred plenary/invited talks (many are available in Websites/ YouTube), organised International conferences, convened and chaired sessions at international/ national fora, conducted short courses on advanced topics/methodologies, completed INR 62 crores worth projects and procured INR 160 crores worth industry-standard data. So far, these have resulted into more than 350 articles and documents, 12 authored books and edited volumes, 2 Patents and 2 Copyrights, 16 Ph.Ds. and 70 Master-dissertations. He is the Subject Editor of Proceedings of INSA (Earth Sciences), and served as the Section Editor for 'Encyclopaedia of Solid Earth Geophysics' (2011 and 2021) by Springer.He is a Fellow of INSA (Delhi), IASc (Bangalore), NASI (Allahabad), and AP and Telangana Academy of Sciences (Hyderabad). He received National Merit Scholarship, Raman Fellowship and BOYSCAST Fellowship, and is honored with Distinguished Alumnus Award by IIT-ISM, AP Scientist Award, National Award of Excellence in Geosciences by MoES, National Mineral Award by MoM, CSIR Young Scientist Award, Krishnan Gold Medal and Decennial Award of IGU. He is serving as the Chairman/Member of numerous National/State-level Committees, Research Councils, Governing Bodies, and Advisory Boards of National Institutes/Universities.