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AN ASSESSMENT OF THE GEOTHERMAL POTENTIAL OF BANGLADESH

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ABSTRACT

Bangladesh is one of the energy stricken countries of the world with only 236 kWh per capita electricity generation and only 49% of its population has access to that electricity. In the context of geothermal water utilization, Bangladesh is still at a very early stage. To date, no systematic study has been done to evaluate the geothermal resources of Bangladesh. However, in a few articles authors have stressed the potential of geothermal energy resources in Bangladesh. Geothermal energy exploration involves cash incentives in the early stages of exploration, but good planning minimizes risks and saves money. In Bangladesh many deep abandoned wells, originally drilled for oil and gas exploration, have been used to extract valuable information about the subsurface geology and temperature of areas of interest. Analysis of the temperature data of these wells indicates that the average geothermal gradient along the southeast part of the Bengal Foredeep region varies from 19.8 to 29.5°C/km and along the northwest stable shelf from 20.8 to 48.7°C/km. An attempt was made to recalculate different geothermometer temperatures using the geochemical data taken from water samples of the basement aquifer of the Madhyapara hard rock mine area, and using acquired knowledge from this training programme. The predicted temperature is quite variable, ranging from 67 to 153°C, which may refer to a potential low-temperature geothermal field in the Madhyapara area. For assessment of the geothermal potential of Bangladesh, it is recommended that preliminary surface geological and geochemical studies be done followed by geophysical investigations (resistivity (MT), seismic, gravity, etc.) and drilling of shallow gradient wells to make a conceptual model of any geothermal systems before proceeding with the most expensive, as well as the most risky part, i.e. drilling of a deep well.

1. INTRODUCTION

1.1 Geographical and other information

Bangladesh, a tropical to subtropical country, is located in the northeast part of South Asia between 20°34′ and 26°38′ North latitude and 88°01′ and 92°42′ East longitude. Bangladesh, with its 160

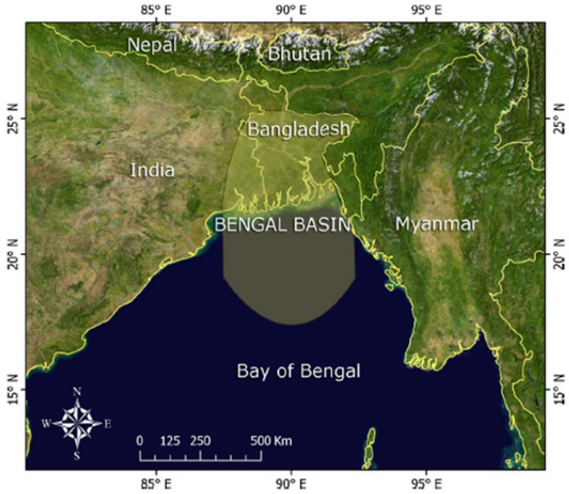


FIGURE 1: Location map of Bangladesh and surroundings (data source: Geography network services hosted by Environmental Systems Research Institute (ESRI)

million people in a land mass of 147,570 km^2, is one of the most densely populated countries in the world with 79% of its population living in rural areas. India surrounds the country on three sides (West, North and East), sharing 3715.18 km of a common border; Myanmar shares a mountainous border in the southeast; altogether this constitutes 93% of the borderline (Figure 1). The Bay of Bengal is open to the south. The coastal zone of Bangladesh consists of about 710 km coastline, the largest patch of a natural mangrove forest shared with India and a long sea beach along the southeast coast. Three major types of landscapes are found in Bangladesh: floodplains (80%), terraces (8%), and hills (12%). Excepting the eastern hilly region, almost all of the country lies in the active delta of three of the world's major rivers: the Ganges, the Brahmaputra, and the Meghna (GBM). The water ecosystem of the country comprises the tributaries and distributaries of these major rivers and numerous perennial and seasonal wetlands like haors, baors and beels. Huge amounts of rainfall runoff occur in the entire GBM catchments during the monsoon season (June-October), while in the dry period the country suffers from severe moisture stress due to negligible rainfall. Most of the land area is being used for agriculture, forest and settlement. Owing to the fertile land, agriculture remained the major occupation for over 60% of the population for centuries. Open water fishing is one of the major earning sources for a significant portion of the population, especially during the monsoon months.

TABLE 1: Present power sector scenario of Bangladesh (Khan, 2011)

Electricity growth	10% in FY 2010 (av. 7.0% since 1990)
Generation capacity	6,727 MW
Highest generation	4,779 MW (29 May, 2011)
Average daily power generation	4,500-4,750 MW
Total demand	6,000 MW
Per capita generation	236 kWh
Access to electricity	49%
Total consumers	12 million

1.2 Energy scenario of Bangladesh

Bangladesh, considered a developing economy with a recorded GDP growth of above 5% during the last few years, is one of the energy starved countries of the world. By some estimates, a GDP growth rate of 1-2% is forgone annually because of a shortage of energy and lower power generation (Table 1). A major portion of energy is consumed for subsistence (e.g. cooking, lighting, heating, etc.) and only a small portion is used for economic growth (e.g. agriculture, industry, transport, commerce, etc.). The total primary energy consumption in 2004 was 30.70 MTOE and the energy consumption mix was estimated as: indigenous biomass 60%, indigenous natural gas 27.45%, imported oil 11.89%, imported coal 0.44% and hydro energy 0.23% (Figure 2). The country's rural population (79%) meets most of its energy needs (domestic, commercial, and industrial needs) from traditional biomass fuels (Islam et al., 2008). The country's per capita annual energy consumption was about 182 kgoe

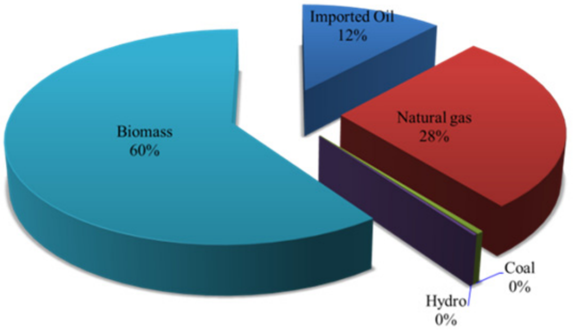


FIGURE 2: Total primary energy supply in 2004 (Islam et al., 2008)

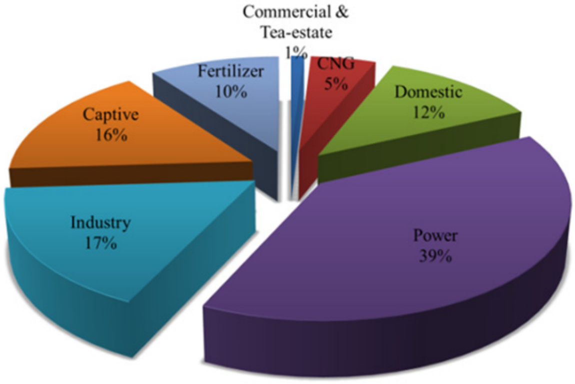


FIGURE 3: Category wise gas distribution in Bangladesh in 2009-2010 (Source: Petrobangla, 2011)

TABLE 2: Present indigenous commercial energy scenario of Bangladesh (Islam, 2010; Petrobangla, 2011)

Total number of gas fields	23
Total recoverable reserve (prov.+prob.)	20.63 TCF
Total consumption up to Dec. '10	9.43 TCF
Remaining reserve up to Dec. '10	11.20 TCF
Present daily gas production	2000 MMCF
Daily gas demand	2500(+) MMCF
Daily shortage of gas supply	500(+) MMCF
Total coal resources (5 fields)	3300 Mtons
Proven in-situ reserves (4 fields)	884 Mtons
Present annual extraction	858,000 tons

in 2008. At present, Bangladesh has an energy supply from both renewable and non-renewable sources, 35% of which comes from biomass. However, 75% of the commercial energy is provided from natural gas (Figure 3) and the lion's share of the rest of the energy is provided by imported oil. Existing gas reserves (Table 2) will be able to meet the increasing gas demand (>7% per annum) only up to 2016 (Guha et al., 2010). However, present production capacity cannot meet the current existing demand. Indigenous coal has yet to make any significant impact on the energy scenario.

1.3 Renewable energy scenario in Bangladesh

Efficient utilization of renewable energy resources in Bangladesh has yet to obtain commercial dimensions and cannot serve as an alternative to conventional energy resources. However, they can serve to supplement the long term energy needs of Bangladesh to a significant level. Harnessing these resources appears to be a promising solution for improving the quality of life of rural villagers. Categories of renewable energy that are being used in limited ways in the country are hydro-, solar- and windpower, bio-gas, and biomass such as wood, rice husks, etc. The present share of renewable energy is around 6%. At present, the national capacity of renewable energy based power, excepting hydro-power, is approx. 50 MW as shown in Table 3. The country has a hydro-electric power plant of capacity 242 MW installed in 1962 which is now generating 224 MW of electricity. Micro-hydro and mini-hydro, however, have limited potential in Bangladesh. Considering the fuel crisis, and exploring new, safe, and sustainable energy resources, the government has taken various steps to promote energy conservation and the use of renewable sources. GoB declared the Renewable Energy Policy of Bangladesh, in effect since 2009 (MEMR, 2008). According to this policy, the government is committed to facilitating both public and private sector investment in renewable energy projects to scale up contributions of existing renewable energy based electricity production. The Policy envisions 5% (at least 500 MW) of the total power generation from renewable sources by 2015 and 10% of the same by 2020. According to the policy an independent institution, Sustainable Energy Development Agency (SEDA), will be established under the Companies Act, 1994, as a focal point for sustainable energy development and promotion, 'sustainable energy' comprising renewable energy and energy efficiency. The policy will be implemented on the following objectives:

TABLE 3: Renewable energy scenario of Bangladesh (Khan, 2011)

Category	**Achievement**
SHS	45 MW
Other solar PV applications	1 MW
Wind energy	2 MW
Biomass based electricity	<1 MW
Biogas based electricity	1 MW
Total	**50 MW**

- Harness the potential of renewable energy resources and the dissemination of renewable energy technologies in rural, peri-urban and urban areas;
- Enable, encourage and facilitate both public and private sector investment in renewable energy projects;
- Develop sustainable energy supplies to substitute indigenous non-renewable energy supplies;
- Scale up contributions of renewable energy to electricity production;
- Scale up contributions of renewable energy both to electricity and to heat energy;
- Promote appropriate, efficient and environmentally friendly use of renewable energy;
- Train personnel to facilitate the use of renewable energy at every level of energy usage;
- Create enabling environmental and legal support to encourage the use of renewable energy;
- Promote the development of local technology in the field of renewable energy;
- Promote clean energy for CDM; and
- Policy setting targets for developing renewable energy resources to meet 5% of the total power demand by 2015 and 10% by 2020.

1.4 Geothermal resources of Bangladesh

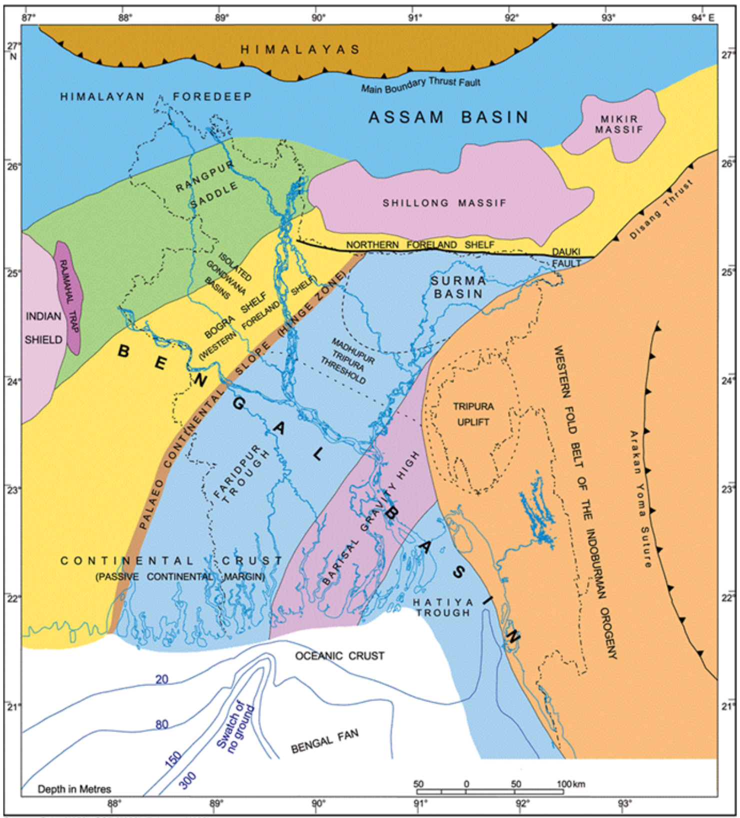
Geothermal resources of Bangladesh have yet to be explored in detail. Current knowledge about these resources and their utilization is very limited compared to other renewable energy sources available in the country. Thus far no systematic field investigation has been done to evaluate the prospects of these resources and their utilization. Only few authors have discussed the potential of geothermal resources of Bangladesh. It is therefore of utmost importance to evaluate the geothermal resources of the country and how they can play a part in the renewable energy scenario of Bangladesh. The geothermal energy resources are considered environmentally friendly, local and sustainable, independent of wind and sun variations. The electricity production cost using geothermal resources (steam/hot water system) is still very low compared to other available energy sources.

Due to the different geo-tectonic setups in Bangladesh, geothermal resources of the country may be broadly classified into two different geothermal provinces: the northwest part of Bangladesh known as the shield areas of the country and, to the southeast, the deep sedimentary basin known as the Bengal Foredeep region which consists of several basement highs and lows as well as the hill ranges of the Chittagong-Tripura folded belt, where a few thermal springs are known to occur. In the northwest part of the country, in the Thakurgaon district, thermal manifestations and related evidence in some shallow aquifers tend to suggest the presence of a geothermal resource. Recent work done by Mizanur Rahman also shows the potential of a geothermal resource in that area (Rahman, 2006). The reported high-temperature water wells show a much higher geothermal gradient compared to the surroundings. In the Bogra shelf region, the Singra-Kuchma-Bogra areas offer potential zones for geothermal exploration (Guha et al., 2010). The Madhyapara hard rock mine area and the Barapukuria coal basin are also zones of interest for geothermal exploration (Kabir, 2008). In the northwest shield, the underlying basement complex is intensely faulted and highly fractured. Some of these major deep seated faults can be delicately identified from gravity and magnetic surveys. These fault systems are thought to act as conduits for transferring heat through the fluid within the pore spaces from beneath to the overlying sedimentary aquifer. The prevailing geological features, including the hydrogeological settings, clustering of basement faults, seismicity and earthquakes, and surface thermal anomalies all point to the existence of possible heat sources at a few km depth beneath the earth’s surface. In the Bengal Foredeep region along the tertiary hill ranges, the Sitakund hilly area, with a few thermal springs, may also be considered an area with geothermal prospects.

2. GEOLOGICAL SETTINGS OF BANGLADESH

2.1 Tectonic framework of Bangladesh

The Bengal Basin is the largest fluvio-deltaic sedimentary system on earth occupying most of Bangladesh, West Bengal of India and part of the Bay of Bengal. Sediments accumulate in the GBM basin and are dispersed into the Bay of Bengal forming the largest deep sea fan in the world. Sedimentation in the Bengal Basin started with the breakup of Gondwanaland. The collision of the Indian plate with the Tibetan plate and with the Burmese plate in the Miocene resulted in a rapid switch in the sedimentation pattern in the Bengal Basin. The basin structure and sedimentation were both strongly influenced by the collision pattern of the plates and by the uplift of the Himalayas (Alam, 1989). Tectonic evolution of the Bengal basin is directly related to the orogenic phases of the mighty Himalayas, although the Cenozoic evolutionary history of the eastern Bengal basin is mainly related to the oblique subduction phases of the Indian plate beneath the Burma plate (Alam et al., 2003). Major tectonic elements of Bangladesh (Figure 4) are briefly discussed in the following.



Source: Guha (1978), GSB (1990), Reimann (1993)

FIGURE 4: Generalized tectonic map of Bangladesh (GSB, 1990)

The northwest stable shelf

The western and northwestern parts of the Bengal Basin are occupied by a shelf, the margin of which has a northeast-southwest trend along which the basement slopes downward to form a hinge zone (Figure 5). The pre-collision geology of Bangladesh can only be studied in northwest Bangladesh, where the continental Gondwana sequences are preserved in graben structures of which the shallowest deposits can be seen in the Barapukuria graben at depths of only 117 m. The shelf region is marked by a series of buried ridges and normal gravity faults. To the northwest the basement slopes upward and forms a prominent ridge, the Rangpur Saddle (Bakhtine, 1966).

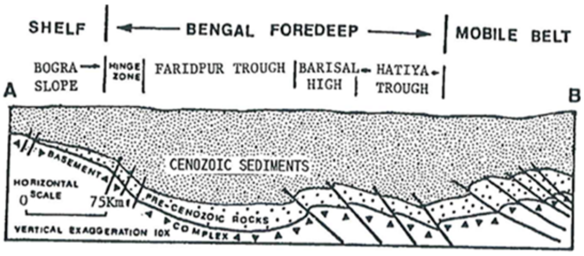


FIGURE 5: Schematic west-east profile across Bengal Basin (after Alam, 1989)

Rangpur saddle

The Rangpur saddle and the so called Garo-Rajmahal gap comprise the most uplifted part of the basement in the country, concealed under a thin veneer of alluvium. In the Madhyapara area, basement rock is encountered at a depth of 130 m. The Rangpur saddle represents a block of the

Indian shield that connects the Shillong massif and the Mikir Hills to the Indian Shield in the southwest. The Shillong massif is considered a large thrusting block of the Indian shield. Seismic data shows that both the northern and the southern slopes of Rangpur saddle are quite gentle. On the southern slope, the basement plunges gently from Madhyapara southeast to the Hinge zone, an area known as the Bogra shelf.

Sub-Himalayan Foredeep
The Sub-Himalayan Foredeep lies south of the Main Boundary Thrust (MBT) all along the foothills of the Himalayas. The Neocene Siwaliks are well developed in this region, attaining a thickness of 3-4.5 km with predominantly sandstones, subordinate shales and clay and gravel beds. The northern margin of this foredeep is strongly folded and faulted. To the northwestern tip of the country, the Salbanhat 1 well intersected the basement at 2500 m depth (BPSD, 1988).

Deep sedimentary basin
Parallel to the hinge zone, the vast area lying between the Hinge Line and the ArakanYoma folded system is known as the Bengal Foredeep region comprising the deeper part of the Bengal Basin. The Hinge zone is a tectonic element of regional importance and has played a major role in the development of the Bengal Basin. It is a narrow zone 25 km wide trending SSW-NNE from Sylhet-Mymensingh-Panba-Calcutta and further southwest along the coastline of Orissa. In the northeast, the Hinge zone is connected to the Dauki fault northeast of the Sylhet trough which is associated with a series of west-east trending faults. The folded belt of the Indo-Burmese mobile belt marks its eastern boundary. According to the gravity surveys and drilling results, the Bengal Foredeep consists of several troughs and structural highs, known as (1) the Faridpur trough; (2) the Barisal-Chadpur high (3) the Hatiya trough (4) the Sylhet trough and (5) the Tangail-Tripura or Madhupur high (Bakhtine,1966; Guha,1978).

Folded belt
The folded belt (or the folded eastern flank of the Bengal Foredeep) represents the most prominent tectonic element of the Bengal Foredeep, consisting of general north-south trending folds parallel to the Arakan Yoma folded system. The folds are characterized by ridges, box-shaped, oriented en echelon with an elevation ranging from 100 to1000 m in Bangladesh. The intensity of the tectonic deformation is relatively severe in the east, gradually diminishing to the west at the eastern fold belt of Bangladesh (Guha, 1978).

2.2 Stratigraphy of Bangladesh

The stratigraphic framework of the Bengal Basin was originally established on the basis of exposures along the eastern fold belts purely in lithostratigraphic correlation to the type sections in Assam, the northeast province of India (Evans, 1932). Most parts of the country are covered by a thick mantle of alluvium (Figure 6) and almost all the strata are devoid of any marker fossils. Stratigraphy of Bangladesh is discussed here under two broad facies: (a) The Shelf facies and (2) The Geosynclinal facies.

Shelf facies
There are no surface outcrops and the rocks were intersected by drill holes. The presence of an Achaean basement in Bangladesh was first reported by Burgess (1959) from a drill hole at Bogra and later similar rocks were encountered in drill holes in the shelf area at varying depths (Ahmed and Zaher, 1965), the shallowest of which were found at Maddhapara, Rangpur saddle at depths of 128-160 m below the surface. The basement complex is unconformably overlain by the coal bearing lower Gondwana Kuchma and Paharpur formations (Ahmed and Zaher, 1965) during the Permo-Carboniferous in intracratonic, fault-bounded basins. The Paharpur formation is unconformably overlain by the basaltic Rajmahal Trap of Upper Gondwana group which is underlain by the Sibganj

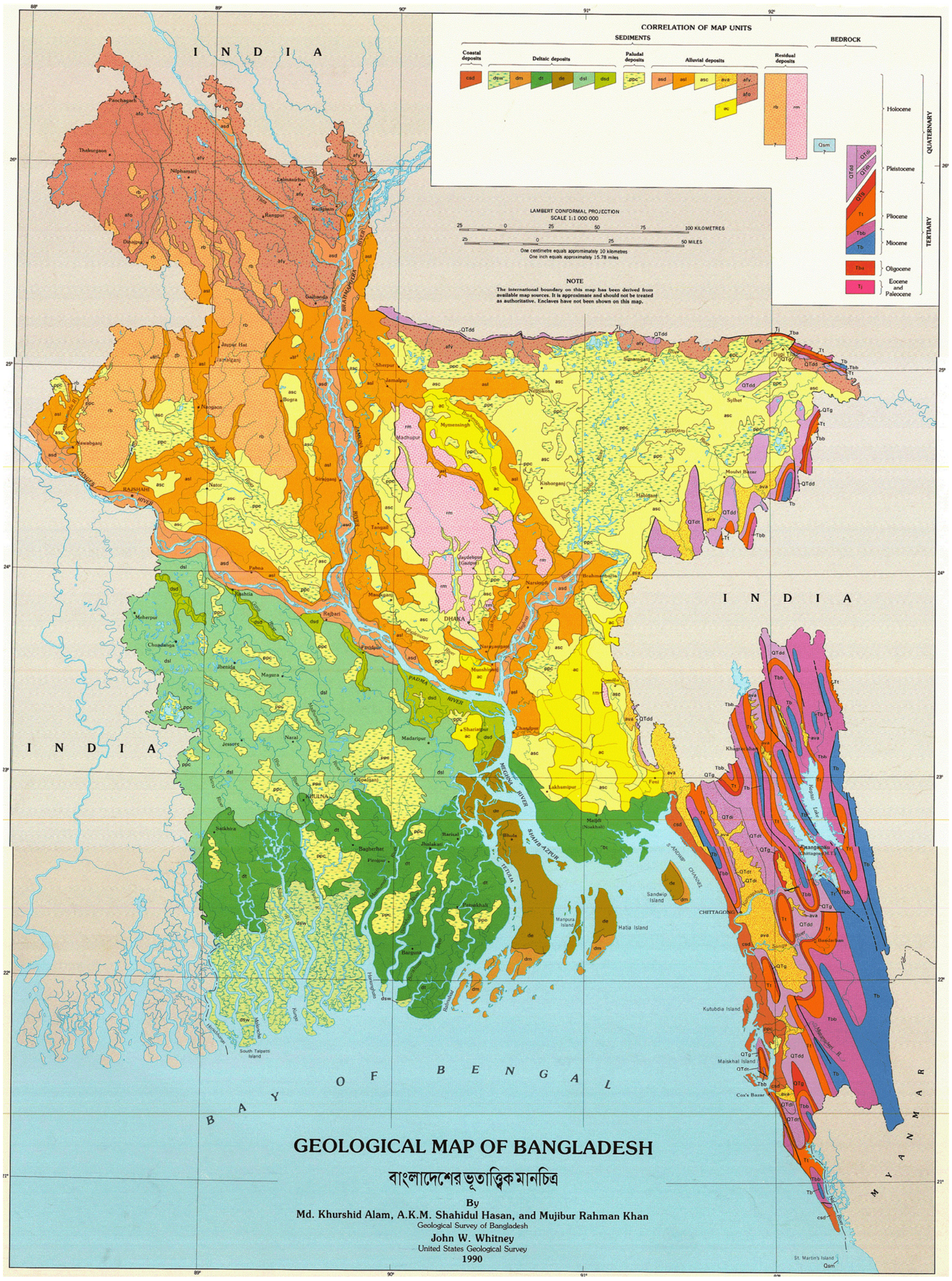


FIGURE 6: Generalized geological map of Bangladesh (GSB, 1990)

formation. The Jainta group which overlies the Sibganj formation is subdivided into (1) Tura sandstone (2) Sylhet limestone and (3) Kopili formation. The Bogra formation which follows unconformably the Kopili formation represents Barail equivalents of Central and lower Assam (Khan and Muminullah, 1980). The Bogra formation is successively overlain by Jamalganj, Dupi Tila and Barind clay formations with recent to sub-recent Alluvium on top. Table 4 summarises different rock formations with the mode of environment of deposition as encountered in deep wells on the northwest stable shelf of Bangladesh.

Stratigraphy of geosynclinal facies

The Barail group is reported as the oldest rock formation in geosynclinal facies found on the northern fringe of the Sylhet trough, intersected in drill holes along the folded belt. The overlying Surma group of rocks are widely exposed and crop out in Sylhet, Chittagong and Chittagong Hill Tracks and are

TABLE 4: Stratigraphic succession of the stable shelf of Bangladesh

Age (approx.)	**Group**	**Formation**	**Lithology**	**Depositional environment**	
Holocene		Alluvium	Silt, clay, sand and gravel	Fluvial-alluvial and Rapidly prograding delta	
Pleistocene-Late Pliocene	Barind (200 m)	Barind clay (50 m)	Yellowish brown to reddish brown clay, silty clay and silty sand with minor sand		
		Dihing (150 m)	Oxidized sand with clay and silicified wood fragments	Fluvial prograding delta-shelf	
Early Pliocene-Late Miocene	Dupi Tila (280 m)	Dupi Tila (280 m)	Claystone, siltstone, sandstone and gravel	Delta front to shelf and slope	
Early to Middle Miocene	Jamalganj group (415 m)	Jamalganj (415 m)	Alternating sandstone, siltstone and shale		
Oligocene	Bogra (165 m)	Bogra (165 m)	Siltstone, carbonaceous shale and fine grained sandstone	Increasing sedimentation rates	
Late Eocene	Jainta (735 m)	Kopili shale (240 m)	Sandstone, locally glauconitic and highly fossiliferous;; shale with thin calcareous bands	Deltaic to slope	
Middle Eocene		Sylhet limestone (250 m)	Nummulitic limestone with sandstone interbeds	Carbonate platform	
Paleocene		Tura sandstone (245 m)	Sandstone, coal and shale	In western Bangladesh Only	Deltaic to outer shelf
Middle to late Createaceous	Rajmahal (840 m)	Sibganj trapwash (230 m)	Coarse yellowish brown sandstone; volcanic materials with clay		Coastal to fluvial-alluvial
Early Cretaceous-Jurassic		Rajmahal traps (610 m)	Amygdaloidal basalt, andesite, serpentinized shale and agglomerate		Subaerial lava flows
Late Permian	Gondwana (955 m)	Paharpur (465 m)	Feldspathic sandstone with thick coal seams		Fluvio-deltaic to shallow marine
Permian-Carboniferous		Kuchma (490 m)	Coarse grained sandstone and conglomerate with thick/thin coal seams		Fluvial to delta plain, coal swamps
Precambrian		Basement complex	Dioritic, granite, granitic gneiss etc.	Stable Gondwana continent	

(Modified from Zaher and Rahman, 1980; Khan, 1991; Lindsay et al., 1991; Reimann, 1993; Alam, 1997; BOGMC, 1997; Alam et al., 2003.)

also encountered in the drill holes. The group is gas bearing. It is divided into (1) Bhuban and (2) Boka Bil formations. Rocks of Tipam group conformably overly the Boka Bil formation. The Tipam group is again divided into (1) Tipam sandstone and (2) Girujan clay. The Girujan clay lies conformably over the Tipam sandstone and is underlain by the Dupi Tila formation and followed by the Madhupur formation and Alluvium at the top. Table 5 summarises different rock formations with their mode of environment of deposition as studied from surface exposures as well as from within deep wells in the geosynclinal part of the country.

TABLE 5: Stratigraphic classification for the Eastern Fold Belt (EFB)

Age (approx.)	**Group**	**Formation**	**Thickness**	**Brief description**
Recent		Alluvium		Silt, clay, sand and gravel
Plio-Pleistocene		Dupi Tila	500 m	Claystone, siltstone, sandstone and gravel, deposits of high sinuous meandering river.
Pliocene	Tipam group	Girujan clay	350 m	Brown, blue and grey mottled clay, interpreted as lacustrine and fluvial over bank deposits.
		Tipam sandstone	900 m	Yellowish brown to reddish brown, coarse -rained, cross-bedded to ripple-laminated with minor siltstone and mudstone, deposited in bed load-dominated low-sinuosity braided-fluvial system
Miocene	Surma group	Boka Bil (Upper, middle, lower)	1200 m	Dark grey shale, siltstone, fine to coarse grained sandstone and occasional intra-formational conglomerate. These rocks deposited in repeated transgressions and regressions of sea.
		Bhuban (Upper, middle, lower)	3000+ m	
Oligocene	Barail group		Lower contact not known	Fine- to very fine-grained carbonaceous sandstone, siltstone and shale, rocks deposited in tide dominated shelf environment.

(Modified from Evans, 1932; Khan and Muminullah, 1988; Reimann, 1993; Sikder and Alam, 2003.)

3. GEOTHERMAL EXPLORATION

3.1 General discussion

Bangladesh has always been noted for its acute power shortage mainly due to an inadequate power generation capacity compared to the increasing energy demand of the country. The per capita energy use in Bangladesh is one of the lowest in the world. Among the possible energy resources that could be explored is the potential geothermal energy in regions of higher geothermal gradients with favourable geo-tectonic settings and ideal petrophysical properties (Guha and Henkel, 2005). Some of them are of great interest including the Singra-Kuchma-Bogra area, the Barapukuria coal mine area, the Madhyapara hard rock mine area and the Thakurgaon thermal area in the northwestern part of Bangladesh, and the Sitakundhilly area along the folded belt region in the southeastern part of Bangladesh where warm springs are to be found. The most important physical parameters in a geothermal system are: temperature, porosity, permeability, chemical content of fluid (salinity) and pressure. All these parameters cannot be measured directly through conventional surface geophysical methods; however, other important parameters can be measured or estimated such as temperature, electrical resistivity, magnetization, density, seismic velocity, thermal conductivity etc., which are linked with the aforementioned parameters (Georgsson, 2009).

The most commonly used methods in geothermal exploration are geological mapping, geochemical sampling and analysis, geophysical methods and exploration drilling. It is necessary to integrate all these methods in order to make a conceptual model of a subsurface geothermal system before proceeding to exploration drilling which is the most expensive and critical part of a geothermal exploration programme. The integrated approach using different datasets has been proven to be a very effective way of locating the most promising areas for geothermal utilization in Hungary (Tulinius et al., 2010). An integrated approach using all of the above methods is, therefore, recommended for assessing the geothermal potential of Bangladesh. The present report does not have much data to focus on for each of the methods recommended but will stress the importance of the individual research methods for geothermal exploration in a brief overview.

3.2 Surface exploration

Once a prospect area has been selected for geothermal research, full surface exploration is conducted. Even though a detailed research plan is always site specific, it will normally include most of the following components, but not necessarily all of them. The first step is always collection of all available information from previous work on the area of interest including geological, geothermal and tectonic maps, topographical information and other infrastructural data. The following steps are to be considered:

Geology (e.g. Fridleifsson, 2011)

- A detailed geological mapping of the geothermal field and its surroundings;
- Detailed mapping of tectonic features, such as faults, fissures and fractures;
- Detailed mapping of surface alteration minerals;
- Mapping of thermal manifestations including the recording of temperature, flow rate, conductivity, etc.;
- Thermal manifestations of tectonic features and volcanism (if present) to get ideas on heat sources, hydrology and flow paths in the reservoir;
- Detailed mapping of groundwater, cold springs, lake levels and groundwater level.

Geochemistry (e.g. Arnórsson, 2011)

- Detailed sampling of thermal water, steam and gases;

- Detailed analyses of chemical elements (both for major and trace elements), chemical species and gases. Geothermometers are generally used to calculate likely reservoir temperatures and the nature of the heat source. Preliminary evaluation of possible scaling and or corrosion problems during utilization.
- Sampling for stable isotope studies. Analyses of stable isotopes (hydrogen, oxygen and possibly carbon and sulphur). Isotope ratios and concentrations are used to infer the origin of the geothermal fluid in the reservoir.

Geophysics (e.g. Georgsson, 2009)
Thermal methods are direct measurements of temperature and/or heat as well as the properties of a geothermal system. The heat exchange mechanisms in the earth i.e. conduction, convection and radiation are considered important for the interpretation of thermal methods. Despite several limitations, thermal methods are important in geothermal exploration. They include the following:

- Mapping of thermal distribution at the surface, including detailed geothermal surface mapping (GPS);
- Soil temperature measurements in the uppermost metre or so;
- Temperature measurements in 20-100 m gradient wells to delineate regional or local gradient anomalies;
- Airborne infrared (IR) survey;
- Regional heat flow survey.

Electrical methods. The electrical resistivity methods are the most important geophysical methods for geothermal exploration. The parameters of interest in a geothermal system are porosity and pore structure (intergranular porosity, fracture porosity, vulgar porosity); temperature and alteration of rocks and salinity of pore fluid can be correlated with the electrical resistivity of the rocks. A full resistivity survey consists of a shallow survey (<1 km depth) and a deep resistivity survey (0.5-10 km depth). The shallow survey is preferably performed using central-loop TEM soundings or audio magnetotelluric (AMT) soundings, but DC methods (Schlumberger) can also be used and the deep survey is usually done by Magnetotelluric (MT) soundings.

Transient Electro Magnetic (TEM) method. The TEM method has now become a routine method in geothermal exploration of the uppermost km of the earth, replacing Schlumberger soundings. In the Central loop TEM sounding method, a constant magnetic field of known strength is generated by transmitting a constant current in the loop. The current is then switched off and the decaying magnetic field induces a secondary current in the ground. The current distribution in the ground in turn induces a secondary magnetic field, which decays with time. The decay rate of the secondary magnetic field is measured by measuring the voltage induced in another small loop located at the centre of the big current loop. The decay rate of the voltage in the small loop is recorded as a function of time after the current is switched off. From these measurements, apparent resistivity is determined. TEM has many advantages over Schlumberger measurements, such as needing less manpower, it is not sensitive to lateral inhomogeneities and has a better resolution (Árnason and Gíslason, 2009; Georgsson, 2009).

The Magnetotelluric (MT) method is a natural-source, electromagnetic geophysical method of imaging structures below the earth's surface from depths of a few 100 metres to several 100 kilometres. The frequency of the signal relates to its probing depth, with low frequencies reaching deeper levels. Thus, frequencies of 0.00001-10 Hz are used for deep crustal investigations, while higher frequencies, like 10-1000 Hz, are used for the upper crust. Natural variations in the earth's magnetic field induce electric currents (or telluric currents) under the earth's surface. MT is a powerful method for probing deep resistivity structures, which gives it an advantage over the other main electrical methods. The equipment is portable and the data collection is simple, involving measurement of the magnetic field components **B** and the induced electrical field **E**, both as a function of time for several hours, at each site. MT measurements are, however, quite sensitive to cultural noise (power lines etc.). Similarly, the measurements probe a large volume of rocks and are, therefore, sensitive to 3-D resistivity variations. Detailed interpretation can, therefore, be difficult and may require 3-D interpretation.

More recently, the method has routinely been used in combination with TEM or AMT, with the TEM or AMT measurements used for mapping the uppermost kilometre in detail in order to enhance the interpretation of the MT measurements, thus leading to better information at deeper levels. This way, good information on the distribution of the resistivity in the deeper parts of the geothermal system can be collected, reaching to 5-10 km depth. Sometimes magnetotelluric measurements are made at audio frequencies using energy from spherics; the method is then referred to as the audiomagnetotellurics method (AMT).

Gravity measurements are used to detect geological formations with different densities. The density contrast leads to a different gravitational force which is measured, and usually presented in mgal or 10^{-3} cm/s^2. The density of the rocks depends mainly on the rock composition and porosity, but partial saturation of the rocks may also influence the values. Generally, sedimentary rocks are lighter than crystalline rocks. The raw data needs to be corrected for several factors (height variation, tidal effect, topography, Bouguer correction, etc.). Gravity surveying methods are useful in detecting underground fault systems. Fault system information can be used to analyse and understand groundwater channels and water flow directions. Gravity data may be used to analyse volcanic rock distribution and then help to discover the heat source.

Magnetic measurements are widely used in geothermal exploration, often together with gravity measurements and seismic refraction, in mapping geological structures. A magnetic anomaly is a local or regional disturbance caused by a change in the magnetisation. It is characterized by the direction and magnitude of the effective magnetisation and the shape, position, properties and history of the anomalous body. In geothermal exploration, magnetic measurements generally aim at locating hidden intrusives and possibly estimating their depth, or at tracing individual buried dykes and faults. They may also aim at finding areas of reduced magnetization due to thermal activity.

Seismic methods measure sound velocity distribution and anomalies in the earth as well as attenuation of the sound waves. Explosions, earth vibrators or sudden fractures in the rocks produce seismic waves. These waves travel at different speeds in different rocks. There are two important types of waves generated. P waves, which travel in the same direction as the wave and are generally faster, and S waves, which travel perpendicular to the wave direction, are slower than the P waves. The seismic methods are grouped as active or passive. The active methods are not used routinely in geothermal exploration but are extensively used in petroleum exploration and are fairly expensive. The two types of active seismic methods are reflection and refraction. They are suitable for well-layered sedimentary rocks rather than volcanic formations. The passive methods are principally used in geothermal exploration by recording earthquakes or micro-earthquakes. The natural seismicity is used to delineate active faults and permeable zones (shear wave splitting) or to locate the boundary between brittle and ductile crust, which can be indicative of the depth to the heat source. S-wave shadows can be used to predict the locations of bodies of partial melt, or magma chambers (Mwangi, 2007; Georgsson, 2009).

Integration of geological and geophysical data

By integrating all the available survey data (geological, thermal, seismic, resistivity and gravity etc.) a clearer and more transparent picture evolves which is listed below:

- Likely temperature of the reservoir fluids;
- Location of heat sources;
- Flow pattern of the reservoir fluids;
- Geological structure and type of the reservoir rocks;
- Estimated volume of abnormally hot rocks; and
- Calculated total natural heat loss

Finally, a conceptual model of the geothermal system can be constructed which complies with all results of the surface exploration and identifies the most promising production areas (Árnason and Gíslason, 2009).

4. GEOTHERMAL GRADIENT OF BANGLADESH

The geothermal gradient of Bangladesh is mostly controlled by the tectono-stratigraphic setup of the Bengal Basin. It is, therefore, necessary to evaluate the geothermal gradient of Bangladesh in order to understand individual tectonic elements with respect to the regional tectonic history. The tectonic framework has been discussed by a number of authors (Guha, 1978; Alam, 1989; Sikder and Alam, 2003). The Bengal Basin of Bangladesh can be subdivided into two parts, namely the Northwest Stable platform and the Southeast Deep Geosynclinal basin known as the Bengal Foredeep. The Bengal Basin is traditionally a cool sedimentary basin with an average temperature gradient of 20°C/km in the southeast deep basin area and 30°C/km in the northwest stable shelf area (Rahman, 2006). The rate of subsidence and sedimentary thickness in the southern part is higher than in the northern part. The available information about the geothermal gradient of the country is based mostly on deep hydrocarbon exploratory well data (Figure 7). In the present study, data has been compiled from previous studies of subsurface temperature and the thermal gradient of Bangladesh (Ismail and Shamsuddin, 1991; Bashar and Karim, 2001; Kabir, 2008). Figure 8 shows the subsurface temperature distributions that were recorded in deep exploratory wells in the two different tectono-stratigraphic regions of Bangladesh.

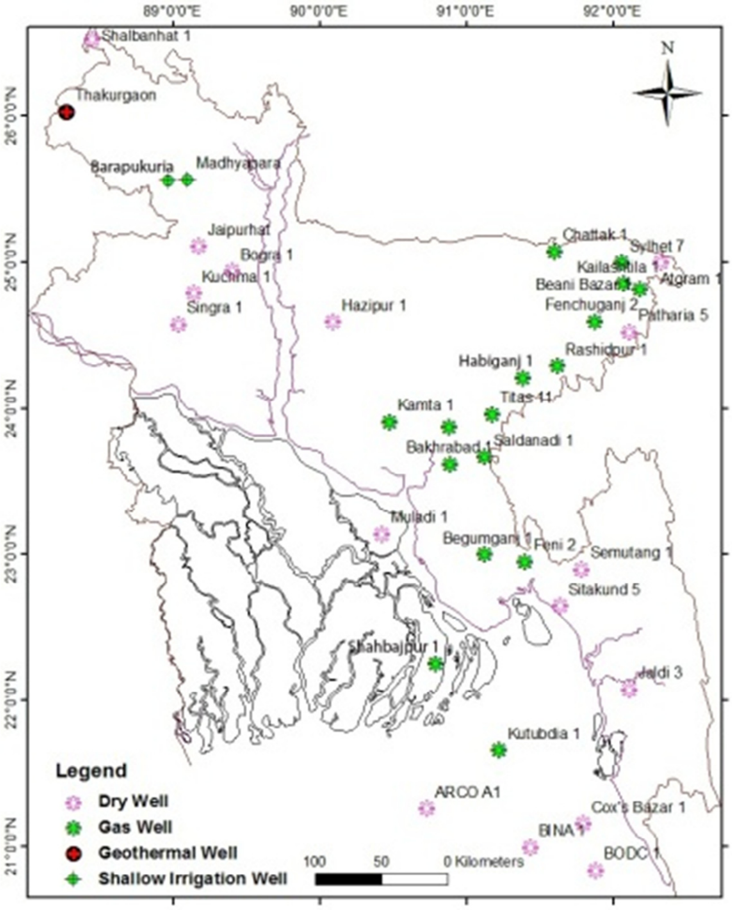


FIGURE 7: Deep well locations in Bangladesh

Geothermal gradients were calculated from corrected BHT (Bottom hole temperature) using Horner´s plot or by simply adding 10°C to the maximum recorded BHTs. Surface temperature is assumed to be 24°C (75°F) for onshore wells, and 15°C (59°F) for offshore wells (Ismail and Shamsuddin, 1991). Geothermal gradients were computed on the assumption of a linear increase in temperature with depth. With this assumption, the temperature of any depth can be expressed by the following equation:

$$T_z = T_o + T_g Z/100$$

where T_z is the wellbore temperature (°C) at depth Z (m);
T_o is the mean surface temperature (°C); and
T_g is the geothermal gradient in (°C/km).

The isogeothermal map of Bangladesh (Figure 9) shows that the geothermal gradient in the portion of the Bengal Foredeep region ranges from about 20 to 30°C/km. It is also observed that there is a trend of increasing geothermal gradients from north to south (i.e. from Sylhet trough to Hatiya trough) and also from east to west (i.e. from folded flank to platform flank). In the Southeast Bengal Foredeep region, the maximum geothermal gradient was found in the deep basin part at Hatiya trough (Shahbajpur 1, 29.5°C/km), and the minimum in the folded flank of the Sylhet trough (Beani Bazar 1 well, 19.8°C/km). A single value of the geothermal gradient for each well was recorded and expressed in units of °C/km for the presentation. From the plotted average curve, temperatures at different depths (at km interval) were taken for drawing an isotherm geothermal gradient. Due to the different tectono-stratigrahic setup of Bangladesh as well as the distribution of deep exploratory wells, the geothermal gradients are discussed under two broad headings as follows.

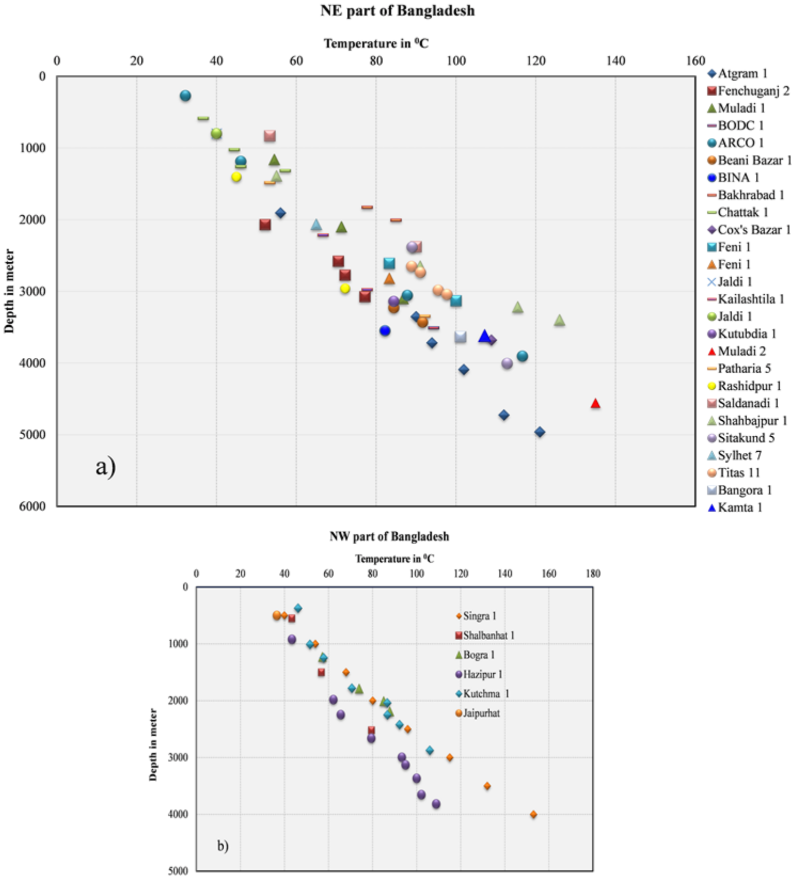


FIGURE 8: Subsurface temperature distribution in
a) Southeastern basin part of Bangladesh;
b) Northwestern stable part of Bangladesh

4.1 Southeast basin part of Bengal Basin

The Bengal Foredeep comprising the southeastern part of Bangladesh is a region of great subsidence of the earth´s crust, occupying the vast area between the Hinge line and ArakanYoma folded system, and plays the most important role in the tectonic history of the Bengal Basin. Based on its geotectonic behaviour, the Bengal Foredeep is again divided into the western unfolded region or deep basin part and the eastern folded region known as the Chittagong-Tripura folded belt, stretching parallel from north to south. The unfolded western part consists of several highs and lows as observed from gravity and magnetic surveys. The Sylhet trough to the northeast also known as the Sylhet basin, and the Faridpur trough to the southwest are separated by a prominent high known as the Tangail-Tripura high and, in the southernmost depression of the basin part, is the Hatiya trough; north of it is the Barisal-Chadpur gravity high. Sediment thickness along the trough region is the highest and is assumed to be around 20 km.

Folded belt
The folded belt (or the folded eastern flank of the Bengal Foredeep) is the most prominent and the youngest tectonic element of the western flank of the Indo-Burman Ranges. This zone of the Bengal foredeep is well known for hydrocarbon prospects and most of the exploratory wells are drilled in this area. The hydrocarbons discovered so far in the country are located in reservoir sands of the Neogene Surma group (Imam and Shaw, 1987). The wells were drilled to depths in the range of about 2100-4977 m below the surface. Temperature data from 30 exploratory wells was used to map the thermal gradients of the region (Table 6). A high rate of sedimentation in the major part of the Tertiary sedimentary sequence has a probable influence on the low geothermal gradient in the deep basin area.

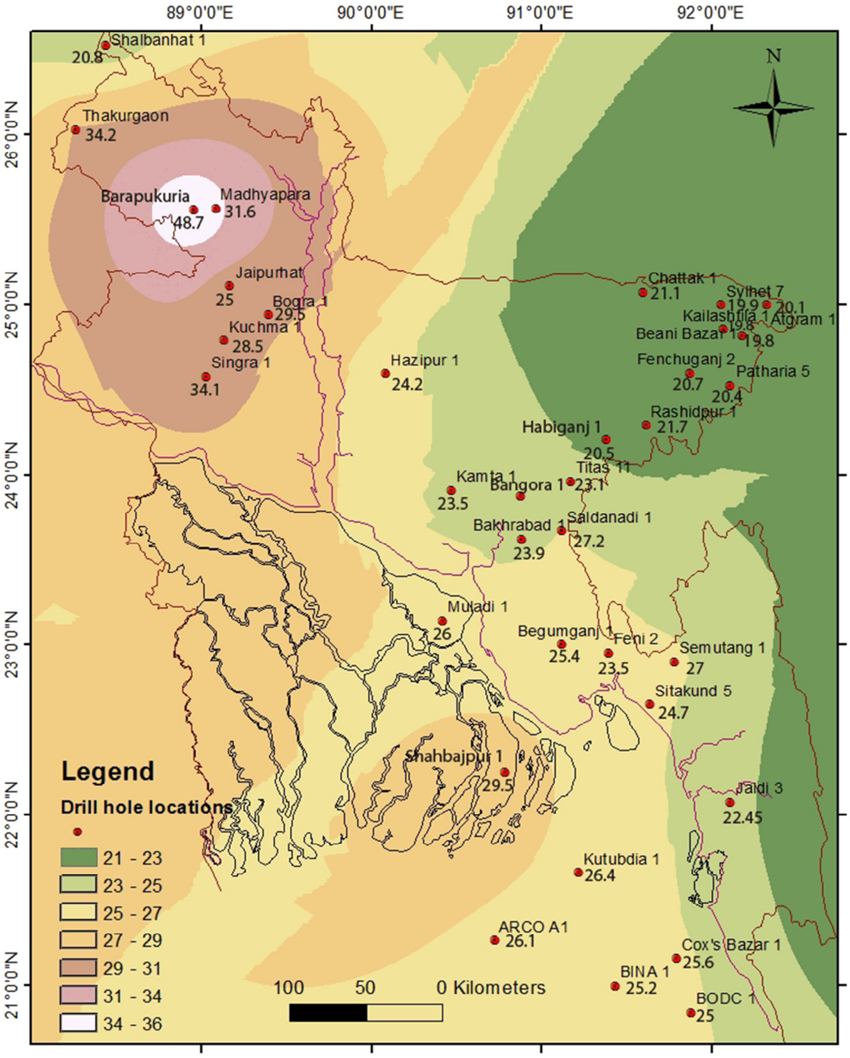


FIGURE 9: Overall geothermal gradient (°C/km) of Bangladesh with individual well gradient

However, hot springs have been observed at Barbarkund and GobaniyaChara in the Sitakund anticline with temperatures up to 35°C (Guha and Henkel, 2005). In the nearby deep well (Sitakund 5 well) the geothermal gradient is found to be 22.5°C/km in sedimentary sequences consisting mainly of shale. The geothermal gradient in the Hatiya trough at Shahbajpur 1 well, 29.5°C/km, is the highest followed by Saldanadi 1, at 27.2°C/km, along the folded belt region of Bangladesh, shown in Table 6.

TABLE 6: Geothermal gradients (°C/km) for the deep wells along the Bengal Foredeep region

Sl/No.	Well name	°C/km	Sl/No.	Well name	°C/km	Sl/No.	Well name	°C/km
1	ARCO A1	26.1	11	Fenchuganj 2	20.7	21	Muladi 2	24.4
2	Atgram 1	20.1	12	Feni 1	23.8	22	Patharia 5	20.4
3	Bakhrabad 1	23.9	13	Feni 2	23.5	23	Rashidpur 1	21.7
4	Bangora 1	21.2	14	Habiganj 1	20.5	24	Saldanadi 1	27.2
5	Beani Bazar 1	19.8	15	Jaldi 1	20	25	Semutang 1	27
6	Begumganj 1	25.4	16	Jaldi 3	22.5	26	Shabajpur 1	29.5
7	BINA 1	25.2	17	Kailashtila 1	19.8	27	Sitakund 5	24.7
8	BODC 1	25	18	Kamta 1	23.5	28	Sylhet 7	19.9
9	Chattak 1	21.1	19	Kutubdia 1	26.4	29	Titas 11	23.1
10	Cox's Bazar 1	25.6	20	Muladi 1	26	30	Hazipur 1	24.2

4.2 Northwest stable shelf part of Bangladesh

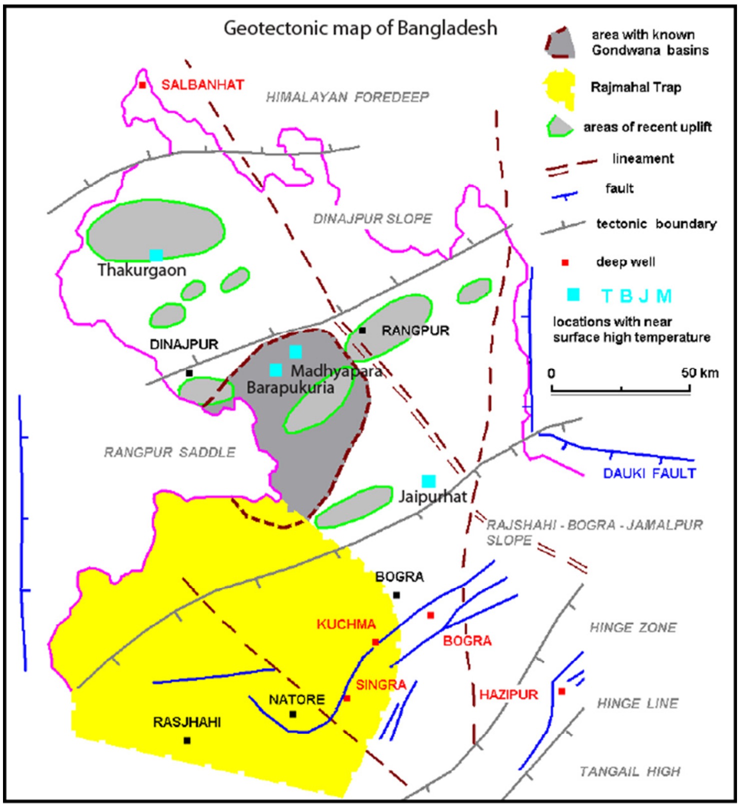


FIGURE 10: Geotectonic map of northwest Bangladesh (after Guha et al., 2010)

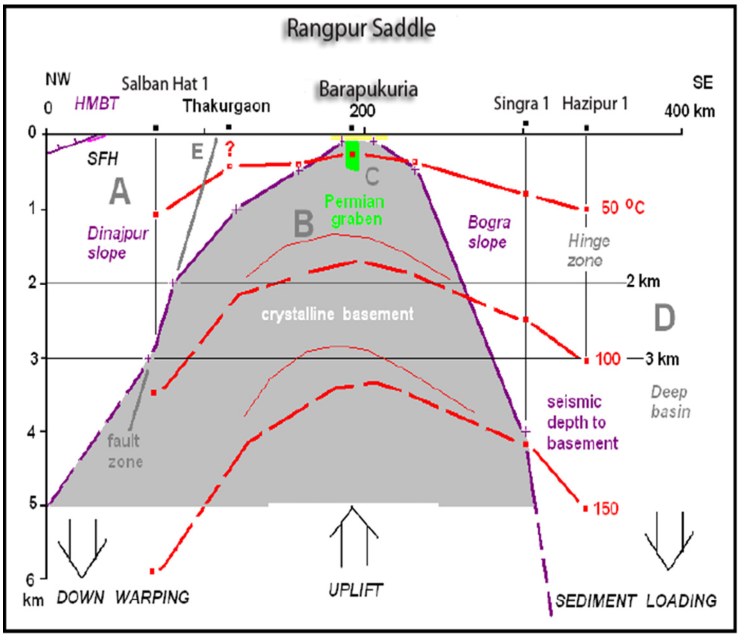


FIGURE 11: Generalised NW-SE across the crystalline basement rise of the Rangpur saddle (Guha, 2010)

The northwest stable shelf area is characterized by limited to moderate thickness of sediments above the Precambrian igneous and metamorphic basements (Figure 10). This unit is geologically stable in relative terms and has not been affected by post collision fold movement. Interpretation of an aeromagnetic map of Bangladesh revealed the existence of a number of well-defined faults in the stable platform (Hunting Geology and Geophysics Ltd., England, 1980). These faults thought to be basement controlled with an associated fracture system development mechanism for transferring heat to the overlying rocks. Some of these faults, bounded by intracratonic grabens, contain Gondwana coal. The area has a minimum sedimentary thickness of as little as 130 m (Figure 11). Temperature data from the deep hydrocarbon exploratory wells as well as many shallow wells helped to identify four prominent zones including three very high thermal anomalous zones in the Stable zone; these zones are discussed below.

Bogra shelf

The Bogra shelf (Bogra slope) represents the southern slope of the Rangpur Saddle which is a regional monocline plunging gently to the southeast to the Hinge zone (see Figure 1). This zone marks the transition between the Rangpur saddle and the Bengal Foredeep from a depositional as well as a structural point of view. The width of the Bogra shelf varies from 60 to 125 km up to the Hinge zone and the thickness of the sedimentary sequence increases to the southeast. Four deep wells have been drilled in the Bogra slope, namely the Singra 1, Bogra 1 and 2 and Kuchma 1 with the highest drilling depth of 4100 m at Singra 1 in the northwest region. The Singra-Kuchma-

Bogra area is characterized by faulting with a vertical throw of 400 m between the Singra and Kuchma wells and 700 m between the Kuchma and Bogra wells (Guha et al., 2010). The Singra 1 well has over 150°C bottom hole temperature which makes this area seem promising for geothermal exploration. The Bogra shelf, with deep wells at Singra, Kuchma and Bogra potentially offers favourable conditions for the consideration of geothermal energy. Table 7 shows the geothermal gradient as observed from the deep wells.

TABLE 7: Geothermal gradients for the deep wells on the northwest Stable shelf region

Sl/No.	**Well name**	**Gradient (°C/km)**
1	Kuchma 1	28.5
2	Shalbanhat 1	20.8
3	Jaipurhat	25
4	Bogra 1	29.5
5	Singra 1	34.1
6	Madhyapara	31.6
7	Thakurgaon	34.2
8	Barapukuria	48.7

Madhyapara hard rock mine area

Madhyapara granite mine is located in Madhyapara of the Dinajpur district in the northwest part of Bangladesh. This area lies within the Rangpur saddle, representing the most uplifted block of basement rock in the northwest stable shelf area (Figure 12). The area has a minimum sedimentary thickness of as little as 130 m, while no Precambrian exposed rock has been found in Bangladesh. The basement rocks are predominantly dioritic with minor granitoids (Hossain et al., 2007). The basement is highly faulted and intensely fractured and produces a significant quantity of water when mined. Two distinct aquifer systems that prevail in the area are the upper DupiTila aquifer and the lower basement aquifer. The aquifer is about 125 m thick and lies 6 m below ground level in most of the area (Reza, 1988). The basement aquifer lies underneath the upper aquifer. The presence of white clay layers in between remained as an aquitard that separates the two aquifers. The confined basement aquifer of Madhyapara granite mine comprises weathered and fresh igneous and metamorphic rocks of Achaean basement complex. Water occurs in the intergranular pore spaces of the weathered part of the basement complex and, along with the fissures and fractures of fresh basement rocks, is responsible for the conduction of heat flow through the rocks. The average elevation of the groundwater table at Madhyapara is 24 m (Bashar and Karim, 2001). The groundwater of the basement aquifer of Madhyapara is marked by higher temperature (40.4°C) than the annual mean surface temperature of about 24.7°C (CMC, 1994). The thermal gradient for the overburden sediments varies from 9 to 29.3°C/km with an average 22.6°C/km; the thermal gradient for the basement rock varies from 19 to 45°C/km with an average 30.9°C/km (NAMNAM, 1999). The basement aquifer is characterized by a high head with artesian flow of water. A recent study at some shallow wells identified a very high anomalous thermal gradient ranging from 32°C/km to 149.4°C/km, as shown in Figure 13 (Rahman, 2006). Another research work revealed that the average thermal gradient was 26.8°C/km for overlying sediments and 32°C/km for the underlying Precambrian basement complex (Kabir, 2008).

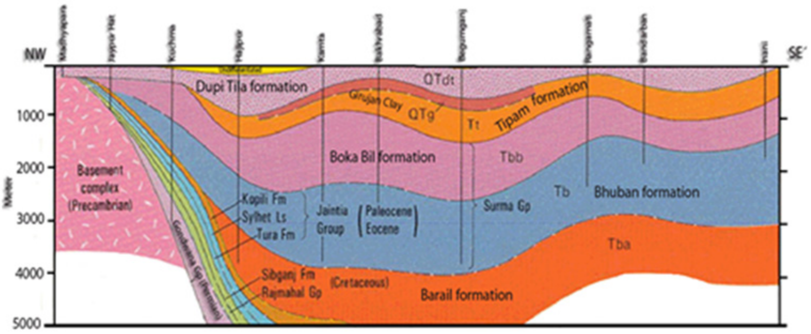


FIGURE 12: Generalized stratigraphic cross-section along northwest to southeast part of Bengal Basin, Bangladesh (GSB, 1990)

Barapukuria coal basin

The Barapukuria coal basin is located in Parbatipurthana of Dinajpur district of Bangladesh. Gondwana coal deposits were found here at the lowest depth (118 m) in the graben structure of the stable shelf. A sedimentary column of about 1200 m of predominantly Permian Gondwana rocks overlies the Precambrian basement (Figure 14). At Barapukuria, 40.5°C was encountered at a depth of

380 m (Wardell Armstrong, 1991) and 52°C at a depth of 440 m (IMC, 1998). A high temperature gradient with an average 48.7°C/km was reported in the coal mine, whereas in the deeper part of the Gondwana basin the thermal anomaly was recorded as high as 116.9°C/km (CMC, 1994), as shown in Figure 15. High temperatures are associated with faulting; spontaneous combustion and traversing of an igneous dyke through the coal seams caused the high heat flow in the region (Kabir, 2008). The southern part of the coal basin is characterized by higher heat flow than the north. Overlying the Lower Dupi Tila formation above the coal seam is clay which acts as a seal to trap heat in the underground chamber. When miners open the southern colliery to extract coal faces high underground temperature, an inrush of water flooding and spontaneous combustion prevents mining operations. The northern part of the basin is comparatively colder and lacks the Lower Dupi Tila clay unit on top of the Gondwana coal. The overlying Upper Dupi Tila Sandstone is a highly porous and permeable water bearing formation constituting the main aquifer system of the area. The low geothermal gradient is possibly caused by the downward vertical movement of cool meteoric water. Some stratigraphic dissimilarity also exists north and south of the basin.

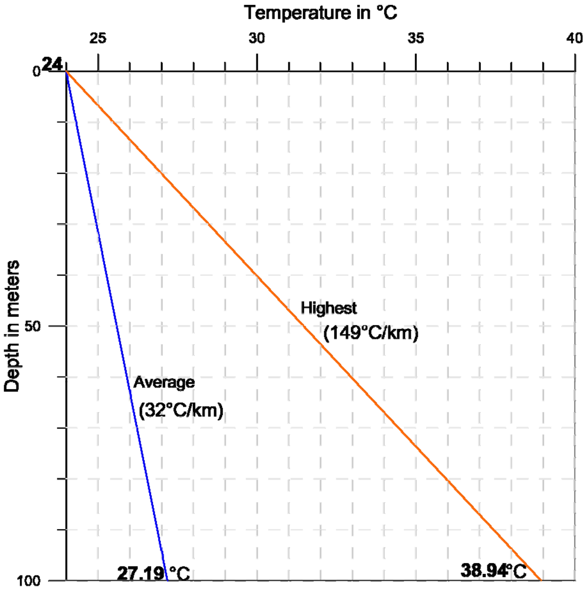


FIGURE 13: Anomalous geothermal gradient at the Madhyapara hard rock mine area

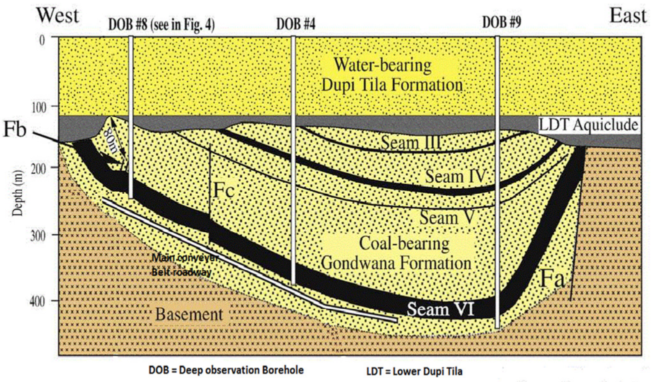


FIGURE 14: W-E cross-section of Barapukuria coal mine area (after Islam and Shinjo, 2009)

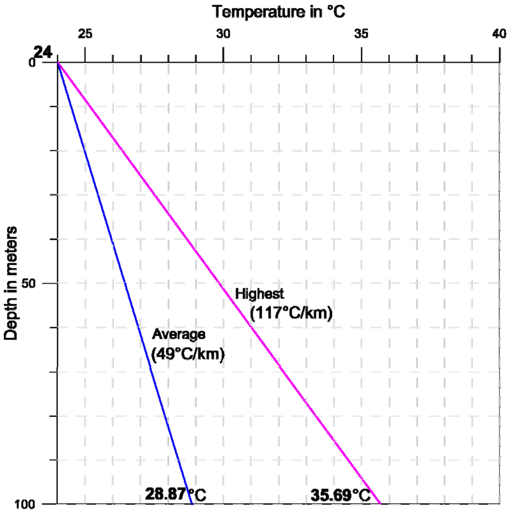


FIGURE 15: Anomalous geothermal gradient at the Barapukuria coal basin

Thakurgaon high-temperature area

The Thakurgaon high-temperature area, located northwest of Barapukuria belongs to the Tista flood plain and constitutes the Bangladesh part of the Himalayan Foredeep region. The depth of the crystalline Achaean basement further north to the fan complex was found at a depth of 2500 m at Shalbonhat 1 well (BSPD, 1988). The basement occurs only at 150 m depth at Phulbari coal basin to the southeast (GSB, 1990). Neogene Siwalik sediments and recent alluvium directly overlie the basement in most of the northwest part of the stable shelf (Rabbani et al., 2000). Although the surface of the Tista alluvial fan appears smooth and undisturbed, the fan is deposited in a tectonic transition zone subject to complex strong forces driven by the collision of the Indian plate with the Eurasian plate to the north. In response to past tectonic events, a series of well-defined deep seated basement faults has occurred (Khan, 1991). The fault systems and associated structures are responsible for conducting heat into the overlying near surface sedimentary aquifer, causing the surface manifestation of geothermal sources in this region. High temperature groundwater was noticed in Barunagaon village (well 278) of the Thakurgaon district during groundwater pumping (Bashar and Karim, 2001). Subsequent research revealed a high anomalous temperature gradient in some groundwater wells (Table 8) in some parts of the Thakurgaon area (Rahman, 2006; Kabir, 2008) as shown in Figure 16. The Geological Survey of Bangladesh also drilled a thermal exploratory well there recently and found a temperature gradient of 34.2°C/km at a depth of 550 m.

TABLE 8: Wellhead temperatures at shallow wells in Thakurgaon region (Kabir, 2008)

Sl/No.	Name	Temperat. (°C)	Depth (m)	Gradient (°C/km)
1	T-278	35	87	126
2	T-277	30	56	107
3	HTW-1	29	27	182
4	HTW-2	27	26	115
5	HTW-3	29	26	192
6	STW	33	36	250

T- Irrigation well; HTW- Hand tube well; STW- Shallow tube well; Aver. surface temp. 24°C.

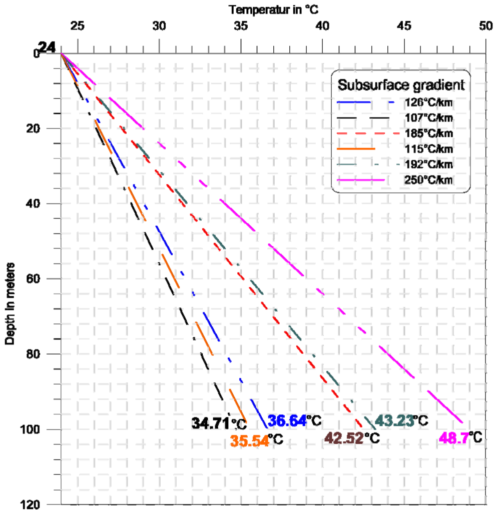


FIGURE 16: Variable temperatures at 100m depth and thermal gradient (°C/km) at Thakurgaon area

5. GEOCHEMICAL METHOD

5.1 Geochemical methods in geothermal exploration

Geochemical methods are an integral part of geothermal exploration techniques especially during pre-drilling stages. Geochemical methods are relatively inexpensive and can provide valuable information on the temperature conditions in a geothermal reservoir and the source of the geothermal fluid that is not obtainable by geological or geophysical techniques. This is a somewhat straight-forward and simple method for an initial assessment of a potential geothermal area. The use of geochemistry in geothermal exploration has a profound importance in inferring subsurface conditions by studying the chemistry of surface manifestations or discharge fluids that carry the signature of the deep geothermal system. Chemically inert constituents that are conserved and not changed by chemical reactions provide information on the sources of the fluid. Such sources are termed tracers. On the other hand, reactive components, such as SiO_2, CO_2, H_2S etc., react with the minerals and other reactive constituents and can thus give information about the subsurface conditions in the form of geoindicators (Giggenbach, 1991). Geothermometers are geoindicators that can be used to estimate subsurface temperatures using the chemical and isotopic compositions of discharges.

5.2 Geothermometers

Chemical and isotope geothermometers constitute important geoindicators for the exploration and development of geothermal resources. They are also very important during exploitation in monitoring the response of a geothermal reservoir to the production load and in elucidating chemical reactions occurring in zones of depressurization around wells that result from boiling and/or cooling by recharging cold water. Care must be taken in applying geothermometers, otherwise the results and interpretations may give rise to serious errors. It is a good practice to compare temperatures indicated by different geothermometers. Note that some geothermometers are empirical, e.g. the Na-K-Ca geothermometer and gas geothermometers (D'Amore and Panichi 1980), whereas others are based on thermodynamic properties, e.g. Na-K and K-Mg geothermometers. As the factors controlling empirical geothermometers are not completely known, theoretical geothermometers may in some cases be more reliable (Karingithi, 2009). Geothermometers are classified into three groups:

- Water or solute geothermometers
- Steam or gas geothermometers
- Isotope geothermometers

Water and steam geothermometers are collectively termed chemical geothermometers. During the ascent of geothermal waters from a deep reservoir to the surface, they may cool by conductive heat loss as they travel through cooler rocks or by boiling because of decreasing hydrostatic head. Yet, cooling may change the degree of saturation with respect to both primary and secondary minerals. As a result, conductive cooling can bring about some modification in the chemical composition of the ascending waters by mineral dissolution or precipitation. Boiling invariably causes changes in the composition of rising geothermal waters. These include degassing and an increase in the solute content of the water due to steam loss. The boiling mechanism affects the gas content of the steam that forms. The principle application of chemical and isotopic geothermometers during geothermal exploration involves the estimation of reservoir temperatures below the zone of cooling. When applying these geothermometers it is invariably assumed that no changes in water composition occur in conjunction with conductive cooling; boiling is taken to be adiabatic. The amount of conductive heat loss of ascending geothermal waters is proportional to the distance travelled and inversely proportional to the flow rate. When geothermometers are applied to estimate subsurface or aquifer temperatures, a basic assumption is that temperature dependent chemical or isotopic equilibria prevail in the source aquifer. Further, as stated above, the approximation is made that chemical and isotopic reactions do not significantly modify the composition of the fluid as it ascends from the source aquifer to the point of sampling, whether it is a thermal spring, fumarole or wellhead. Equilibrium between the mineral-solution or solute-solute is assumed for geothermometry to be applied. Equilibrium between quartz and solution as well as between alkali feldspar and solution is invariably attained in geothermal reservoirs when temperatures exceed about 150-180°C. Accordingly, the application of the quartz and the Na/K geothermometers to high-temperature geothermal reservoirs can be regarded as thoroughly established.

5.2.1 Water geothermometers

The most important water geothermometers are silica (quartz and chalcedony), Na-K ratio and Na-K-Ca geothermometers.

Silica geothermometers

The silica geothermometer is based on experimentally determined variations in the solubility of different silica species in water, as a function of temperature and pressure. The basic reaction for silica dissolution is:

$$SiO_{2(qtz)} + 2H_2O = H_4SiO_2$$

In most geothermal systems, deep fluids at temperatures >180°C are in equilibrium with quartz; quartz is stable up to 870°C and has the lowest solubility compared to other silica polymorphs. Quartz is common as a primary and secondary (hydrothermal) rock-forming mineral. Silica polymorphs with a less ordered crystalline structure (i.e. chalcedony, opal ct, cristobalite) have higher solubilities than quartz and form at cooler temperatures of <180°C. The quartz geothermometer is best for reservoir conditions >150°C. Below this temperature chalcedony rather than quartz probably controls the dissolved silica content. Table 9 shows several types of silica geothermometers used in geothermometry.

TABLE 9: Some selected Silica geothermometers

Geothermometer	**Equation (°C)**	**Range (°C)**	**Source**
Quartz	$\frac{1309}{5.19 - log\ S} - 273.15$	25-250	Fournier (1977)
Quartz (adiabatic)	$\frac{1522}{5.75 - log\ S} - 273.15$	25-250	Fournier (1977)
Chalcedony	$\frac{1112}{4.91 - log\ S} - 273.15$	120-180	Arnórsson et al. (1983)
Amorphous silica	$\frac{731}{4.52 - log\ S} - 273.15$	25-250	Fournier (1977)
Opal	$\frac{781}{4.51 - log\ S} - 273.15$	25-250	Fournier (1991**)**

S represents silica concentration as SiO_2 in mg/kg

Na-K geothermometer

The response of the sodium/potassium (Na/K) ratio, decreasing with increasing fluid temperature, is based on a temperature dependant cation exchange reaction between albite and K feldspar.

$$\underset{Albite}{NaAlSi_3O_8} + K^+ = \underset{K\ feldspar}{KAlSi_3O_8} + Na^+$$

Waters from high temperature reservoirs (180°C) of chloride waters are suitable for this geothermometer. For lower temperature reservoirs where fluids have long residence times, the Na-K geothermometer may, in some cases, be applicable. The advantage of this geothermometer is that it is less affected by dilution or steam loss given that it is based on a ratio. The geothermometer is applicable to 350°C, as the re-equilibration is slower than that of the silica-quartz geothermometer. Therefore, the Na-K geothermometer may give indications regarding the deeper part of the system in comparison to the silica-quartz geothermometer, depending on the system's hydrology. Table 10 summarizes some of the commonly used Na-K geothermometers.

TABLE 10: Some selected Na-K geothermometers

Geothermometer	**Equation (t°C)**	**Source**
Na-K	$\frac{1217}{1.438 - \log(\frac{Na}{K})} - 273.15$	Fournier (1979)
	$\frac{1390}{1.75 - log\ (\frac{Na}{K})} - 273.15$	Giggenbach (1988)
	$\frac{933}{0.993 - log\ (\frac{Na}{K})} - 273.15$	Arnórsson et al., (1983)

Some limitations - the Na-K geothermometer works well under the following conditions:

- For waters indicating reservoir temperatures >100°C
- For waters containing low Ca; i.e. if the value of (log ($Ca^{1/2}$/Na) + 2.06) is negative
- For near neutral pH chloride waters.

Na-K-Ca geothermometer

The Na-K-Ca geothermometer was developed by Fournier and Truesdell (1973) for application to waters with high concentrations of calcium. This is an empirical geothermometer and theoretical constraints include equilibrium between Na-K feldspars plus conversion of calcium alumino silicate minerals (e.g. Plagioclase) to calcite. The main advantage of the Na-K-Ca geothermometer in comparison with the quartz geothermometer, and especially the Na-K geothermometer, is that it does not give high and misleading results for cold and slightly thermal, non-equilibrated waters. The assumptions included in development of the empirical equation are:

- Excess silica is present;
- Aluminium is conserved in a solid phase.

The following considerations apply in the application of this geothermometer:

1) Calculate $\{\log(Ca^{1/2}/Na) + 2.06\}$; if its value is positive, then use $\beta = 4/3$ in the formula in determining the temperature. If that calculated temperature is <100°C, then this temperature is appropriate.
2) If the $\beta=4/3$ calculated temperature is >100°C, or the value of $\{\log(Ca^{1/2}/Na) + 2.06\}$ is negative, then use $\beta=1/3$ to calculate the temperature. The following equation is used for the Na-K-Ca geothermometer:

$$t°\mathrm{C} = \frac{1647}{\log(\frac{Na}{K}) + \beta\log(\frac{Ca^{0.5}}{Na}) + 2.24} - 273.15$$

$\beta = 4/3$ for $Ca^{1/2}/ Na > 1$ and $t < 100°C$;
$\beta = 1/3$ for $Ca^{1/2}/ Na > 1$ and $t_{4/3} < 100°C$

5.2.2 Steam (gas) geothermometers

Surface manifestations in most geothermal fields consist mainly of fumaroles, springs and hot grounds. Where groundwater is deep, water springs may not be available. When this is the case, water geothermometers cannot be used to predict the subsurface temperatures. There are 3 types of gas geothermometers, based on the following:

- Gas-gas equilibria;
- Mineral-gas equilibria involving H_2S, H_2 and CH_4 but assuming CO_2 to be externally fixed according to empirical methods;
- Mineral-gas equilibria.

The first two groups of geothermometers require a relative abundance of gaseous components in a gas phase, whereas the third group is based on the gas concentrations in steam.

5.2.3 Isotope geothermometers

Fractionation of isotopes of light elements between compounds is quite significant and temperature dependent. The fractionation is largest for lighter elements found in geothermal systems such as helium, hydrogen, carbon, oxygen, and sulphur. The distribution of the stable isotope of H, C and O between aqueous and gaseous compounds has been used as geothermometers. Isotope exchange reactions may be between gases and steam phase, a mineral and gas phase, water and a solute or a solute and a solute. Although there are many isotope exchange processes, only few have been used for geothermometry. These are based on simplicity of sample collection and preparation, ease of isotopic measurement, a suitable rate of achieving isotopic equilibrium and knowledge of the equilibrium constants. The following have been used:

- Oxygen isotopes;
- Carbon dioxide and methane isotope geothermometer;
- Methane-hydrogen gas isotope geothermometer;
- Water-hydrogen gas isotopic geothermometer;
- Sulphate-water oxygen isotope geothermometer;
- Sulphate-hydrogen sulphide geothermometer.

5.3 The log (Q/K) diagram

The Saturation Index (*SI*) is the degree of saturation of minerals in aqueous solutions. This method involves a comparison between ionic activity products and the thermodynamic activity product. An expression of the saturation index (*SI*) is:

$$SI = \log(\frac{Q}{K})$$

where Q is the calculated ion activity product; and
K is the equilibrium constant.

Saturation Index:

- If *SI* is negative: Undersaturated, no potential to scale;
- If *SI* is positive: Supersaturated, scale form precipitation may occur;
- If *SI* is zero: Equilibrium, borderline scale potential.

The values for Q and K can be calculated using the WATCH program on the basis of the calculated chemical speciation in natural waters (Arnórsson and Bjarnason, 1993). For a mineral in equilibrium with the aqueous solution, the temperature corresponding to the intersection point of the mineral equilibrium curve and the SI=0 line gives the theoretical equilibrium temperature. The characteristics of convergence of log(Q/K) curves for the mineral assemblage to zero at the temperature of equilibrium can be used to confirm the most probable temperature at which the mineral used as a chemical geothermometer reaches or approaches the equilibrium line, SI=0 (Reed and Spycher, 1984).

5.4 Scaling and corrosion

Mineral scale formation or scaling is a very common phenomenon observed in almost all geothermal energy exploration fields. All geothermal fluids contain dissolved minerals. These minerals are deposited at different points of the operation, adversely affecting the operation by restricting fluid flow. The formation of scales has always been a difficult challenge for the geothermal industry. Changes in water temperature, pressure, pH and mineral saturation are unavoidable when fluid is tapped from geothermal reservoirs by production wells drilled into a reservoir. As a consequence, minerals may deposit in producing aquifers, within the wells, in pipelines, steam separators and other surface equipment and in injection wells. The most common scales consist of calcium carbonate and amorphous silica but scales of various oxides, silicates and sulphides are also known.

5.4.1 Calcite scaling

Calcite scaling largely occurs in response to cooling and degassing of geothermal water, as it boils by depressurization. Calcite solubility is retrograde, i.e. it decreases with increasing temperature. Degassing of water due to boiling leads to a sharp rise in the pH of water which, in turn, increases the ionic activity of carbonate ions (CO_3^{2-}) becoming over-saturated:

$$CaCO_3 = Ca^{2+} + CO_3^{2-}$$

Cooling, which occurs due to depressurized boiling, counteracts the effect of CO_2 degassing with respect to the state of calcite saturation. The release of CO_2 and the deposition of calcite can be expressed as:

$$Ca^{2+} + 2HCO_3^- \Leftrightarrow CaCO_3 + CO_2 + H_2O$$

Calcite scale formation is most troublesome around 200°C because CO_2 solubility is at a minimum at this temperature; it decreases at both higher and lower temperatures. The intensity of calcite scale formation increases with increasing salt content of the water (Arnórsson, 2004).

5.4.2 Prediction of calcite scale

Langelier Saturation Index (LSI)

This method is widely used to predict calcite scaling from the chemical component of the geothermal fluid. The Langelier Saturation index (*LSI*) is an equilibrium model derived from the theoretical concept of saturation and provides an indicator of the degree of saturation of water with respect to calcium carbonate (Langelier, 1936, 1946). It can be shown that the Langelier saturation index (*LSI*) approximates the base 10 logarithm of the calcite saturation level. The Langelier saturation level approaches the concept of saturation using pH as a main variable. The *LSI* can be interpreted as the pH change required for water to approach equilibrium. Water with a Langelier saturation index of 1.0 is one pH unit above saturation. Reducing the pH by 1 unit will bring the water into equilibrium. This occurs because the portion of total alkalinity present as CO_3^{2-} decreases as the pH decreases, according to the equilibrium describing the dissociation of carbonic acid:

$$H_2CO_3^- \Leftrightarrow HCO_3^{2-} + H^+$$

$$H_2CO_3^- \Leftrightarrow CO_3^{2-} + H^+$$

The LSI is probably the most widely used indicator of cooling water scale potential, but it provides no indication of how much scale or calcium carbonate will actually precipitate to bring the water to equilibrium. It simply indicates the driving force for scale formation and growth in terms of pH as a master variable. *LSI* is defined as:

$$LSI = pH - pH_s$$

where *pH* is the measured water *pH*

pH_s is the *pH* at saturation in calcite or calcium carbonate and is defined as:

$$pH_s = (9.3 + A + B) - (C + D)$$

where $A = (\log_{10}[TDS] - 1)/10$;
$B = -13.12 \times \log_{10}(°C + 273) + 34.55$;
$C = \log_{10}[Ca^{2+} \text{ as } CaCO_3] - 0.4$;
$D = \log_{10}[\text{alkalinity as } CaCO_3]$

- If *LSI* is negative: No potential to scale, the water will dissolve all $CaCO_3$;
- If *LSI* is positive: Scale can form and $CaCO_3$ precipitation may occur;
- If *LSI* is close to zero: Borderline scale potential. Water quality or changes in temperature, or evaporation could change the index.

Saturation Index method

This method involves the comparison of the calcium and carbonate ion activity product to the thermodynamic activity product. An expression of this, the saturation index, $SI = log (Q/K)$ is sometimes used to predict scales formation.

- If SI is negative: No potential to scale, the water will dissolve $CaCO_3$

- If SI is positive: Scale can form and $CaCO_3$ precipitation may occur
- If SI is zero: Borderline scale potential.

5.4.3 Silica scaling

Silica scaling is usually the largest problem as displayed practically in all high-temperature geothermal fields. The solubility of silica is proportional to the temperature, the opposite of carbonates. Amorphous silica deposition is controlled by kinetics and can begin on the surface several minutes or hours after reaching supersaturation. Silica scales are hard to remove mechanically. The formation of silica scales is a physical-chemical process. It is controlled by the solubility, temperature, composition, pH of solution, rate of growth, dimension, concentration of colloidal particles, and hydrodynamic conditions in brine flow. Depending on the degree of supersaturation processes of nucleation and colloidal particles, growth develops as a result of the interaction of siliceous groups (Iler, 1979) and the aggregation of particles. Colloidal particles are moved to the surface by mass transfer in a flow and silica precipitates finely as a solid amorphous matter. An increase in alkalinity (pH>8.0) speeds up the aggregation of particles (Kashpura and Potapov, 2000).

5.5 Corrosion

The term corrosion is used about the chemical destruction of materials. Iron and ordinary unalloyed steels corrode easily into rust. The most common case of corrosion is wet corrosion. The corrosive processes are very complex and take place in widely differing conditions. Different types of corrosion such as pitting, crevice corrosion, stress corrosion cracking (SCC), sulphide stress cracking are common while galvanic corrosion, corrosion fatigue and exfoliation are less common in geothermal systems (Hayashi, 1988). The most common corrosive species in geothermal fluids are the hydrogen ion, chloride ion, hydrogen sulphide, carbon dioxide, oxygen and iron.

5.6 Application of geochemical methods

The present work is an accomplishment of current knowledge acquired on the geochemical method of geothermal exploration. For the current study, reuse of previously analysed 17 water samples from the basement aquifer of the Madhyapara granite mine area was taken into consideration (Bashar and Karim, 2001). The samples were collected from a basement aquifer where the flow of water was artesian and flowing through fissures at different mining levels (ventilation level, sub level and production level) from the hard rock mine area. Samples were analysed in the chemical laboratory of the Institute of Nuclear Science and Technology (INST), Bangladesh Atomic Energy Commission (Table 11). The data required for the standard practice of geochemical analysis in geothermal exploration is relatively absent and data quality is also poor. Madhyapara area comprises two distinct types of aquifer systems. In the lower basement aquifer, groundwater occurs in the interconnected fractures and fissures of weathered and fresh Archean crystalline igneous and metamorphic rocks at a depth of about 130 m below ground level. A kaolinitic clay aquitard separates the upper unconfined aquifer consisting of rocks of Eocene Tura and Pliocene Dupi Tila formations.

5.7 Classification of thermal water

For graphical presentation of the water samples, spreadsheet analyses of geothermal water and the gas geochemistry were used (Powell and Cumming, 2010). Cross-plots and ternary diagrams were generated from measured concentrations of chemical species using formulas based on equilibrium reactions and empirical relationships. The spreadsheet takes tabulated water chemistry data input in ppm weight and stable isotope data in per mil and tabulates geothermometers and quality assurance parameters. The Na-K-Mg triangular diagram of Giggenbach (1991) is probably the most widely used cation geothermometry plot, a ternary combining the sodium-potassium (Na-K) geothermometer with the potassium-magnesium (K-Mg) geothermometer. The plot is also known as the Giggenbach plot. Giggenbach (1991) called this type of plot a "geoindicator" because it organizes the plotted data points in a manner that illustrates both the evidence that supports the interpretation of equilibrated water at high temperature but also the influence of shallow processes and possible equilibration at lower temperature. The Na-K-Mg triangular indicates the equilibrium temperatures of minerals (feldspars, clay) containing these elements, and is used to identify the equilibrium between the geothermal fluids and rock and to determine the reservoir temperature.

The Na-K-Mg ternary plot shows that most of the samples (BD1, 2, 4-8, 10-17) are in a partial equilibrium condition and a few samples (BD 3, 9) are in immature water condition. So, the water samples did not attain equilibrium between water and rock (Figure 17). The calculated equilibrium temperatures are in the range of 70-140°C, indicating that the hot water comes from a low-temperature geothermal source.

The Cl-SO_4-HCO_3plot illustrates the proportions of the major anions present in geothermal water in a format based on Giggenbach (1991) as shown in Figure 18. Different types of thermal waters can be distinguished, such as peripheral or bicarbonate (HCO_3) water, mature water etc. From the plots, Figure 18 shows that most of the samples are located within the region of high bicarbonate concentration and are classified as peripheral waters that may have mixed with cold groundwater.

TABLE 11: Water chemistry data of Madhyapara granite mine area (Bashar and Karim, 2001)

Sample	**pH**	**Na^+**	**K^{2+}**	**Ca^{2+}**	**Mg^{2+}**	**Cl^-**	**HCO_3^-**	**SO_4^{2-}**	**NO_3^-**	**$Fe^{(total)}$**	**As**	**Zn**	**Cu**	**Cr**	**Pb**	**Ni**	**Cd**	**Th**	**Estimated temperature (°C)**	
no.		**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**		**Na/K**	**Na-K-Ca**
1	7.5	60	0.9	1.3	0.02	34.4	87	10.5	<0.1	0.03	<0.003	0.03	0.04	0.22	0.3	0.16	0.01	3.3	95	108
2	8	61	1.7	1.4	0.03	29	110	9.9	<0.1	0.06	<0.003	0.01	0.05	0.18	0.28	0.14	0.011	3.6	128	132
3	8	59	1.4	1.3	0.82	43	97	9.8	<0.1	0.09	0.01	0.02	0.06	0.22	0.24	0.15	0.01	6.6	119	126
4	8	59	1.1	1.2	0.02	34.6	87	10	<0.1	0.15	<0.003	0.02	0.04	0.15	0.26	0.13	0.01	3.1	106	117
5	7.7	60	1.3	1.2	0.08	35.8	83	10.4	<0.1	0.13	0.01	0.01	0.05	0.14	0.33	0.2	0.012	3.3	114	124
6	8	62	1.1	1.3	0.04	35.9	89	9.7	<0.1	0.18	0	0.02	0.05	0.14	0.31	0.16	0.01	3.4	104	115
7	8	59	1.2	1.0	0.01	35.1	81	9.5	<0.1	0.18	0.01	0.01	0.69	0.18	0.26	0.13	0.01	2.5	110	123
8	7.5	61	0.7	1.6	0.13	32	83	10	<0.1	0.36	<0.003	0.02	0.03	0.13	0.27	0.17	0.011	4.5	83	96
9	8	60	0.6	1.1	0.66	32	106	9.9	<0.1	0.15	<0.003	0.02	0.01	0.13	0.39	0.14	0.014	5.5	77	95
10	7.6	60	0.6	1.0	0.05	34	103	9.5	<0.1	0.23	<0.003	0.03	0.06	0.16	0.32	0.17	0.02	2.7	76	96
11	7.7	99	1.1	0.8	0.06	41.2	140	42.7	<0.1	0.35	<0.003	0.03	0.04	0.27	0.33	<0.002	<0.006	2.3	81	109
12	7.4	111	2.7	1.2	0.33	83.2	116	31.5	<0.1	0.17	0.01	0.04	0.15	0.03	0.35	<0.002	0.012	4.3	120	138
13	7.5	94	1	1.0	0.38	40.1	149	28	<0.1	0.93	0.01	0.11	0.06	0.2	0.25	0.08	0.006	4.1	79	104
14	8	113	2.3	0.8	0.13	38.4	197	32.5	<0.1	0.14	<0.003	0.05	0.11	0.07	0.46	<0.002	0.012	2.6	111	136
15	8	98	3	0.9	0.33	44.4	169	15.9	<0.1	0.16	0.02	0.02	0.07	0.14	0.19	0.03	<0.006	3.5	133	150
16	8	97	1.3	1.1	0.37	43.1	167	19.4	<0.1	0.44	<0.003	0.06	0.11	0.18	0.41	<0.002	0.011	4.4	88	110
17	7.7	92	1.1	0.7	0.09	37.6	136	37.9	<0.1	0.05	0.01	0.02	0.05	0.19	0.34	0.08	0.007	2.1	84	112

5.8 Geothermometer analyses

Using different geothermometers based on the relative abundance of Na, K and Ca as proposed by different authors, a wide variety of subsurface temperature has been observed (Table 12). The calculated subsurface temperatures are summarized as follows:

- The Na-K geothermometer temperatures are in the range of 76-133°C (Fournier, 1979), 39-99°C (Arnórsson, et al., 1983) and 98-153°C (Giggenbach, 1988).
- The K-Mg geothermometer temperatures are in the range of 37-79°C (Giggenbach, 1988).
- The Na-K-Ca geothermometer gives reservoir temperatures between 65 and 134°C (Fournier and Truesdell, 1973).

Calculated temperatures for the analysed water samples are quite variable. The temperatures predicted by the K-Mg geothermometer are the lowest. Temperature increases with the increase of silica content and differences gradually become smaller. The results from the three Na-K geothermometers are also remarkably variable. It is obvious that the Na-K geothermometer by Giggenbach (1988) yields relatively higher values compared to the other two. The reason is probably due to the specific mineral which controls the mineral-fluid equilibration.

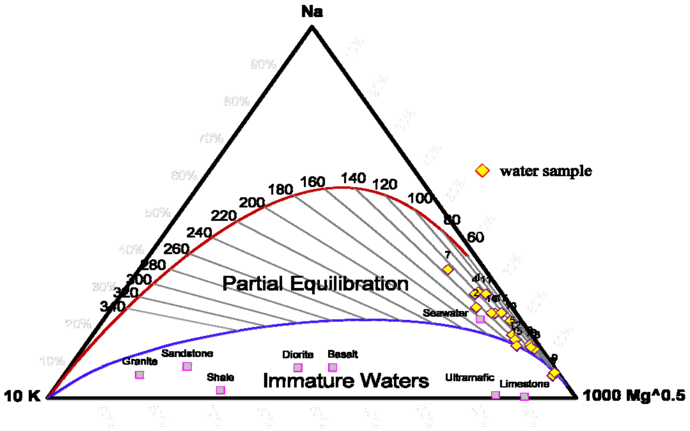


FIGURE 17: Classification of water samples from Madhyapara hard rock mine, Bangladesh, based on the Na-K-Mg ternary plot

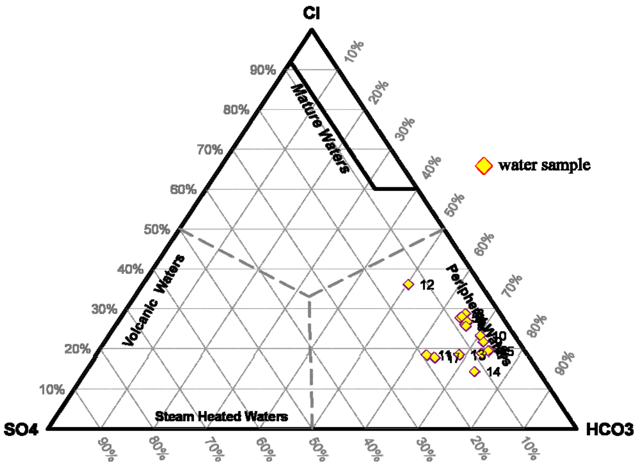


FIGURE 18: Classification of water samples from Madhyapara hard rock mine, Bangladesh, based on the Cl-SO_4-HCO_3plot

5.9 Mineral-solution equilibrium

In this study, the WATCH program was used to calculate the log (*Q*/*K*) for the temperature range 70-160°C. Only calcite was selected to calculate its state of equilibrium. The calculated saturation index (*SI*=log *Q*/log *K*) vs. temperature for all the water samples are shown in Figure 19. The water sample plot shows that most of the samples are in a state of equilibrium for calcite but a few plots (BD 14, 15, 16) are above the equilibrium line (SI=0), i.e. a few samples are supersaturated with respect to calcite (Figure 19). Another typical relationship, between the Na-K-Ca and Na-K is plotted and shown in Figure 20. The water samples plot around the equilibrium line, i.e. they are near to the state of equilibrium.

TABLE 12: Different geothermometer temperatures (°C) for the water samples of Bangladesh

Sample no.	[1]Na-K-Ca	[2]Na-K	[3]Na-K	[4]Na-K	[4]K-Mg
1	74	95	58	116	84
2	94	127	93	147	95
3	88	118	83	139	52
4	82	106	70	126	89
5	88	114	78	134	76
6	81	103	67	124	81
7	89	110	74	131	101
8	62	82	45	104	57
9	65	76	39	98	37
10	67	76	39	98	64
11	97	81	43	102	76
12	123	120	85	140	77
13	88	79	41	100	53
14	124	110	74	131	84
15	134	133	99	153	79
16	95	90	52	111	59
17	100	84	47	105	71

[1]Fournier and Truesdell,1973; [2]Fournier,1979; [3]Arnórsson et al., 1983; [4]Giggenbach, 1988;

5.10 Saturation state of calcite

The solubility of calcite is retrograde in nature. Boiling of reservoir waters leads to degassing of the waters, hence raising the pH of the solution. Disassociation constants of aqueous carbon dioxide (H_2CO_3) and bicarbonates (HCO_3^-) decrease as well. The result is an increase in the carbonate ion (CO_3^{2-}) concentrations largely responsible for calcite saturation levels. The combined ionic activities of Ca^{2+} and CO_3^{2-} may lead to oversaturation of the solution with calcite. The chemical results of the waters from the Madhyapara hard rock mine area indicate that the reservoir waters are either under-saturated or close to saturation with calcite at quartz equilibrium temperatures (Figure 21). Flashing of the aquifer waters increases the saturation state of the waters with calcite and further boiling leads to oversaturation of the waters. Enhanced boiling results in decreased calcite over-saturation, principally due to the retrograde solubility of calcite. These results indicate the possibility of calcite precipitation occurring at temperatures in the range of 100-140°C for the analysed samples.

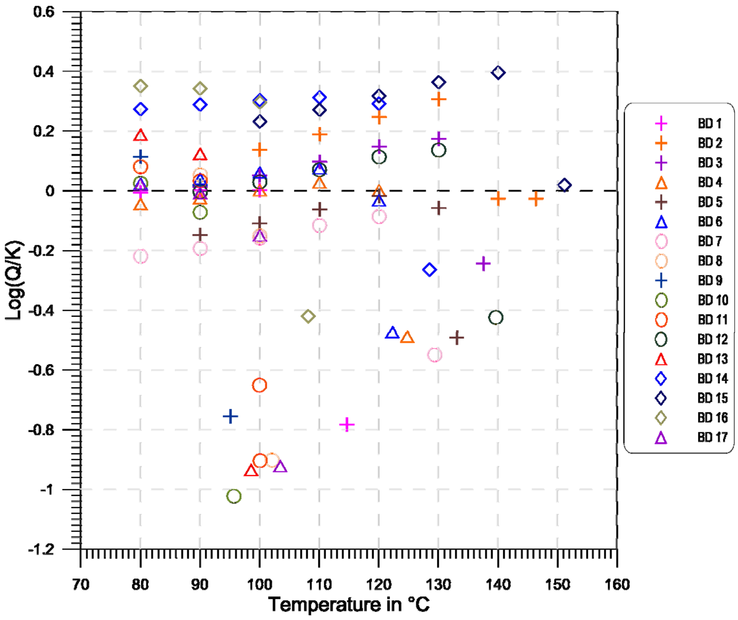


FIGURE 19: Saturation state of calcite

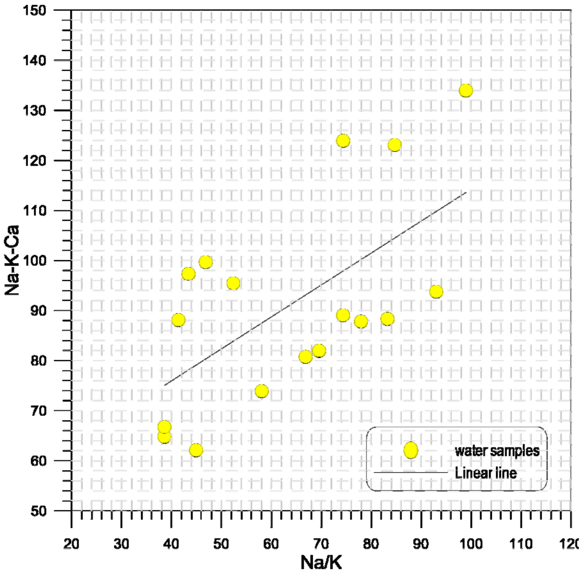


FIGURE 20: Na-K-Ca temperatures vs. Na-K temperatures plotted for the 17 samples

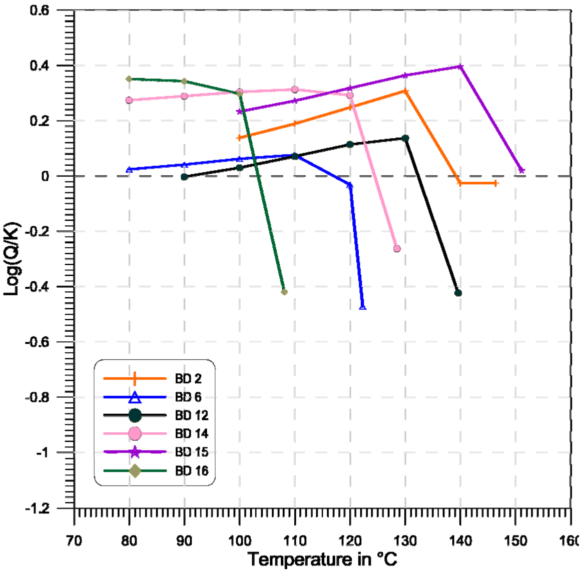


FIGURE 21: Prediction of saturation state of calcite for selected water samples

6. DISCUSSION AND CONCLUSIONS

Power and energy are prerequisites for higher economic growth, poverty alleviation and social development of a least developed country (LDC) such as Bangladesh. Per capita energy consumption of Bangladesh is one of the lowest in the world. To date only 49% of its population has access to electricity. Bangladesh's present power generation capacity is about 6,727 MW. Currently, power generation is highly dependent on natural gas, which accounts for 73% of the total electricity generation installed capacity. But the existing gas reserves can only serve for another 10 years amidst increasing demands for more gas. The present supply cannot fulfil the existing gas demand. Indigenous coal has yet to make any significant impact on the energy scenario. Utilization of renewable energy resources (solar, wind, biomass, hydro, geothermal, tidal wave etc.) has yet to reach commercial dimensions and cannot serve as alternates to conventional energy resources. The recently adopted renewable energy policy of Bangladesh has mandated the contribution of renewable energy resources at 5% by 2015 and 10% by 2020 of the total power demand. Geothermal technology in Bangladesh is quite new. No systematic work has been done so far to assess the geothermal prospects of Bangladesh. The present study is an outcome of the current concern over renewable energy exploration and an attempt to understand the technical know-how for assessing geothermal prospect areas in order to exploit the potential geothermal energy.

Geothermal energy exploration involves initial cash investments, requiring good planning to minimize risks and save money. It is necessary in the early stages to prioritize the areas to be investigated. The average geothermal gradient along the southeast part of Bengal Foredeep region of Bangladesh varies from 19.8 to 29.5°C/km and on the northwest stable shelf part of Bangladesh it varies from 20.8 to 48.7°C/km. In Bangladesh many deep abandoned wells initially drilled for oil and gas exploration could provide valuable information about subsurface geology and the temperatures of areas of interest. All previously explored areas were surveyed seismically along with other proven geophysical methods. In the northwest stable shelf part of Bangladesh, the Singra-Kuchma-Bogra area of the Bogra shelf requires considerable attention with its 4 deep wells with an average geothermal gradient >30°C/km and in favourable geological conditions. A systematic study of these wells using the available data (geology, geophysical logs, temperature/pressure, core/cuttings etc.) would provide valuable information on the subsurface geothermal system. The Barapukuria coal mine area, the Madhyapara hard rock mine area and the Thakurgaon thermal areas also lying in the northwest part of

Bangladesh are identified as high thermal anomalous zones, so for them further study is stressed. The Sitakund area along the folded belt of southeast Bengal Foredeep region, where local warm springs occur is another promising area for geothermal exploration. An attempt was made to calculate different geothermometer temperatures using the geochemical data of the water samples of the basement aquifer of the Madhyapara hard rock mine area and the acquired knowledge from this training. Some of the data required for the standard practice in geochemical analysis of geothermal exploration is relatively absent in the previously analysed data. The cation plot shows that most of the waters are in partial equilibrium with a few samples indicating immature waters while the anions plot suggests that the waters are peripheral. Different geothermometers have been used for calculating the temperatures of the water samples. The predicted temperature found quite variable ranges from 67 to 153°C. The calculated saturation index (SI=log Q/log K) vs. temperature for all the samples showed that there was no indication of silica scaling; but for calcite, most of the samples were in equilibrium and a few of them were supersaturated so they might form scales.

The assessment of an area in the context of subsurface geothermal exploration requires a detailed study of all surface exploration methods such as geological, geochemical and geophysical methods as well as drilling data. Afterward, integrating all the available information needs to be done for a better understanding on the subsurface geothermal condition, including the likely temperature of the reservoir fluids, heat sources, flow pattern of reservoir fluids and geological structure of the reservoir, the volume of the hot rocks, and the natural heat loss. A conceptual model of the geothermal system has to be drawn which will comply with all results of the surface exploration before proceeding further. The drilling of a deep exploration/production well in a geothermal system is considered the most expensive part of the programme as well as the most risky part of a geothermal exploration.

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