



Newly Discovered Geothermal Spring in Polonnaruwa, Sri Lanka

Study on Geothermal Resources of South Asia

Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka

December 2011

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STUDY ON GEOTHERMAL RESOURCES OF SOUTH ASIA

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December, 2011

CONTENTS

Executive Summary.....	xi
Chapter – 1 Introduction	1
1.1 Background.....	1
1.2 Objectives of the Study	2
1.3 Methodology and Terms of Reference.....	2
1.4 List of Geothermal Related Institutions in SAARC Countries	3
Chapter – 2 Understanding Geothermal Energy	7
2.1 Internal Structure of Earth	7
2.2 Heat Expulsion	8
2.3 Geothermal Fields	10
2.4 Geothermal Energy for Power Generation	11
2.5 Types of Power Generation Plants	12
2.5.1 Dry Steam System.....	13
2.5.2 Flash Steam System	13
2.5.3 Binary Cycle System.....	14
2.5.4 Geothermal Heat Pumps	15
2.6 Geothermal Power Generation and Direct uses in the World	15
2.7 Environmental Impacts.....	19
2.8 Mitigation of Geothermal Emissions	21
2.8.1 Hydrogen Sulfide (H ₂ S)	21
2.8.2 Mercury	21
2.8.3 Noise Pollution.....	21
2.8.4 Water Use	21
2.8.5 Water Quality	21
2.8.6 Land Use	21
2.8.7 Induced Seismicity	22

2.8.8	Impact on Wildlife and Vegetation.....	22
2.9	Economics of Geothermal Energy	22
2.10	Bibliography.....	29
Chapter – 3	Geothermal Resources of Afghanistan.....	35
3.1	Geology of Afghanistan	35
3.2	Potential of the Hindu Kush Geothermal Province	39
3.3	Potential of Active Magmatic and Volcanic Geothermal Province	42
3.4	Geopressured Prospect	44
3.5	Potential of Harirud-Badakhshan Geothermal Province.....	44
3.6	Potential of Helmand-Arghandab Geothermal Province	46
3.7	Potential of Farahrud Geothermal Province	46
3.8	Potential of Baluchistan Geothermal Province	47
3.9	Surface Indications of Geothermal Potentials.....	47
3.10	Hydrogeochemistry of Thermal Waters	47
3.11	Dynamics of Hydrothermal Activities	49
3.12	Conclusions and Recommendations	51
3.13	Bibliography.....	52
Chapter – 4	Geothermal Resources of Bangladesh	55
4.1	Geological Framework.....	55
4.2	Surface Indicators of Geothermal Activity	59
4.2.1	Warm Ground.....	60
4.2.2	Hot Steaming Ground	60
4.2.3	Hot Pools.....	60
4.2.4	Hot Lakes	60
4.2.5	Hot Springs.....	60
4.2.6	Fumaroles	60
4.2.7	Geysers	60

4.2.8	Hydrothermal Eruptions	61
4.2.9	Geothermal Seepages.....	61
4.3	Geothermal Gradients.....	61
4.4	Geothermal Prospects of Sub-himalayan Foredeep	64
4.5	Geothermal Prospects of Rangpur Saddle	65
4.6	Geothermal Prospects of Bogra Shelf	66
4.7	Geothermal Prospects of Deep Sedimentary Basin	70
4.8	Geothermal Prospects of Folded Belt	70
4.9	Conclusions and Recommendations	71
4.10	Bibliography.....	73
Chapter – 5 Geothermal Resources of Bhutan		77
5.1	Geological Framework.....	77
5.1.1	Bhutan Stratigraphy.....	77
5.1.2	Structural Geology.....	81
5.2	Surface Indications of Geothermal Energy.....	85
5.3	Conclusions.....	89
5.4	Bibliography.....	90
Chapter – 6 Geothermal Resources of India		95
6.1	Geological Framework of India.....	95
6.1.1	Tectonic Evolution	95
6.2	Stratigraphy	97
6.2.1	Precambrian Super-eon.....	97
6.2.2	The Dharwar System.....	97
6.2.3	The Archean System	98
6.2.4	Palaeozoic.....	99
6.2.5	Mesozoic.....	99
6.2.6	Cenozoic.....	100

6.3	History of Geothermal Studies	100
6.4	Geothermal Resources of India	103
6.5	Potential of Beas and Parbati Valley Geothermal Province	104
6.6	Potential of Tapoban Geothermal Province	104
6.7	Potential of Sohana Geothermal Province	105
6.8	Potential of West Coast Geothermal Province	105
6.9	Conclusions.....	105
6.10	Bibliography.....	108
Chapter – 7 Geothermal Resources of Nepal		113
7.1	Geological Framework.....	113
7.1.1	Gangetic Plain	114
7.1.2	Sub-himalayan (Siwalik) Zone.....	116
7.1.3	Lower Siwalik	117
7.1.4	Middle Siwalik.....	118
7.1.5	Upper Siwalik	118
7.1.6	Lesser Himalayan Zone	118
7.1.7	The Greater Himalayan Zone	120
7.1.8	The Tibetan-Tethys Zone	120
7.2	Physiography of the Nepal Himalaya	121
7.3	Surface Manifestations of Geothermal Resources.....	123
7.3.1	The Darchula District Thermal Springs	123
7.3.2	The Bajhang District Thermal Springs.....	124
7.3.3	The Jumla District Thermal Springs	124
7.3.4	The Dhanchauri Area Thermal Springs	125
7.3.5	Riar Thermal Spring	125
7.3.6	The Mayangdi Thermal Spring.....	125
7.3.7	Surai Khola Thermal Spring.....	125

7.3.8	Thak Khola – Mustang Thermal Spring	125
7.3.9	The Western Region Thermal Springs	125
7.3.10	The Eastern Region Thermal Springs	125
7.4	Geothermal Potential	126
7.5	Estimation of Reservoir	129
7.6	Conclusions.....	131
7.7	Bibliography.....	132
Chapter – 8 Geothermal Resources of Pakistan		135
8.1	Plate Tectonics (After Wandrey, Law, and Shah, 2000)	135
8.2	Stratigraphy (After Wandrey, Law, and Shah, 2000).....	139
8.2.1	Precambrian and Paleozoic Stratigraphy.....	139
8.2.2	Mesozoic Stratigraphy.....	140
8.2.3	Cenozoic Stratigraphy.....	142
8.3	Surface Indications of Geothermal Source.....	143
8.4	Geothermal Potential of Himalaya-Karakorum-Hindu Kush Zone	145
8.4.1	Murtazabad Hot Spring	147
8.4.2	Budelas Hot Springs.....	147
8.4.3	Tatta Pani Hot Springs	148
8.4.4	Moshkin Valley Hot Springs.....	148
8.4.5	Darkot Hot Spring	148
8.4.6	Choutron Hot Spring.....	148
8.4.7	The Other Hot Spring in Baltistan.....	149
8.4.8	Garam Chashma	149
8.4.9	Reservoir Temperature.....	150
8.4.10	Geothermal System and Main Mantle Thrust	150
8.5	Geothermal Prospects of Chagai Volcanic Arc Zone	152
8.5.1	Chicken Dik Spring.....	152

8.5.2	Koh-e-Sultan Springs.....	152
8.5.3	Chemical Properties of Geothermal Water	153
8.6	Geothermal Prospects in Geopressed Areas	154
8.6.1	Upper Indus Basin Geothermal Prospects.....	155
8.6.2	Salt Range Hot Springs.....	155
8.6.3	Middle Indus Geothermal Prospects	155
8.6.4	Hot Spring Occurrences	156
8.6.5	Geothermal Prospects of Lower Indus Basin.....	157
8.6.6	Hot Springs in Lower Indus Basin	158
8.7	Conclusions.....	159
8.8	Bibliography.....	160
Chapter – 9	Geothermal Resources of Sri Lanka	165
9.1	Tectonics of Sri Lanka	165
9.2	Stratigraphy	168
9.2.1	Crustal Units	168
9.2.2	Sedimentary Rocks	170
9.3	Surface Manifestations of Geothermal Resources.....	171
9.4	Hydrogeological Studies	176
9.5	Geothermal Potential	178
9.6	Conclusions.....	178
9.7	Bibliography.....	180
Chapter – 10	Conclusions and Recommendations	185

LIST OF TABLES AND FIGURES

Tables

Table 2.1: The Electricity Power Generation by Leading 25 Countries in the World (after IGA, 2010) ..	16
Table 2.2: Summary of Direct-use Data from Individual Countries (After IGA, 2010)	17
Table 2.3: Emissions from Geothermal and Coal Based Power Plants (after Kagel et al. 2007)	20
Table 2.4: Selected Cost Parameters of a Geothermal Power Plant (After Kagel, 2006)	27
Table 4.1: The Generalized Stratigraphy of the Bengal Basin	59
Table 4.2: Temperature Data Collected from Exploration Wells Located in the Eastern Bengal Basin ..	68
Table 4.3: Temperature Data Collected from Exploration Wells	69
Table 6.1: Geothermal Studies currently being undertaken in India	106
Table 7.1: Physiographical Divisions of the Nepal Himalaya (Modified after Upreti, 1999)	122
Table 7.2: Geothermal Localities and their Salient Features (After Ranjit 2005)	126
Table 7.3: Chemical Composition of Some Thermal Spring Waters (After Ranjit 2005)	127
Table 7.4: Isotopic Composition of Waters from Central Nepal (Modified After Grabczak and Kotarba, 1985)	130
Table 8.1: Physical and Chemical Characteristics of Hot Springs in Himalaya-Karakoram-Hindukush Areas (After Todaka et al., 1999)	151
Table 8.2: Physical and Chemical Characteristics of Hot Springs in Chagai Volcanic Arc (After Todaka et al., 1999)	154
Table 8.3: Physical and Chemical Characteristics of Karachi Hot Springs	159
Table 9.1: Electrical Conductivity and pH Variation in the Kinniya Hot Spring	177
Table 9.2: Electrical Conductivity and pH Variation in the Madunagala Hot Spring	178

Figures

Figure 2.1: Interior of Earth and its Temperatures (After Kiouss and Tilling; Butler, 1995)	7
Figure 2.2: Major Plate Boundaries (Topinka, USGSICVO, 1997)	8
Figure 2.3: Schematic Diagram of the Dry Steam Power Plant	13
Figure 2.4: Schematic Diagram of the Flash Steam Power Plant	14
Figure 2.5: Schematic Diagram of the Binary Cycle Power Plant	14
Figure 2.6: Sulfur Dioxide and Carbon Dioxide Emissions from Fossil-Fueled and a Geothermal Power Plants (After Goddard & Goddard, 1990)	20
Figure 2.7: Levelized Costs of Selected Technologies (After Blodgett and Slack, 2009)	28
Figure 3.1: Geological Map of Afghanistan (After Geological Survey of Afghanistan)	36
Figure 3.2: Major Structural Features of Afghanistan (After Saba et al., 2004; Schindler, 2002)	40

Figure 3.3: Occurrences of Geothermal Springs (After Saba et al. 2004)	41
Figure 3.4: Neotectonic Activity in the Hindu Kush Resulting in Uplift and Displacement of the Crust (Photo of the Bande-Azhdar, Bamiyan), (After Saba et al., 2004).....	42
Figure 3.5: The Obe Shefa Hot Spring, Obe Township, 120 km to the East of Herat City, with a Surface Temperature of 52°C and a Very Hot Ground in a Granitic Contact Zone. (After Saba et. al 2004).....	45
Figure 3.6: Southern View of the Kalu Valley with Hot Spring (After Saba et. al 2004)	46
Figure 4.1: Tectonic Map of Bangladesh and Adjoining Areas (After Banglapedia, 2006).....	56
Figure 4.2: Geological Map of Bangladesh showing Extent of Sedimentary and Igneous Rocks.	58
Figure 4.3: Locations of Exploratory Wells Used in this Study	62
Figure 4.4: Average Geothermal Gradient in Bengal Basin(BAPEX, and Matin et al., 1982).....	63
Figure 4.5: Characteristics Geothermal of Basinal Areas (After BAPEx and Matin et al., 1982)	63
Figure 4.6: Geothermal Map of Bangladesh at 3 km Depth. (After Guha et al., 2010).....	64
Figure 4.7: Generalized Section NW-SE Across the Crystalline Basement Rise of the Rangpur Saddle (Gray). (After Guha et al., 2010)	65
Figure 4.8: Near surface temperature profiles in: A) Madhyapara (<i>alluvium, clay, sandstone, hard rock, not shown</i>), B) Barapukuria (Pliocene sediments (clay yellow), Gondwana sandstone and coal beds (dark gray)), and C) Thakurgaon (alluvium, clay (blue), sand, that illustrate the high near surface temperature regime in the Rangpur Saddle (After Guha et al., 2010). It may be noted that the Geological Survey of Bangladesh drilled a well at Thakurgaon in 2011 up to the depth of 561m and recorded 44.75°C temperature at 560m depth.....	66
Figure 4.9 : Litho-stratigraphic correlation between the wells Singra, Kuchma and Bogra, showing vertical displacements related to faulting and the occurrence of potentially permeable lithologies at depth where temperatures are above the minimum required for electricity production. (After Guha et al, 2010).....	67
Figure 5.1: Geological Map of the Bhutan Himalaya (after Gansser 1983)	78
Figure 5.2: Geological Map of the Kuru Chu Valley, Bhutan	79
Figure 5.3: Balanced Cross-section of the Kuru Chu Region, Bhutan	82
Figure 5.4: Simplified Geological Map of Bhutan Showing Occurrence of Leucogranite in the Greater Himalayan Sequence (After Grujic et al., 2002)	85
Figure 5.5: Road Map of Bhutan Showing Important Locations in Bhutan	86
Figure 5.6: Route of Trekking for Duer Hot Spring	88
Figure 5.7: People Taking Bath in Hot Springs for Health Benefits	89
Figure 6.1: Northward Flight of the Indian Plate	96
Figure 6.2: Distribution of Dharawars System in India	98
Figure 6.3: Geoethermal Regions in Central India (After Chandrasekharam, 2000)	103
Figure 7.1: Geological Map of Nepal (Modified from Dahal, 2006)	113
Figure 7.2: Generalized Cross Section of Himalaya (Modified After Dahal 2006)	114
Figure 7.3: Subsurface Condition of Terai Zone of Nepal (After Dahanu, 2006)	116

Figure 7.4: Geological Map of Hetauda-Bakiya Khola Area (After Ulak and Nakayama, 1999)	117
Figure 7.5: Interbedding Sandstone and Mudstone in Middle Siwalik, Butwal-Tansen Section of Siddhartha Highway	118
Figure 7.6: Aerial Photograph of Udaypur District (Eastern Nepal) Well Marked Main Boundary Thrust (MBT) is Passing through Middle of Photograph	119
Figure 7.7: MBT Observed in Butwal-Tansen Section of Siddhartha Highway	119
Figure 7.8: South Tibetan Detachment System Separating Higher Himalayan Zone from Tibetan - Tethys Zone, Chhaktan Khola, North West from Kokhethati, Mustang (Adopted from Dahal 2006).	121
Figure 7.9: Cliff of limestone belongs to Tibetan-Tethys Zone, Jomsom, Mustang (Adopted from Dahal 2006).....	121
Figure 7.10: Physiography of the Nepal Himalaya (After Dahal and Hasegawa, 2008)	123
Figure 7.11: Location of Geothermal Springs in Nepal (After Ranjit 2005).....	124
Figure 7.12: $\delta^{18}\text{O}$ - δD Correlation of Analyzed Waters (Grabczak and Kotarba, 1985)	129
Figure 8.1: Northward Drift of Indian Plate since Cretaceous (Modified from Scotese and Others, 1988; Scotese, 1997)	137
Figure 8.2: Tectonic Map of Pakistan	139
Figure 8.3: Generalized Stratigraphy of the Upper Indus Basin Area (Modified from OGDC, 1996; Quadri and Quadri, 1996; Kemal, 1992; Raza, 1992; Iqbal and Shah, 1980; and Shah, 1977).....	141
Figure 8.4: Geological Map of Pakistan	143
Figure 8.5: Locations of Known Geothermal Springs in Pakistan (After AEDB)	144
Figure 8.6: The Occurrences of Geothermal Resources in Pakistan.....	145
Figure 8.7: Tectonic sketch map of Northern Pakistan and surrounding regions. Modified from Zanchiet al., 2000 and Boulin, 1988. MFT: Main Frontal Thrust, MBT: Main Boundary Thrust, MMT: Main Mantle Thrust; SS: Shyok Suture; TMF: Tirich Mir Fault Zone, EHK East Hindu Kush, ACM Alitchur mountains, RPZ: Rushan-Pshart Zone; WAS: Wanch-Akbaital Suture, N-P: North Pamir, C-P: Central Pamir, SE-P: SE Pamir, SW-P: SW Pamir, WAZ: Waziristan, K: Kabul. 1: Quaternary, 2: Tertiary foredeeps, 3: Paleozoic belts, 4: Terranes of Gondwanan affinity, 5: Kabul Block, 6: Wasser-Panjao Suture, 7: Waziristan ophiolitic complex, 8: Kohistan-Ladakh arc terranes, 9: Himalayas. Heavy lines represent main sutures. (After Gaetani et al., 2004).	146
Figure 8.8: Views of Chutran Hot Spring.....	149
Figure 8.9: View of Garam Chasma Pool.....	150
Figure 8.10: Depth of Geopressured Neogene Sequence in Upper Indus Basin (After Wandrey et al., 2004).....	155
Figure 8.11: Cross Section of Middle Indus Basin Showing the Depth of Geopressured Neogene Sequence (After Wandrey et al, 2004)	156
Figure 8.12: View of Hot Spring in Bugti Area	157
Figure 8.13: Cross Section of Lower Indus Basin Showing the Depth of Geopressured Neogene Sequence (After Wandrey et al, 2004)	157

Figure 9.1: Geological Map of Sri Lanka.....	167
Figure 9.2: The Location of Important Geothermal Springs in Sri Lanka.....	172
Figure 9.3: Location Map of the Wahawa Hot Spring.....	173
Figure 9.4: Views of the Wahawa Spring-1	174
Figure 9.5: Views of the Kanniya Hot Spring.....	175
Figure 9.6: Views of the Mahaoya Hot Springs	175
Figure 9.7: View of Newly Discovered Geothermal Spring in Polonnaruwa.....	176

EXECUTIVE SUMMARY

The global geothermal industry will be more than triple from its current installed base from 10.5 GW to over 31 GW by 2020 (Emerging Energy Research, 2009). At present majority of generation capacity is concentrated in the U.S., the Philippines, Indonesia, Mexico, Iceland and New Zealand.

Harnessing the geothermal potential in SAARC countries will have a significant impact on their economic development as the countries are energy deficient and heavily rely on imported fuel for electric power generation. Utilization of geothermal energy is not only cost effective but also provides energy security to the region. The impact of utilization of fossil fuel can be viewed in term of the unreliable cost and incremental cost fluctuation of fuel cost coupled with the harmful effects on environment. Therefore, geothermal energy will have an important input in reducing burden on foreign exchange resources and it will contribute towards environment protection.

The tectonic and geological setting of the South Asia indicates that SAARC region is endowed with a ample geothermal potential which has not yet been used, and has only been explored to a limited extend despite existence of favorable conditions for its exploration and development for power generation as well as its direct use. Partially developed hydroelectricity sector, meager economy, and short of technological knowledge had a restraining influence on levels of exploration and development for geothermal energy resources in SAARC Member States.

Currently, the highly exasperated price of imported fossil fuels and prolonged period of drought in some member countries resulting in shortfalls in electricity supply from the hydropower stations, demands that energy mix in these countries be diversified and alternative sources of energy be explored. Geothermal power is a reliable, low-cost, environmental friendly, alternative energy supply and an indigenous, renewable energy source, suitable for electricity generation in times to come.

This report has been prepared by collecting, reviewing, compiling and interpreting the relevant online material and published literature on the geothermal resources of SAARC Region. The data collected was freely used where ever it was needed, the data was condensed. For the benefit of those who wish more detailed information a bibliography has been attached with each chapter. However, the SAARC Energy Centre or any of its employee(s), makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information.

Where it was possible the efforts were made to discuss the three facts of geothermal energy i.e. 1) resource base, 2) its potential for electric power generation and 3) potential nonelectric use for each of the SAARC Country. The potential for geothermal energy was evaluated in the light of geological and geophysical frame work, surface manifestations and research carried out for its utilization by the researchers from abroad or from within the country. As such evaluation of geothermal energy potential and its utilization has been heavily based on published projections made by professionals and organizations in SAARC member countries. The information thus

obtained has not been amended or edited. Secondly historical use of geothermal springs, and their relevance to geology and geophysics has also been highlighted. The geothermal resource base underlying the continental crust to a depth of 3 km and at temperatures higher than 60°C has been considered worth exploiting.

Geothermal resource of each country has been discussed in separate chapters. Bangladesh, India and Nepal are making efforts for setting up geothermal power plants of limited capacity. Afghanistan, Pakistan and Sri Lanka need to further explore the true potential and should make efforts for attracting domestic and international investments for establishing geothermal power base plants to meet the power deficiency. According to Emerging Energy Research, geothermal power plant investment could reach between US\$13 billion and US\$19.9 billion annually by 2020.

Bhutan has significant hydrothermal resources and the country intends have energy mix by introducing solar, wind, biomass and small hydropower projects. It needs to start a systematic exploration program of its geothermal resources as most of the knowledge about its geothermal springs is derived from travel and tour operators for touristic attractions.

Geological studies show that the Maldives started as a chain of oceanic volcanoes. Subsequently, these volcanoes subsided into the ocean often leaving just part the crater exposed. As the volcanoes sank reefs were formed. Sometimes the volcanoes sank faster than the reefs could grow leaving them under water. In other instances the reefs were left exposed and formed Atolls. Today the Maldives consists of 1192 island. This indicates the possibility of geothermal resource which needs to be explored through modern technology. Since data pertaining to known geothermal energy resources for Maldives was not available; it has not been discussed in the report.

The data available for this study is mainly limited to the surface manifestation of geothermal energy mainly in the form of hot springs. Evaluation of these indications in the context of regional setting facilitated interpretation of the following potential locations for further exploration in SAARC countries.

1. **Afghanistan:** Hindu Kush geothermal springs seem suitable sites for further exploration for power generation and direct uses. Geothermal manifestations in these areas are mostly marked in the fracture systems of active faults within basins and linear faulted valleys or wide valleys of the southern structural component of Afghanistan.
2. **Bangladesh:** Saddle and Bogra Shelf areas have a thin veneer of sedimentary overburden above igneous/metamorphic basement with relatively higher temperature regime due to uplifted basement. Abandoned onshore wells with high geothermal gradients in Bangladesh may be tested for geothermal energy exploration.
3. **Bhutan:** Most of the thermal springs are sporadically located in Greater Himalayan regions near the exposure of leucogranites. Further research in the area is needed to determine potential geothermal locations.

4. **India:** It has a history of geothermal exploration and some of the areas are in advance stage of setting up thermal power plants. Tattapani geothermal field where a project for tapping the electric generation for 5 MWe capacity is being planned; other promising geothermal sites are Puga, Chhumathang and Manikaran. Proposal of setting up geothermal power plants are under consideration at Khammam district of Andhra Pradesh and in Gujarat state.
5. **Nepal:** In the central region of Sribagar area thermal spring (surface temperature 73°C), and Sadhu Khola spring area (surface temperature 68°C) can be considered as candidate for generation of electricity due to possibility of a large geothermal reservoir.
6. **Pakistan:** Murtazabad area in the Himalaya-Karakorum-Hindu Kush Zone represents one of the major geothermal occurrences, with seven hot springs discharging hot water flowing at the rate of 50 to 1200 liter per minute with the surface temperature from 40 to 94°C. The other potential area worth investigation is Koh-e-Sultan spring area in Baluchistan Province. Although the surface temperature and discharge of these hot springs is low, it is interpreted that due to several phases of volcanic activity a substantial geothermal reservoir may exist.
7. **Sri Lanka:** A number of springs exhibit out flow temperatures ranging from 34°C to 61°C. Wahawa hot springs are the most favorable location for consideration of further investigation. These springs show measured temperatures between 50 to 60°C with a flow rate of 0.016 liter/sec, with an area of discharge of about 10x5m, with sulfurous gas bubbling through mud.
8. **Maldives:** There is no Information on geothermal occurrences.

For direct use, the potential for geothermal is very large, as space heating and water heating are a significant part of the energy budget in big cities of the SAARC countries. The literature review for the report indicate that there are widespread low-temperature geothermal occurrences in most of the areas of thermal springs, which can be widely used for space heating, balneology, fish farming and greenhouses during the cold winter months.

In conclusion, geothermal energy for power generation and its direct use in the SAARC region is viable option but further research and exploration is required. In this context significant allocation of funds are needed to ensure economic feasibility and to identify a stable source of heat for high temperature geothermal applications.

CHAPTER – 1

INTRODUCTION

1.1 Background

In 2010 the fossil fuels contribution was 87% in the total primary commercial energy consumption of the world. The renewable energy (wind, geothermal, solar, biomass and waste) in power generation grew by 15.5% in 2010 and accounted for 1.3% of global primary energy consumption and share of renewable energy in global power generation was 3.3% (BP Statistics 2011).

It is increasingly becoming evident that current pattern of rising conventional energy consumption cannot be sustained in the future due to two reasons: the environmental consequences of heavy dependence on fossil fuels and the depletion of fossil fuels. In recent years, global warming has emerged as the most serious environmental threat ever faced by mankind. Urban air pollution and acid rains are also major problems associated with the use of fossil fuels. Therefore, at present, a near consensus appears to be emerging that renewable energy technologies need to be promoted if global energy supplies are to be placed on an environmentally sustainable path.

Despite the efforts of various research institutions, universities of developing countries and international development organizations, renewable energy technologies are yet to make a substantial contribution for betterment of the quality of life in the developing countries. In this background, SAARC Energy Centre envisaged a study on Geothermal Resources of SAARC Region.

Geothermal energy is energy derived from the heat of the earth's core. It is clean, abundant, and reliable. If properly developed, it can offer a renewable and sustainable energy source. There are three primary applications of geothermal energy: electricity generation, direct use of heat, and ground-source heat pumps. Direct use includes applications such as heating buildings or greenhouses and drying foods, whereas ground source heat pumps are used to heat and cool buildings using surface soils as a heat reservoir. Tapping a long, successful track record and a growing urgency to increase renewables generation worldwide, geothermal project activity is escalating significantly after relatively slow growth over the past two decades. Attractive for its unique combination of base load power, cost-competitiveness and zero-emissions, geothermal power is gaining increased attention from governments and the private sector as a renewable generation technology with scaling potential.

According to recent market forecasts, the global geothermal industry will more than triple from its current installed base from 10.5 GW to over 31 GW by 2020 (Emerging Energy Research, 2009). In addition, according to Emerging Energy Research, geothermal power plant investment could reach between US\$13 billion and US\$19.9 billion annually by 2020. At present majority of generation capacity is concentrated in the U.S., the Philippines, Indonesia, Mexico, Iceland and New Zealand.

Some geothermal exploration has been carried in SAARC Countries like Afghanistan, Bangladesh, India, Pakistan to name a few, that has generated valuable data through surface, geoscientific studies. According to Geological Survey of India (GSI) about 10,000 MW could be generated from geothermal resources located in various parts of India. Similarly in Pakistan hot springs in Karachi, Chagai Volcanic Arc and Northern part of the country may prove potential sites for geothermal energy. It is expected other SAARC countries may have geothermal resources, which could be utilized for power generation. This will reduce their dependence on imported oil and it will contribute towards energy security. Keeping in view the potential of this renewable energy resource SAARC Energy Centre proposed the present study to highlight the known geothermal sites.

1.2 Objectives of the Study

- to explore and evaluate an alternate and non-conventional energy resources for meeting increasing energy demands of South Asia
- to assess the geothermal resource potential of the region
- to facilitate and promote regional R&D activities on geothermal energy

1.3 Methodology and Terms of Reference

SAARC Energy Centre (SEC) has engaged the short-term expert to compile available published information and data with relevant regional and international organizations on the geothermal resources of SAARC Member States.

The term of reference as set by SEC include the followings:

- i. Review the status of technology pertaining exploration and utilization of geothermal resources including direct use as a source of heat and power generation.
- ii. Enumerate economic and environmental aspects with reference to regional and international perspectives;
- iii. Provide a comprehensive account of SAARC countries scenario, institutions and organizations involved in geothermal resources exploration and exploitation;
- iv. Describe R&D activities and programmes of South Asia;
- v. Collate available information on geological, geophysical, geochemical studies in the region;
- vi. Identify potential geothermal zones and sites for power generation in the region;

The primary objective of this report is to gather hitherto scattered geothermal energy data of SAARC region so as to provide fundamental information base to serve as an access and analysis point which would be available to SAARC member countries to chalk out programmes for development geothermal resources and further studies in this regard. As such an attempt has been made to congregate as much data as possible from all available resources. The report contains and identifies key data and information on the geothermal resources and shows the gaps to be filled in for developing them.

1.4 List of Geothermal Related Institutions in SAARC Countries

The following organizations are engaged in undertaking research in geological, geophysical and geochemistry on geothermal resources in SAARC countries.

Afghanistan

Afghanistan Geological Survey

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CHAPTER – 2

UNDERSTANDING GEOTHERMAL ENERGY

2.1 Internal Structure of Earth

The word geothermal comes from Greek words geo (earth) and thermal (heat) meaning heat from the earth. The earth is divided into six regions (Jordan, 1979). **Figure 2.1** shows three main layers of earth - the core, the mantle and the crust and their characteristics. The core is the inner part of the earth, the crust is the outer part and between them is the mantle. The oceanic crust is thinner under the oceans (6-11 km thick); while continental crust is about 25-90 km thick. The rigid layer about 100-200 km thick comprising the crust and the upper mantle is defined as lithosphere. The Mohorovicic discontinuity is the separation between the crust and the upper mantle. Below the lithosphere between about 100 and 250 kilometers depth, upper mantle exhibits plastic properties and is defined as asthenosphere. The lower mantle flows slowly, at a rate of a few centimeters per year. Convection (heat) currents carry heat from the hot inner mantle to the cooler outer mantle. The mantle is about 2,750 km thick. The mantle gets warmer with depth; the top of the mantle is about 870°C; towards the bottom of the mantle, the temperature reaches about 2,200-3,700°C. The mantle contains most of the mass of the Earth. The Gutenberg discontinuity separates the outer core and the mantle.

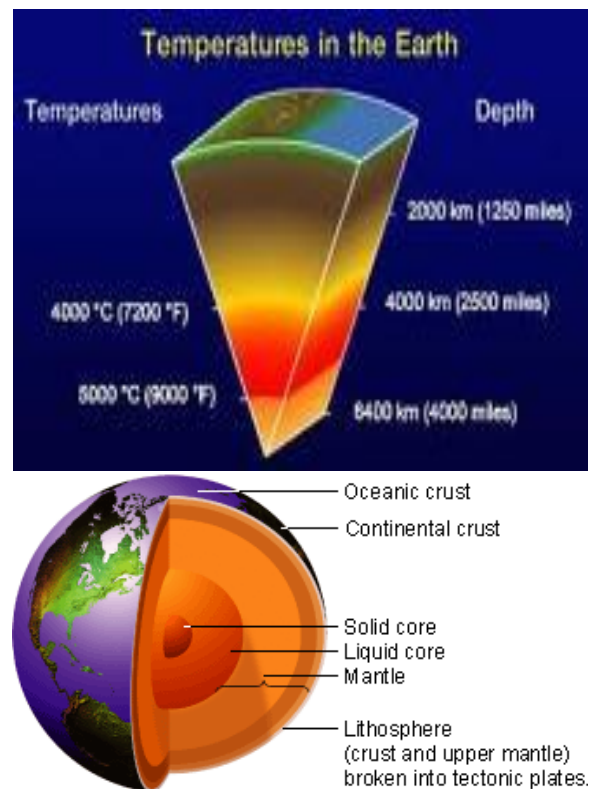
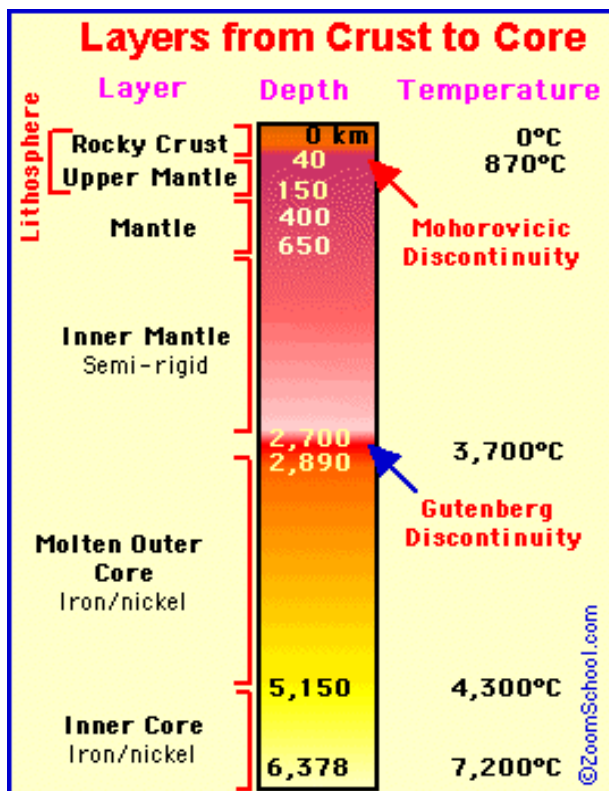


Figure 2.1: Interior of Earth and its Temperatures (After Kious and Tilling; Butler, 1995)

The core of the earth is about 3,440 km in radius. The inner core may have a temperature up to about 7,200 °C, which is hotter than the surface of the Sun. The inner core (which has a radius

of about 1,228 km is solid. The outer core is in a liquid state and is about 2,260 km thick. Heat is continually produced there, mostly from the decay of naturally radioactive materials such as uranium and potassium. The amount of heat within 10,000 meters of Earth's surface contains 50,000 times more energy than all the oil and natural gas resources in the world (Anne, 2003).

2.2 Heat Expulsion

Heat from inner earth gets transferred to surface and this heat transfer is the major mover of lithosphere, which is broken into huge plates (**Figure 2.2**) that move apart (Divergent Plates) or push together (Convergent Plates). Convection of semi-molten rock in the upper mantle helps drive plate slowly (only a few centimeters each year) atop the less rigid mantle.

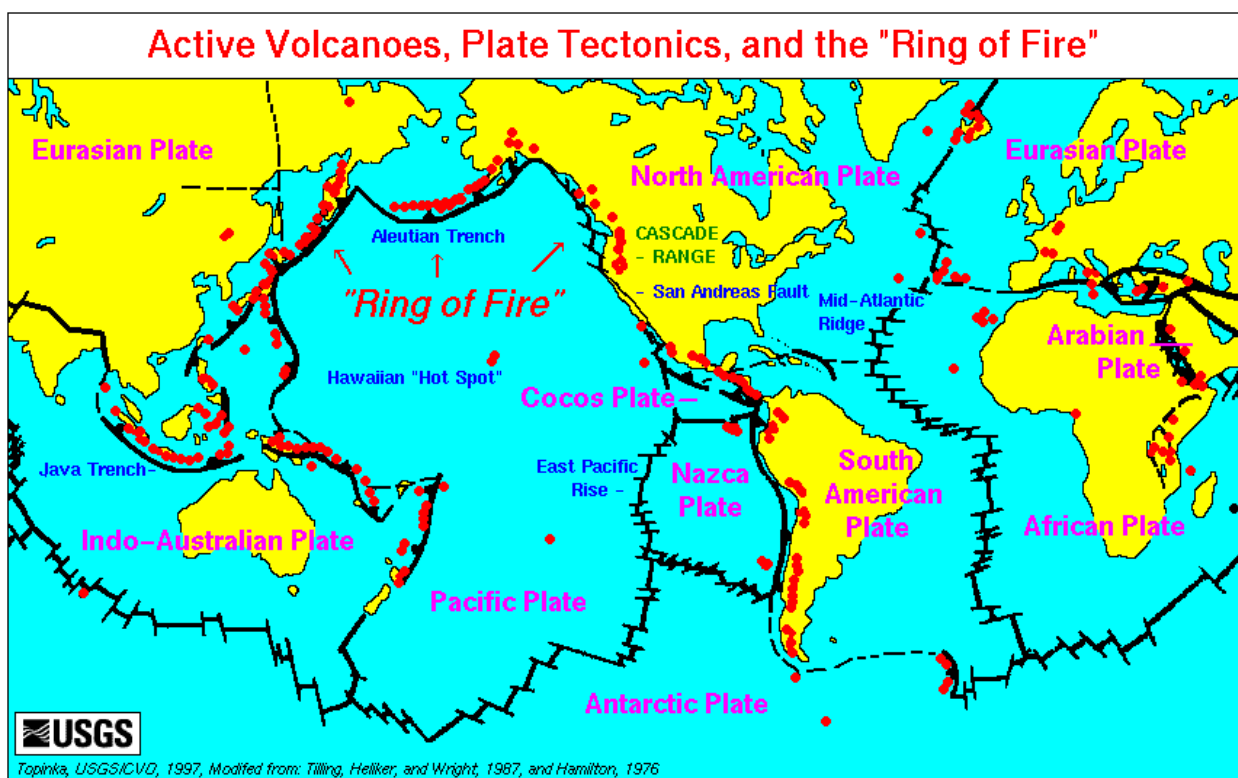


Figure 2.2: Major Plate Boundaries (Topinka, USGSICVO, 1997)

The areas with the highest underground temperatures are in regions with active or geologically young volcanoes. These "hot spots" occur at plate boundaries or at places where the crust is thin enough to let the heat through. The Pacific Rim, often called the Ring of Fire for its many volcanoes, has many hot spots, including some in Alaska, California, and Oregon. Nevada has hundreds of hot spots, covering much of the northern part of the USA. Likewise new crust forms along mid-ocean spreading centers and continental rift zones. When plates collide, one can slide beneath another and plumes of magma rise from the edges of sinking plates. Thinned or fractured crust allows magma to rise to the surface as lava. Most magma doesn't reach the surface but heats large regions of underground rock. These regions are also seismically active. Earthquakes and magma movement break up the rock covering, allowing water to circulate.

Seismically active hotspots are not the only places where geothermal energy can be found. There is a steady supply of milder heat—useful for direct heating purposes—at shallow depths below the surface virtually in any location on Earth, which has enough heat to control the temperature in buildings in the community. In addition, there is a vast amount of heat energy available from dry rock formations very deep below the surface (4–10 km). Using a set of emerging technologies known as Enhanced Geothermal Systems (EGS), we may be able to capture this heat for electricity production on a much larger scale than conventional technologies allow.

Surface water can seep down faults and fractured rocks for miles and after being heated returns towards the surface as steam or hot water it can form fumaroles, geysers, hot springs and mud pots. The water in these systems can be more than 200°C. When the rising hot water and steam is trapped in permeable and porous rocks under a layer of impermeable rock, it can form a geothermal reservoir. There is a continual flow of heat energy outwards towards the surface. The surface manifestations of heat flow from the earth are volcanoes, hot springs and geysers.

As earlier mentioned that as heat from inner earth gets transferred to surface and this heat transfer is the major mover of tectonic plates. On places where tectonic plates are connected, leaking of magma to upper layers is possible and this magma then gets cooled creating in process new layer of the Earth's crust. When magma gets to surface it can create volcanoes, but in most cases stays beyond surface making huge reservoirs and here it's cooled in the process that lasts from 5000 to one million years. Areas underneath which these magma pools can be found have higher temperature gradient which means that temperature rises very fast as the depth increases and these areas are therefore favorable for exploitation of the geothermal energy.

The Earth's internal thermal energy flows to the surface by conduction at a rate of 44.2 terawatts (Pollack et. al,1993)and is replenished by radioactive decay of minerals at a rate of 30TW (Rybach, 2007).These power rates are more than double the world's current energy consumption from all primary sources, but most of this energy flow is not recoverable. In addition to the internal heat flows, the top layer of the surface to a depth of 10 meters is heated by solar energy during the summer, and releases that energy and cools during the winter.

Outside of the seasonal variations, the geothermal gradient of temperatures through the crust is 25–30 °C per kilometer of depth in most of the world. The conductive heat flux averages 0.1 MW/km². These values are much higher near tectonic plate boundaries where the crust is thinner. They may be further augmented by fluid circulation, either through magma conduits, hot springs, hydro thermal circulation or a combination of these.

A geothermal heat pump can extract enough heat from shallow ground anywhere in the world to provide home heating, but industrial applications need the higher temperatures of deep resources. The thermal efficiency and profitability of electricity generation is particularly sensitive to temperature. The more demanding applications receive the greatest benefit from a high natural heat flux, ideally from using a hot spring. The next best option is to drill a well into a hot

aquifer. If no adequate aquifer is available, an artificial one may be built by injecting water to hydraulically fracture the bedrock. This last approach is called hot dry rock geothermal energy in Europe, or enhanced geothermal systems in North America. Much greater potential may be available from this approach than from conventional tapping of natural aquifers (Holm, 2010).

Estimates of the potential for electricity generation from geothermal energy vary six fold, from 0.35 to 2TW depending on the scale of investments (Fridleifsson, et.al, 2008). Upper estimates of geothermal resources assume enhanced geothermal wells as deep as 10 kilometers, whereas existing geothermal wells are rarely more than 3 kilometers deep (Fridleifsson, et.al, 2008). Wells of this depth are now common in the petroleum industry. The deepest research well in the world, the Kola super deep borehole is 12 kilometers deep (Cassino, 2003). This record has recently been imitated by commercial oil wells, such as Exxon's Z-12 well in the Chayvo field, Sakhaline (Watkins, 2008).

2.3 Geothermal Fields

The source of heat is generally a magmatic intrusion into earth crust. The magma intrusion generally measures 600-900°C at depth of 7-15 km. The bed rock containing the intrusion conducts heat to overlying aquifers capped by a seal of shale in an anticlinal structure. A productive geothermal generally produces about 20 tons of steam or several hundred tons of hot water per hour.

There are three general types of geothermal fields: hot water, wet steam and dry steam. Hot water fields contain reservoirs of water with temperature between 60-100°C, and are suitable for space heating and agricultural applications. For hot water fields to be commercially viable, they must contain a large amount of water with temperature of at least 60°C and lie within 2000m depth.

Wet steam fields, contain water under pressure and usually measure 100°C. These are the most common commercially exploitable fields. When the water is brought to the surface, some of the water flashes into steam, and the steam may drive turbines that can produce electrical power.

Dry steam fields are geologically similar to wet steam fields, except that superheated steam is extracted from aquifer. Dry steam is relatively uncommon.

Because superheated water explosively transforms into steam when exposed to atmosphere, it is much safer and generally more economical to use geothermal energy to generate electricity. Because of relatively low temperature of steam/water, geothermal energy may be converted into electricity with an efficiency of 10-15% as opposed to 20-25% for coal or oil fired generated electricity.

To be commercially viable, geothermal electrical generation plants must be located near large source of easily accessible geothermal energy. A further complication in practical utilization of geothermal energy may derive from corrosive properties of most ground water and steam. While geothermal energy is generally presented as nonpolluting energy source, water from geothermal

fields often contains large amounts of hydrogen sulfide and dissolved metals, making its disposal difficult.

Geothermal energy sources for space heating and agriculture have been extensively used in Iceland, and to some degree Japan, New Zealand and former Soviet Union. Other applications include paper manufacturing and water salination.

The hot water reservoirs heated by molten rock usually at depths of up to 3,000 m are considered workable. Wells similar to those used to produce crude oil and natural gas are drilled to recover the water. Once captured, steam and hot water are separated. The steam is cleaned and sent to the power plant. The separated water is returned to the reservoir, helping to regenerate the steam source.

Only a small group of places around the globe provide the special conditions needed to generate geothermal energy. At these locations, deep fractures in the earth's crust allow the molten magma to surge close enough to the earth's surface to heat water underground.

2.4 Geothermal Energy for Power Generation

In addition to providing clean, renewable power, geothermal energy has significant environmental advantages. Geothermal emissions contain few chemical pollutants and little waste. It consists of mostly water, which is re-injected into the earth.

Geothermal energy is a reliable source of power that can reduce the need for imported fuels for power generation. It's also renewable because it is based on a practically limitless resource of natural heat within the earth.

Unlike most power stations, a geothermal system does not create any pollution. It may once in a while release some gases from deep down inside the earth, that may be slightly harmful, but these can be contained quite easily.

The cost of the land to build a geothermal power plant is usually less expensive than constructing an oil, gas, coal, or nuclear power plant. The main reason for this is the land space, as geothermal plants take up very little room, so there is no need to purchase a larger area of land. Since geothermal energy is very clean, so it invites tax cuts, and/or no environmental bills or quotas to comply with the countries carbon emission scheme (if they have one).

No fuel is used to generate the power, which in return, means the running costs for the plants are very low as there are no costs for purchasing, transporting, or cleaning up of fuels you may consider purchasing to generate the power.

The overall financial aspect of these plants is outstanding, as it requires providing power to the water pumps, which can be generated by the power plant itself anyway.

There are some disadvantages of geothermal energy utilization. Geothermal heat is extracted from deep within the earth's crust, and this is the main disadvantage concerning finding a suitable build location.

There are some other deciding factors that may convince a constructor to build a different type of renewable energy power plant in a different location.

So, the main disadvantages of building a geothermal energy plant mainly lie in the exploration stage. During exploration, researchers will do a land survey (which may take several years to complete) and then post their findings to the company that contracted the survey.

Many companies who order surveys are often disappointed, as quite often the land they were interested in cannot support a geothermal energy plant. To extract the heat we have to find certain hot spots within the earth crust, these are very common around fault lines, but who wants to build their geothermal energy plant next to a fault line if it is an active one.

Some areas of land may have the sufficient hot rocks to supply hot water to a power station, but what if these areas are contained in high up in mountains.

The questions that are usually asked during a survey are: Is the rock soft enough to drill through? Do the rocks deep down contain sufficient heat? Will this heat be sustainable for a significant amount of time? Is the environment fit for a power plant? If the answer to these basic questions is yes, a more in depth survey should go ahead.

Another big disadvantage of geothermal energy extraction is that in many cases, a site that has happily been extracting steam and turning it into power for many years may suddenly stop producing steam. This can happen and last for around 10 years in some cases.

Developers of such sites must be careful and aware that in some cases, harmful gases can escape from deep within the earth through the holes drilled by the constructors. The plant must be able to contain any leaked gases, but disposing of the gas can be very tricky to do safely. It is important to take care of a geothermal site because if the holes were drilled improperly, then potentially harmful minerals and gas could escape from underground. These hazardous materials are nearly impossible to get rid of properly. Pollution may occur due to improper drilling at geothermal stations. Unbelievably, it is also possible for a specific geothermal area to run dry or lose steam.

2.5 Types of Power Generation Plants

The most common current way of capturing the energy from geothermal sources is to tap into naturally occurring "hydrothermal convection" systems where cooler water seeps into earth's crust, is heated up, and then rises to the surface. When heated water is forced to the surface, it is a relatively simple matter to capture that steam and use it to drive electric generators. Geothermal power plants drill their own holes into the rock to more effectively capture the steam.

There are three designs for geothermal power plants, all of which pull hot water and steam from the ground, use it, and then return it as warm water to prolong the life of the heat source. In the simplest design, the steam goes directly through the turbine, then into a condenser where the steam is condensed into water. In a second approach, very hot water is depressurized or "flashed" into steam which can then be used to drive the turbine. In the third approach, called a binary system, the hot water is passed through a heat exchanger, where it heats a second liquid such as isobutene in a closed loop. The isobutane boils at a lower temperature than water, so it is more easily converted into steam to run the turbine. The working of the three systems is shown below in the schematic diagrams (**Figure 2.3, Figure 2.4 and Figure 2.5**).

2.5.1 Dry Steam System

Power plants using dry steam systems were the first type of geothermal power generation plants built. They use steam from the geothermal reservoir as it comes from wells and route it directly through a turbine/generator unit to produce electricity. An example of a dry steam generation operation is at the Geysers Region in northern California.

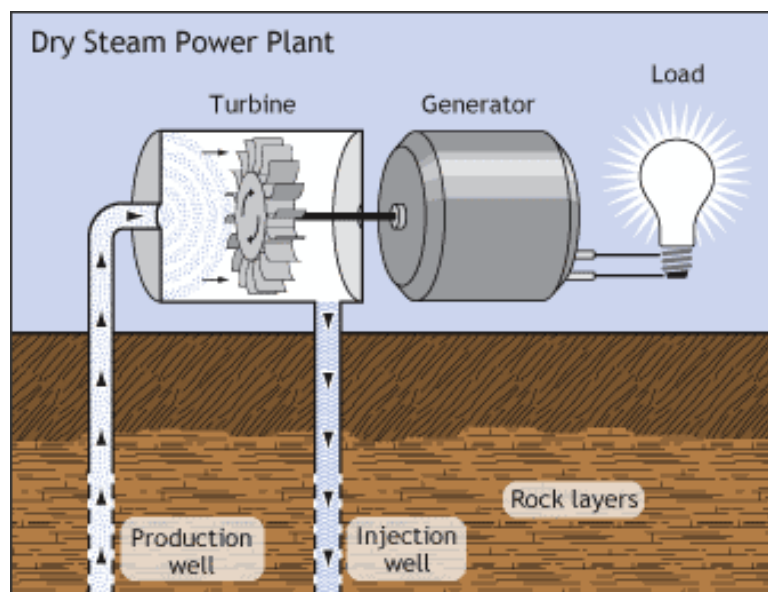


Figure 2.3: Schematic Diagram of the Dry Steam Power Plant

2.5.2 Flash Steam System

Flash steam plants are the most common type of geothermal power generation plants in operation today. They use water at temperatures greater than 182°C that is pumped under high pressure to the generation equipment at the surface. Upon reaching the generation equipment, the pressure is suddenly reduced, allowing some of the hot water to convert or "flash" into steam. This steam is then used to power the turbine/generator units to produce electricity. The remaining hot water not flashed into steam, and the water condensed from the steam, is generally pumped back into the reservoir. An example of an area using the flash steam operation is the Cal Energy Navy I flash geothermal power plant at the Coso geothermal field.

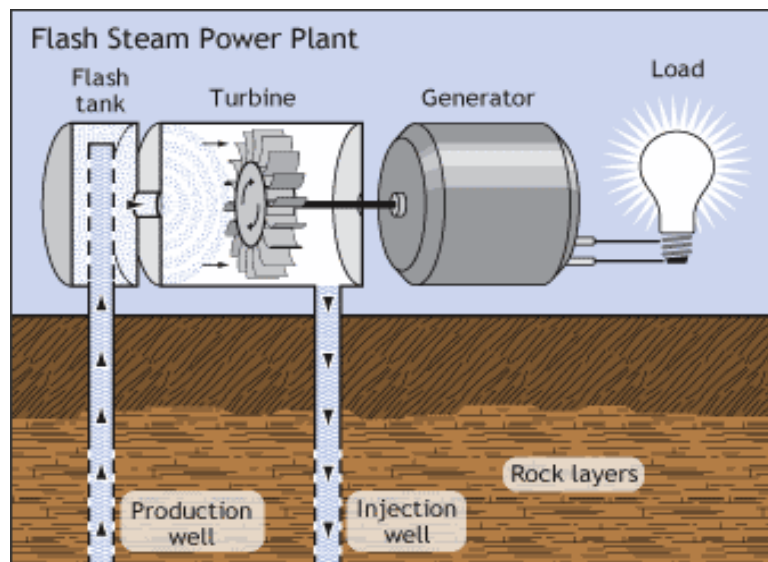


Figure 2.4: Schematic Diagram of the Flash Steam Power Plant

2.5.3 Binary Cycle System

Binary cycle geothermal power generation plants differ from dry steam and flash steam system because the water or steam from the geothermal reservoir never comes in contact with the turbine/generator units. In the binary system, the water from the geothermal reservoir is used to heat another “working fluid,” which is vaporized and used to turn the turbine/generator units. The geothermal water and the “working fluid” are each confined in separate circulating systems or “closed loops” and never come in contact with each other. The advantage of the binary cycle plant is that they can operate with lower temperature waters (110-182°C) by using working fluids that have an even lower boiling point than water. They also produce no air emissions. An example of an area using a binary cycle power generation system is the Mammoth Pacific binary geothermal power plants at the Casa Diablo geothermal field.

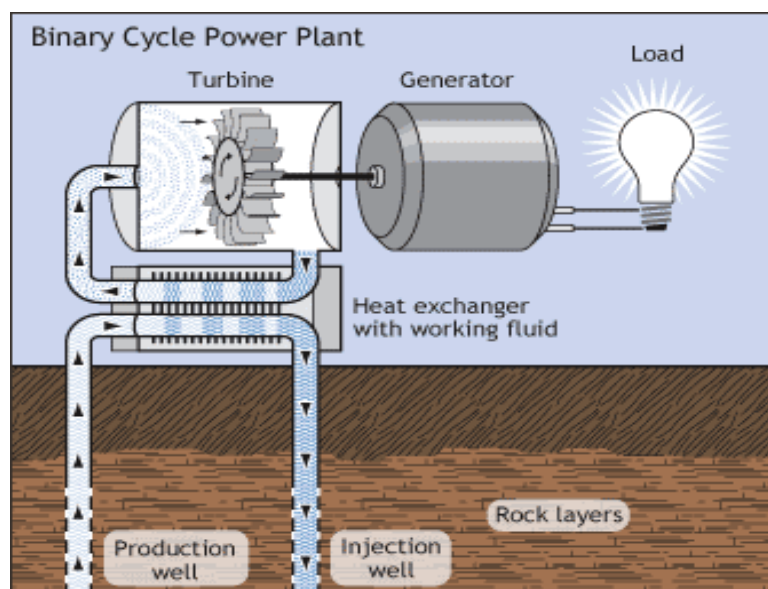


Figure 2.5: Schematic Diagram of the Binary Cycle Power Plant

The choice of which design to use is determined by the resource. If the water comes out of the well as steam, it can be used directly, as in the first design. If it is hot water of a high enough temperature, a flash system can be used, otherwise it must go through a heat exchanger. Since there are more hot water resources than pure steam or high-temperature water sources, there is more growth potential in the heat exchanger design.

The largest geothermal system now in operation is a steam-driven plant in an area called the Geysers, north of San Francisco, California. Despite the name, there are actually no geysers there, and the heat that is used for energy is all steam, not hot water. Although the area was known for its hot springs as far back as the mid-1800s, the first well for power production was drilled in 1924. Deeper wells were drilled in the 1950s, but real development didn't occur until the 1970s and 1980s. By 1990, 26 power plants had been built, for a capacity of more than 2,000 MW.

2.5.4 Geothermal Heat Pumps

The shallow ground, the upper 3 meter of the earth, maintains a nearly constant temperature between 10°C and 16°C. Like a cave, this ground temperature is warmer than the air above it in the winter and cooler than the air in the summer. Geothermal heat pumps take advantage of this resource to heat and cool buildings.

Geothermal heat pump systems consist of basically three parts: the ground heat exchanger, the heat pump unit, and the air delivery system (ductwork). The heat exchanger is basically a system of pipes called a loop, which is buried in the shallow ground near the building. A fluid (usually water or a mixture of water and antifreeze) circulates through the pipes to absorb or relinquish heat within the ground.

2.6 Geothermal Power Generation and Direct uses in the World

Presently, some sixty countries around the world are either plugging into the earth, tapping its heat, and drawing some of it off in the forms of steam and hot water to run geothermal power plants and produce electricity, or are in the process of developing their geothermal resources. Other countries use this source for residential and district heating systems, heating greenhouses for growing vegetables, fruits, and flowers, or simply use it for balneological applications. It is suggested that wherever geothermal energy is used, in the long run, it turns out to be cheaper than oil or coal, natural gas or nuclear power (Goldin, 1981; WEA, 2000).

International Market Update 2010 by SUSTAINABLE BUSINESS.COM reports that 24 countries increased power online by 20 percent since an International Geothermal Association report in 2005. With over 10,000 megawatts (MW) installed, geothermal power is providing electricity worldwide to over 52 million people. The reviews revealed that: (1) geothermally-fueled electric power is being generated in 24 nations as of 2010; (2) the installed capacity has reached 10709.7 MWe, which is about 20% increase since 2005. **Table 2.1** below shows the countries generating geothermal power in 2010.

Roughly half the world's existing electricity generating capacity is in the United States and Philippines. Indonesia, Mexico, Italy, and Japan account for most of the remainder. Altogether some 24 countries now convert geothermal energy into electricity. El Salvador, Iceland and the Philippines respectively get 26, 25 and 18 percent of their electricity from geothermal power plants (www.geo-energy.org).

Beyond geothermal electrical generation, an estimated 100,000 thermal megawatts of geothermal energy are used directly without conversion into electricity- to heat homes and greenhouses and as process heat in industry. This includes for example, the energy used in hot baths in Japan and to heat homes in Iceland and greenhouses in Russia. (sustainabloghttp://s.tt/12wCQ)

Table 2.1: The Electricity Power Generation by Leading 25 Countries in the World (after IGA, 2010)

Country	1990 MWe	1995 MWe	2000 MWe	2005 MWe	2010 MWe
Argentina	0.7	0.6	0	0	0
Australia	0	0.2	0.2	0.2	1.1
Austria	0	0	0	1	1.4
China	19.2	28.8	29.2	28	24
Costa Rica	0	55	142.5	163	166
El Salvador	95	105	161	151	204
Ethiopia	0	0	8.5	7	7.3
France (Guadeloupe)	4.2	4.2	4.2	15	16
Germany	0	0	0	0.2	6.6
Guatemala	0	33.4	33.4	33	52
Iceland	44.6	50	170	322	575
Indonesia	144.8	309.8	589.5	797	1197
Italy	545	631.7	785	790	843
Japan	214.6	413.7	546.9	535	536
Kenya	45	45	45	127	167
Mexico	700	753	755	953	958
New Zealand	283.2	286	437	435	628
Nicaragua	35	70	70	77	88
Papua New Guinea	0	0	0	39	56
Philippines	891	1227	1909	1931	1904
Portugal (The Azores)	3	5	16	16	29
Russia (Kamchatka)	11	11	23	79	82
Thailand	0.3	0.3	0.3	0.3	0.3
Turkey	20.6	20.4	20.4	20.4	82
USA	2774.6	2816.7	2228	2544	3093

Source: International Geothermal Association

Besides power resources, geothermal energy can be harnessed for other means as well. Table is a summary, by country, of the peak flow rates, capacity, annual utilization, and capacity factor,

wells drilled, professional person-years and investment reported by the various authors. There are 55 countries reporting use of geothermal energy, as compared to 28 in 1995 and 24 in 1985.

As may be seen from **Table 2.2** that the geothermal energy is extensively used in many countries, including China, Hungary, Iceland, Italy, Japan, Mexico, New Zealand, the Philippines, and the USA (California).

Table 2.2: Summary of Direct-use Data from Individual Countries (After IGA, 2010)

Country	1995 Power MWt	1995 Energy TJ/year	2000 Power MWt	2000 Energy TJ/year	2005 Power MWt	2005 Energy TJ/year	2010 Power MWt	2010 Energy TJ/year
Albania					9.6	8.5	11.5	40.5
Algeria	100	1657	100	1586	152.3	2417	55.6	1723.1
Argentina			25.7	449	149.9	609.1	307.5	3906.7
Armenia		1	15		1	15	1	15
Australia			34.4	351	109.5	2968	33.3	235.1
Austria	21.1	200	255.3	1609	352	352	662.9	3727.7
Belarus					1	13.3	3422	33.8
Belgium	3.9	101.6	3.9	107	63.9	431.2	117.9	547
Bosnia &Herzegovina							21.7	255.4
Brazil					360.1	6622.4	360.1	6622.4
Bulgaria	133.1	778.5	107.2	1637	109.6	1671.5	98.3	1370.1
Canada	1.7	47	377.6	1023	461	2546	1126	8873
Caribbean Islands			0.1	1	0.1	2.8	0.1	2.8
Chile			0.4	7	8.7	131.1	9.1	131.8
China	1915	16981	2282	37908	3687	45373	8898	75348.3
Colombia			13.3	266	14.4	287	14.4	287
Costa Rica					1	21	1	21
Croatia			113.9	555	114	681.7	67.5	468.9
Czech Republic			12.5	128	204.5	1220	151.5	922
Denmark	3.5	45	7.4	75	821.2	4360	200	2500
Ecuador					5.2	102.4	5.2	102.4
Egypt			1	15	1	15	1	15
El Salvador							2	40
Estonia							63	356
Ethiopia					1	15	2.2	41.6
Finland			80.5	484	260	1950	857.9	8370
France	599	7350	326	4895	308	5195.7	1345	12929
Georgia	245	7685	250	6307	250	6307	24.5	659.2
Germany	32	303	397	1568	504.6	2909.8	2485.4	12764.5
Greece	22.6	135	57.1	385	74.8	567.2	134.6	937.8

Country	1995 Power MWt	1995 Energy TJ/year	2000 Power MWt	2000 Energy TJ/year	2005 Power MWt	2005 Energy TJ/year	2010 Power MWt	2010 Energy TJ/year
Guatemala	2.6	83	4.2	117	2.1	52.5	2.3	56.5
Honduras			0.7	17	0.7	17	1.9	45
Hungary	340	5861	472.7	4086	694.2	7939.8	654.6	9767
Iceland	1443	21158	1469	20170	1791	23813	1826	24361
India			80	2517	203	1606.3	265	2545
Indonesia			2.3	43	2.3	42.6	2.3	42.6
Iran					30.1	752.3	41.6	1064.2
Ireland					20	104.1	152.9	764
Israel	44.2	1196	63.3	1713	82.4	2193	82.4	2193
Italy	307	3629	325.8	3774	606.6	7554	867	9941
Japan	319	6942	1167	26933	413.4	5161.1	2099.5	15698
Jordan			153.3	1540	153.3	1540	153.3	1540
Kenya			1.3	10	10	79.1	16	126.6
South Korea			35.8	753	16.9	175.2	229.3	1954.7
Latvia							1.6	31.8
Lithuania			21	599	21.3	458	48.1	411.5
F.Y.R. of Macedonia	69.5	509.6	81.2	510	62.3	598.6	47.2	601.4
Mexico			164.2	3919	164.7	1931.8	155.8	4022.8
Mongolia					6.8	213.2	6.8	213.2
Morocco							5.	79.1
Nepal			1.1	22	2.1	51.4	2.7	73.7
Netherlands			10.8	57	253.5	685	1410.3	10699.4
New Zealand	264	6614	307.9	7081	308.1	7086	393.2	9552
Norway			6	32	450	2314	3300	25200
Papua New Guinea					0.1	1	0.1	1
Peru			2.4	49	2.4	49	2.4	49
Philippines			1	25	3.3	39.5	3.3	39.6
Poland	63	740	68.5	275	170.9	838.3	281	1501.1
Portugal			5.5	35	30.6	385.3	28.1	386.4
Romania	137	2753	152.4	2871	145.1	2841	153.2	1265.4
Russia	210	2422	308.2	6144	308.2	6143.5	308.2	6143.5
Serbia					88.8	2375	100.8	1410
Slovak Republic	99.7	1808	132.3	2118	187.7	3034	132.2	3067.2
Slovenia	37	761	42	705	48.6	712.5	104.2	1136.4
South Africa							6.01	114.8
Spain					22.3	347.2	141	684
Sweden	47	960	377	4128	3840	36000	4460	45301
Switzerland	110	3470	547.3	2386	581.6	4229.3	1060.9	7714.6

Country	1995 Power MWt	1995 Energy TJ/year	2000 Power MWt	2000 Energy TJ/year	2005 Power MWt	2005 Energy TJ/year	2010 Power MWt	2010 Energy TJ/year
Tajikistan							3	55.4
Thailand			0.7	15	1.7	28.7	2.5	79.1
Tunisia			23.1	201	25.4	219.1	43.8	364
Turkey	140	1987	820	15756	1177	19623.1	2084	36885.9
Ukraine					10.9	118.8	10.9	118.8
United Kingdom			2.9	21	10.2	45.6	186.6	849.7
USA	1874	13890	3766	20302	7817.4	31239	12611.5	56551.8
Venezuela			0.7	14	0.7	14	0.7	14
Vietnam					30.7	80.5	31.2	92.3
Yemen			1	15	1	15	1	15
Yugoslavia	80	2375	80	2375				
Total	8604	112441	15145	190699	27824.8	261418	50583	438071

Source: International Geothermal Association

2.7 Environmental Impacts

Increasing interest in controlling atmospheric pollution and the spreading concern about global warming provide a framework for a continuing strong market for geothermal electrical generation and heat energy extraction. Geothermal development will serve the growing need for energy sources with low atmospheric emissions and proven environmental safety. Among all renewables, the geothermal energy currently produces the third most energy, after hydroelectricity and biomass. This source of energy does not require fuel-burning to produce heat or electricity, thus, with its proven technology and abundant resource, can make a significant contribution towards reducing the emission of greenhouse gases.

Geothermal fluids contain minerals leached from the reservoir structure, as well as a variable quantity of gases, mainly nitrogen, carbon dioxide and small amounts of hydrogen sulphide, and ammonia. The amounts depend on the geological conditions encountered in the different fields. Virtually the entire minerals content of the fluid and some of the gases are reinjected back into the reservoir. Only an inconsiderable amount of no condensable gas is released into the environment.

The industrial exploitation of a geothermal system is based on the heat mining from the rocks by using the geothermal fluids as vectors, without any specific process of CO₂ generation. Geothermal power plants emit little carbon dioxide (fossil-fuel power plants produce 1000 to 2000 times as much), no nitrogen oxides, no particulate matter, and very low amounts of sulfur dioxide. Steam and flash plants emit mostly water vapor.

Binary power plants run on a closed-loop system, so no gases are emitted as shown in the following chart (**Figure 2.6**). In the chart, the amount of sulfur dioxide and carbon dioxide

emissions between two fossil-fueled power plants (coal, and oil) and a geothermal power plant with and without waste gas reinjection into the ground has been compared.

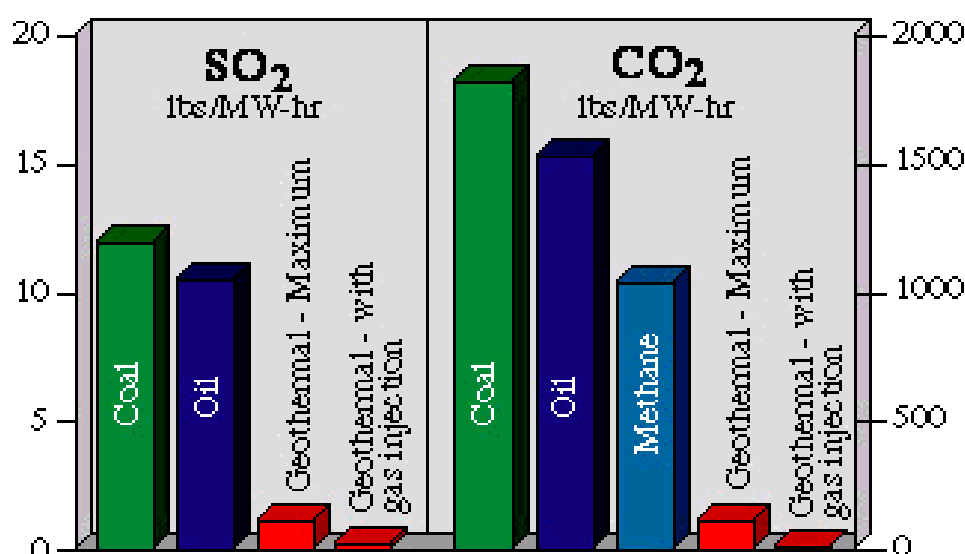


Figure 2.6: Sulfur Dioxide and Carbon Dioxide Emissions from Fossil-Fueled and a Geothermal Power Plants (After Goddard & Goddard, 1990)

Nowadays geothermal power plants are designed to virtually prevent air emissions. Kagel et al. (2007) has mentioned that a case study has shown a coal based power plant updated with scrubbers and other emissions control technologies emits 24 times more carbon dioxide, 10,837 times more sulfur dioxide, and 3,865 times more nitrous oxides per megawatt hour than a geothermal steam plant. They have also listed averages of four significant pollutants, as emitted from geothermal and coal facilities as shown in **Table 2.3** below.

Table 2.3: Emissions from Geothermal and Coal Based Power Plants (after Kagel et al. 2007)

Emissions	Nitrogen oxide	Sulphur dioxide	Particular matter	Carbon Dioxide
Impact	Lung irritation, coughing, smog Formation, Water quality deterioration	Wheezing, chest tightness, respiratory illness, ecosystem damage	Asthma, bronchitis, cancer, atmospheric deposition, visibility impairment	Global warming, increase sea level, flood risk, glacial melting
Geothermal emissions (lb/MWh)	0	0-0.35	0	0-88.8
Coal emissions (lb/MWh)	4.31	10.39	2.23	2191
Emissions offset by geothermal use. (per year)	32 thousand tons	78 thousand tons	17 thousand tons	16 million tons

2.8 Mitigation of Geothermal Emissions

2.8.1 Hydrogen Sulfide (H₂S)

Hydrogen sulfide is now routinely reduced at geothermal power plants as the hydrogen sulfide from geothermal no condensable gases is converted over 99.9 percent into elemental sulfur, which can then be used as a non-hazardous soil amendment and fertilizer feedstock. Since 1976, hydrogen sulfide emissions have declined from 1,900 lbs/hr to 200 lbs/hr or less, although geothermal power production has increased from 500 megawatts (MW) to over 2,000 MW (Kagel et al. 2007).

2.8.2 Mercury

Although mercury is not present in every geothermal resource, where it is present, mercury reducing equipment's typically reduce emissions by 90 percent or more. The comparatively highest mercury emitters, two facilities at The Geysers in California, release mercury at levels that do not trigger any health risk analyses under strict California regulations (Kagel et al. 2007).

2.8.3 Noise Pollution

According to common sound level standards, normally geothermal power plant operation typically produces less noise than the equivalent produced by the leaves rustling from breeze. It is thus not considered an issue of concern.

2.8.4 Water Use

Geothermal plants use 5 gallons of freshwater per megawatt hour, while binary air-cooled plants use no fresh water. This compares with 361 gallons per megawatt hour used by natural gas facilities.

2.8.5 Water Quality

Geothermal fluids used for electricity are injected back into geothermal reservoirs using wells with thick casing to prevent cross-contamination of brines with groundwater systems. As such there is no impact on ground water and affect the surface waterways.

2.8.6 Land Use

Geothermal power plants can be designed to blend-in to their surrounding more so than fossil fuel fired plants, and can be located on multiple-use lands. Over 30 years, the period of time commonly used to compare the life cycle impacts from different power sources; a geothermal facility uses 404 square meters of land per gig watt hour, while a coal facility uses 3632 square meters per gig watt hour. Low-temperature geothermal applications are usually no more disturbing of the environment than regular water wells. Geothermal development projects often coexist with agricultural land uses, including crop production or grazing.

Subsidence, or the slow, downward sinking of land, may be linked to geothermal reservoir pressure decline. Injection technology, employed at all geothermal sites in the United States, is an effective mitigating technique.

2.8.7 Induced Seismicity

While earthquake activity, or seismicity, is a natural phenomenon, geothermal production and injection operations have at times resulted in low-magnitude events known as micro earthquakes. These events typically cannot be detected by humans, and are often monitored voluntarily by geothermal companies.

2.8.8 Impact on Wildlife and Vegetation

Before geothermal construction can begin, an environmental review may be required to categorize potential effects upon plants and animals. Power plants are designed to minimize the potential effect upon wildlife and vegetation, and they are constructed in accordance with a host of regulations that protect areas set for development.

2.9 Economics of Geothermal Energy

Heat production from renewable energy sources is considered to be commercially competitive with conventional energy sources and represented half of newly installed electric capacity worldwide in 2010, and they are becoming increasingly important in the heating and transport Sectors (Reni, 2011). Of these, biomass constitutes 93% of the total direct heat production from renewable energy sources, geothermal 5%, and solar heating 2% (IGA, 2011).

In order to enhance the usage of geothermal energy research sponsored by developed countries and companies continues to improve geothermal technology. Despite higher initial cost, the life-cycle cost of geothermal energy utilization is reasonably low. When the environmental benefits are factored in, the case for increased geothermal use among other renewables is undeniable (IGA, 2011).

Current geothermal power plant installation costs are in the range 1000-3000 USD/kW, which is equivalent to the production cost of 2.2 to 5.4 US cents/kWh. The investment cost of a conventional direct heat district heating system is in the range 400-1400 USD/kW. This corresponds to a production cost of some 0.8-3 US cents/kWh (IGA, 2001). A comparison of the renewable energy sources by UN World Energy Assessment Report shows that the current electrical energy cost is 2-10 US cents/kWh for geothermal and hydro, 5-13 US cents/kWh for wind, 5-15 US cents/kWh for biomass, 25-125 US cents/kWh for solar photovoltaic and 12-18 US cents/kWh for solar thermal electricity (WEA, 2000). These figures indicate that currently electricity produced by geothermal power plants is becoming cost-competitive with other forms of energy.

It is also apparent that the cost of geothermal electrical energy generation is compatible with the cost that is incurred in laying pipelines for importing fossil fuel from neighboring countries. An example is of Afghanistan which is paying for electricity purchased for a period of ten years from

Iran and Turkmenistan respectively at the rate of 2.8 US cents/kWh and 2.0 US cents/kWh (Saba et al. 2004). These prices are on top of the installation expenses of 16 million USD for 132km of high voltage lines and a transfer substation with a capacity of 50MWe from Iran; and 6.3 million USD for 120 km transfer lines and 2.3 million USD transfer substation with a capacity of 30MWe from Turkmenistan, respectively (DEPCH, 2003). For the time being these projects may seem to be right and proper deals, and the immediate cost to Afghanistan is much lower than if it had developed few small-scale geothermal power plants. But, if we factor in the price that would be paid out of the country's reserves for the consumption of the power supply, continuously for the lifetime of these projects, the lost of job opportunities for the local population, the underdeveloped renewable energy potentials of the country, environmental, strategic, as well as national security issues, then they may not be sweet deals at all (Saba et al. 2004).

Though, such cross-border projects may be viable options for certain SAARC countries, they may not be feasible options for supplying energy to remote communities. Small scale geothermal power plants can be extremely useful substitute to meet the demands of isolated and remote communities. Such plants could not only provide significant power to the isolated populations, but could also open up new venues for local small industries and creating job opportunities for people who are in dire need of it.

Since electricity supply is in serious shortage all over SAARC Region, in particular in their remote rural areas, it is severely affecting their overall modernization efforts and economic development. Development of industry, agriculture and food processing is not possible without a sustainable supply of electricity. Moreover, increasing forest cutting and use of animal waste is progressively damaging the severely degraded natural environment of these countries. Potential geothermal energy reserves in SAARC Region could provide part of the electricity needs required to satisfy the demand. Electrical power production is the most profitable use of geothermal energy, and worldwide has grown the most, comparing to other geothermal applications. Electricity is produced with geothermal steam in 21 countries, with the USA being the top producer. In the Philippines, about 22% of the electricity is generated with geothermal steam. Other countries presently generating 10-20% of their electricity with geothermal energy are Costa Rica, El Salvador, Iceland and Nicaragua (Huttrer, 2001). Currently many developing countries such as Turkey, Kenya, Taiwan, Chile, and Tibet in China are also developing their geothermal fields.

To generate electricity from geothermal hot water, two prerequisites are required to be fulfilled: adequate technology, and an abundant high-temperature water or steam. At present, efficient and durable technology is readily available to produce low-cost electricity from the geothermal resources. The studies have shown that the tectonic structure of SAARC Region countries imply adequate hot water circulation systems underground. But only under certain conditions of depth, temperature, and chemistry does it pay to drill into these systems. Favorable conditions for identification of suitable sites require further explorations to be undertaken.

In planning for a geothermal electrical plant, the following questions has to be answered: how much steam can be exploited form the geothermal fields, how long will the steam last, and where should the drilling take place? When the hot-water wells are of low temperature, either a flash steam or a binary cycle system would be installed. These systems are used where the geothermal fluids are just barely mineralized. Additionally, the costs of these systems are higher than the simple steam and turbine system. However, low temperature water can be used very economically for non-electrical purposes.

In water-dominated geothermal systems water comes into the wells from the reservoir, and the pressure decreases as the water moves toward the surface, allowing the water to boil. Only part of the water boils to steam, and a separator is installed between the wells and the power plant to separate the steam and water. The steam goes into the turbine, and the low temperature water is then circulated through heat exchangers to heat a secondary liquid, usually an organic compound such as isobutene, with a low temperature of boiling. The resulting organic vapor then drives another type of turbine, called a binary power system. The cooler water then could be used for direct applications and at the end reinjected back into the reservoir to sustain the geothermal hydraulic system (Wikipedia, 2010).

In a flash system, where the steam is the dominant phase, the hot geothermal fluid is piped up to a separator. As soon as the pressure is released, some of this fluid flashes into steam that rushes off to turn a turbine that spins a generator. The spent steam is then chilled in a condenser and changed to water to be pumped back into the ground. However, in a binary system, a heat exchange method is used. In this system, heat from the geothermal fluid is transferred to another liquid, a refrigerant such as Freon or isobutane that vaporizes and turns into a highly pressurized gas that flows up a pipe leading to the turbine. The vaporized refrigerant is then recycled back into the system to continue its work.

Direct-use geothermal technologies use naturally hot geothermal water for commercial applications. Masses in SAARC Region know the medicinal and healing properties of hot water springs, especially its therapeutic power for skin conditions and rheumatic arthritis. Medicinal bathing or balneology is an important sector to be considered for modern developments of some of the well-known healing hot springs in the region. This has the potential to attract tourism in the region and to contribute in the improving standard of life and the overall wellbeing of the people, while creating hundreds of new and permanent jobs. As such it is necessary to preserve some of their current available geothermal resources in their natural state and use them only for recreation and tourism industry. Thus, not all of the resources currently known may be made available for development.

Shallow resources suitable for heat pumps are available and accessible in the remote parts of the region. Geothermal Heat Pumps (GHP), which can be used almost anywhere remote as well as in urban areas, utilize the constant temperature of the top 15-18 meters of Earth's surface to heat buildings in the winter and cool them in the summer. This mode of using geothermal energy has enjoyed the largest growth rate in recent years all over the world (IGA, 2001).

Geothermal heat pumps can contribute significantly to improving energy utilization efficiency and are developing considerable momentum. If installation of GHPs is combined with the construction of the foundations of new buildings, its initial capital cost significantly decreases, as successfully demonstrated in the construction of GHP loops that have been incorporated in the foundation piles of the new International Airport Building in Zurich (IGA, 2001). In GHP applications, USA leads the way with approximately 400,000 GHP units (about 4800 MW of heat energy) and energy production of 3300 GWh/y in 1999 (Lund and Boyd, 2000) followed by Switzerland, which is traditionally not known for hot springs or geysers. The energy extracted out of the ground with heat pumps in Switzerland amounts to 434 GWh/y, with an annual growth rate of 12% (Rybach, et al., 1999). It is suggested that any major construction project in SAARC Region should consider incorporating this option in the design of the projects.

Other non-electrical applications of geothermal energy can involve a wide variety of end uses, such as chemical industry, greenhouse industry, food processing, and fish farming, etc. The technology, reliability, economics, and environmental acceptability of direct use of geothermal energy have been demonstrated throughout the world. Currently the main types of direct uses are bathing/swimming/balneology (42%), space heating (35% including 12% with geothermal heat pumps (GHPs), greenhouse (9%), fish farming (6%), and industry (6%) (Lund and Freeston, 2000).

Some economically feasible and useful applications of low-temperature waters are suggested to be: hatching and fish farming, greenhouse by combined space and hotbed heating, mining, fruit drying and processing, food processing, refrigeration by ammonia absorption, wool processing, carpet cleaning, tourist and therapeutic bathing facilities, district heating, drying and curing of light aggregate cement slabs, extraction of industrial chemical salts by evaporation and crystallization, biodegradation, fermentation, mushroom farming, and other small-scale local industries.

Direct application uses, however, are more site specific for the market, as steam and hot water is rarely transported long distances from the geothermal site. The production cost/kWh for direct utilization is highly variable, but commonly under 2 US cents/kWh, proven so economic for Chinese, that their direct utilization is expanding at a rate of about 10% per year, mainly in the space heating, bathing, and fish farming sectors. Other examples of a high growth rate in the direct use of geothermal are found in developing countries such as Turkey and Tunisia. In the latter, for example, geothermal heated greenhouses have expanded from 10,000m² in 1990 to 955,000m² in 1999, with the main products in the greenhouses for export to Europe, creating thousands of new jobs in this oasis (Fridleifsson, 2000). Turkey, while developing its geothermal resources for electricity production, is focused on the recreational and other direct applications of this natural resource.

Using geothermal resources for power can help protect against volatile electricity prices. For any power plant, the price of the fuel used to generate power influences the price of the electricity produced; if the price of fuel is unpredictable, the price of electricity is unpredictable. Unlike traditional power plants that require fuel purchases, geothermal power plants secure their fuel

supply before the plants begin operating. Since the price of geothermal resources will not change, it is possible to know what the price of electricity generated at a geothermal power plant will be over time. The price of electricity from new geothermal power plants ranges from between \$0.05 per kWh and \$0.08 per kWh. Once capital costs for the projects are recovered, the price of power can decrease below \$0.05 per kWh (National Geothermal Collaborative, 2004).

Factors affecting the cost of geothermal power development and production are needed to be fully comprehended before engaged in geothermal project development and power production.

In order to understand the structure and parameters affecting the cost of geothermal power development, the cost of power is split into its major components and analyzes the various factors influencing each cost component.

Geothermal power production costs are composed of two major cost components: paying back of the initial capital investment and power production operation and maintenance costs. Both these components are affected by a series of parameters.

Capital costs of geothermal projects are site and resource specific apart of lease acquisition, permitting, exploration, confirmation and site development costs as well as a series of associated costs lumped together as soft costs. The resource temperature, depth, chemistry and permeability are major factors affecting the cost of the power project. The resource temperature will determine the power conversion technology (steam vs. binary) as well as the overall efficiency of the power system. The site accessibility and topography, local weather conditions, land type and ownership are additional parameters affecting the cost and time required to bring the power plant online.

Capital structure and financial conditions (debt length and interest rate) accessible to the developer also have a major impact on the resulting power production costs. These financial parameters also impact the cost of the interests paid during construction or the cost related to any time delays. Market parameters also impact the price of goods and services needed during construction. Raw material and service costs may become volatile and rise significantly due to market imbalance.

The project size determines the extent of economies of scale, and its type (Greenfield vs. expansion) provides information about the extent of new exploration, confirmation and infrastructure construction work needed to build the project.

Power plant and steam field operation and maintenance (O&M) costs correspond to all expenses needed to keep the power system in good working status. O&M costs are also strongly affected by site and resource characteristics, notably through the resource depth and chemistry. Important economies of scale apply to labor costs of large power plants. (Hance, 2006)

Important trade-offs between initial capital costs and later O&M costs were noted in the early years of the industry. These may be explained by the lack of experience of the industry and the high interest rates of the late seventies.

Geothermal production costs are thus extremely related to the site and resource characteristics. Market parameters however seriously impact capital costs and, to a lesser extent, O&M costs. Future projects may concern sites and resources with less favorable characteristics. Regular industry growth is therefore the best way to learn how to deal with more difficult conditions at reasonable cost. Market parameters also play an important role on the resulting cost of power but are behind the control of developers. A more favorable legislative framework could reduce permitting procedures and delays and provide guarantees helping developers leverage less expensive capital.

Geothermal's upfront cost, comprising mainly of exploration and development, make up the majority of cost accrued over the life of the plant. The operation and maintenance (O&M) phase accounts for a very small percentage of total costs, but can vary depending upon the location of the facility. O&M costs are low because geothermal relies on a sustainable, environmentally friendly, low-maintenance fuel that is basically free once it is developed. Most geothermal developers agree that the levelized cost of power for new geothermal projects ranges from about 5.5 to 7.5 cents per kilowatt-hour (kWh). The following **Table 2.4** displays the average cost figures for several phases of geothermal development.

Table 2.4: Selected Cost Parameters of a Geothermal Power Plant (After Kagel, 2006)

Phase	Sub-phase	Cost USD/kW	Cost for 50 MW Plant (USD)
Exploration		150	7.5 million
Site Development	Permitting	20	1 million
	Drilling	750	37.5 million
	Steam Gathering	250	12.5 million
	Power Plant Equipment & Construction	1500	75 million
	Transmission	100	5 million

While the cost of a new geothermal power plant is higher than that of a comparable natural gas facility, in the long run the two are similar over time. This is because natural gas construction costs account for only one third of the total price of the facility, while the cost of the fuel at a natural gas facility represents two thirds of the cost. The initial construction costs of a geothermal facility, in contrast, represent two thirds or more of total costs. So although initial investment is high for geothermal, natural gas and geothermal are still economically comparable over a long term. A comparison of the levelized cost of different technologies is shown in **Figure 2.7** below.

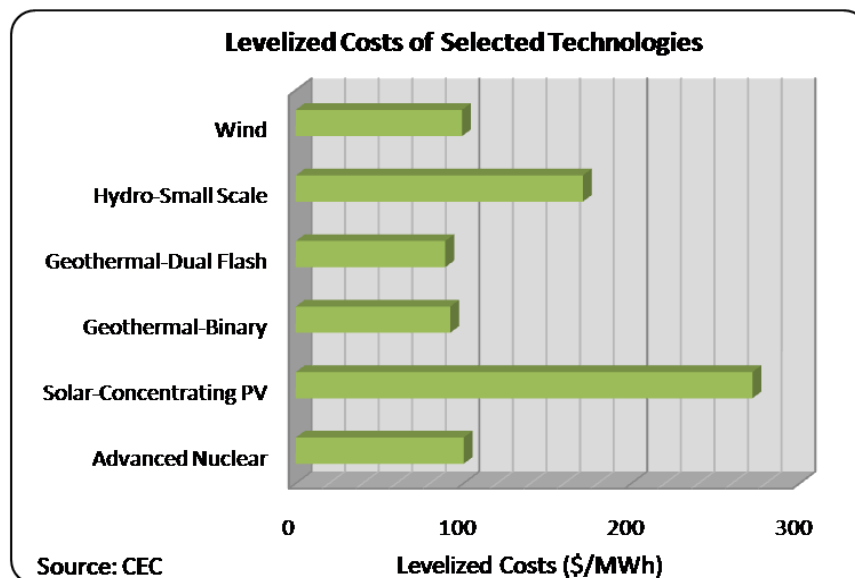


Figure 2.7: Levelized Costs of Selected Technologies (After Blodgett and Slack, 2009)

Using geothermal resources for power can help protect against volatile electricity prices. For any power plant, the price of the fuel used to generate power influences the price of the electricity produced; if the price of fuel is unpredictable, the price of electricity is unpredictable. Unlike traditional power plants that require fuel purchases, geothermal power plants secure their fuel supply before the plants begin operating. Since the price of geothermal resources will not change, it is possible to know what the price of electricity generated at a geothermal power plant will be over time. The price of electricity from new geothermal power plants ranges from between \$0.05 per kWh and \$0.08 per kWh. Once capital costs for the projects are recovered, the price of power can decrease below \$0.05 per kWh (National Geothermal Collaborative, 2004).

It is important to note, when considering the figures in the table above, that actual cost figures vary considerably from site to site based upon a number of factors. These factors include:

1. Type of project: expansion of an existing project will entail less exploration cost than a Greenfield project (one that hasn't been previously drilled), where specific resource locations are unknown.
2. Plant size: the larger the plant, the less the cost per megawatt (economies of scale).
3. Well characteristics: depth, diameter, productivity, subsurface geology, rock formation properties.
4. Site accessibility and location.
5. Time delays.
6. Ease with which the resource can be retrieved, influenced by permeability, depth of the reservoir, and pressure.
7. Characteristics of the geothermal fluid/steam, including chemistry and temperature.

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CHAPTER – 3

GEOTHERMAL RESOURCES OF AFGHANISTAN

3.1 Geology of Afghanistan

This section is derived from several published articles of Afghanistan Geological Survey, and papers published in various journals and books by Sborsschckikov, et al. (1973), Treloar and Izatt, (1993), Shareq (1981), Bowersox and Chamberlin (1995), Leven (1997), Badshah et al. (2000), Brookfield and Hashmat (2001), Schindler (2002), and Saba et al. (2004).

Since ancient times, Afghanistan has been known as a source of precious and semi-precious stones, such as spinel and lapis that were mined in the mountains of Badakhshan (Bowersox and Chamberlin, 1995). These gemstones have been referenced for centuries in travel manuscripts and ancient Persian poems. Some of the earliest indications of mining, anywhere in the world, come from Afghanistan and date back 6,000 years (Bowersox & Chamberlin, 1995; Kuo, 2006).

Afghanistan sits astride the collision zone of the Indo-Pakistan and Asian crustal plates which has given rise to the Himalayas, and as a result has some of the most complex and varied geology in the world (Treloar and Izatt, 1993). Studies by Afghanistan Geological Survey indicate that the oldest rocks are Archaean which are succeeded by rocks from the Proterozoic and every Phanerozoic system up to the present day. Accordingly the bedrock geology of Afghanistan can be thought of as a jigsaw of crustal blocks separated by fault zones, each with a different geological history and mineral prospectivity. This jigsaw has been put together by a series of tectonic events dating from the Jurassic (**Figure 3.1**).

The country has a long and complicated tectonic history, partly related to its position at the western end of the Himalayas. The tectonic history of the area appears to be the result of successive accretion of fragments of Gondwanaland to the active margin of Laurasia since the end of the Palaeozoic. Hence, Afghanistan is an assemblage of crustal blocks separated by fault zones, each with a different geological history. This diverse geological foundation has resulted in significant potential for geothermal resources (Schindler, 2002).

According to Brookfield and Hashmat (2001) the North Afghan platform has a pre-Jurassic basement unconformably overlain by a Jurassic to Paleogene oil- and gas-bearing sedimentary rock platform cover, unconformably overlain by Neogene syn- and post-orogenic continental clastics.

The pre-Jurassic basement has four units: (1) An? Ordovician to Lower Devonian passive margin succession developed on oceanic crust. (2) An Upper Devonian to Lower Carboniferous (Tournaisian) magmatic arc succession developed on the passive margin. (3) A Lower

Carboniferous? (Visean) to Permian rift–passive margin succession. (4) A Triassic continental magmatic arc succession.

The Mesozoic–Palaeogene cover has three units: (1) A? Late Triassic to Middle Jurassic rift succession is dominated by variable continental clastics. Thick, coarse, lenticular coal-bearing clastics were deposited by braided and meandering streams in linear grabens, while bauxites formed on the adjacent horsts. (2) A Middle to Upper Jurassic transgressive–regressive succession consists of mixed continental and marine Bathonian to Lower Kimmeridgian clastics and carbonates overlain by regressive Upper Kimmeridgian–Tithonian evaporite-bearing clastics. (3) A Cretaceous succession consists of Lower Cretaceous red beds with evaporites, resting unconformably on Jurassic and older deposits, overlain (usually unconformably) by Cenomanian to Maastrichtian shallow marine limestones, which form a fairly uniform transgressive succession across most of Afghanistan. (4) A Palaeogene succession rests on the Upper Cretaceous limestones, with a minor break marked by bauxite in places. Thin Palaeocene to Upper Eocene limestones with gypsum are overlain by thin conglomerates, which pass up into shales with a restricted brackish-water ? Upper Oligocene–?Lower Miocene marine fauna.

The Neogene succession consists of a variable thickness of coarse continental sediments derived from the rising Pamir Mountains and adjacent ranges. Almost all the deformation of the North Afghan platform began in the Miocene.

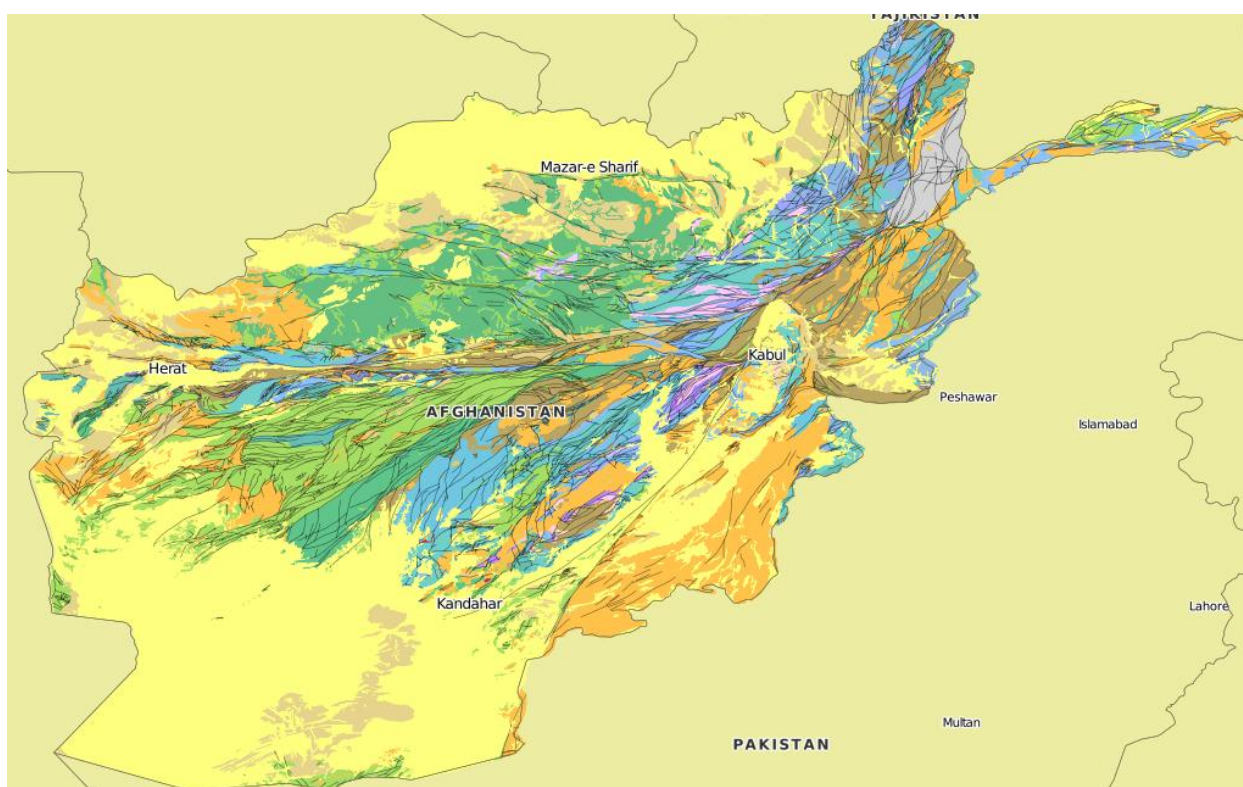


Figure 3.1: Geological Map of Afghanistan (After Geological Survey of Afghanistan)

A synthesis of the available tectonic, structural, magmatic and geochronologic data from Afghanistan and western Pakistan suggests that collision between the Indian Plate and the

Afghan Block (a collage of blocks assembled during the Cimmeride orogeny), took place during the Pliocene. Prior to this, the thinned western margin of the Indian Plate, together with the transitional to oceanic crust which separated the Indian Plate from the Afghan Block, was overlain by a wedge of Tertiary clastic sediments deposited in a large flexural basin that included what is now the Katawaz basin. At least three phases of collision can thus be recognized in the northwest Himalaya: the first, at about 100 Ma involved the suturing of the Kohistan-Ladakh-East Nuristan island arc to southern Asia; the second, at about 55 Ma involved India-Asia collision and the third, during the Pliocene, involved India-Afghanistan collision. During the Eocene and Miocene, the Afghan block was displaced southwards in response to Indian indentation into Asia. Simultaneous counterclockwise rotation of the Afghan Block resulted in intracontinental extension causing alkaline magmatism and right lateral displacements along the Herat Fault. As the Indian Plate moved northward with respect to Afghanistan, some of the wedge of clastic sediments deposited on the Indian transitional crust were accreted to the leading edge of the Afghan block and displaced sinistrally with respect to the rest of the sediments in the wedge. These displaced sediments now form the Makran sequence. Collisional structures on both sides of the India-Afghan collision zone in the Helmand block and the Sulaiman-Kirthar Ranges probably represent the inversion of continental margin basins rather than thrust belts with large shortening amounts. After initial inversion, the dominant feature of this highly oblique collision has been transpressional tectonics. Prior to its final docking with the Afghan Block, the Kabul block was a continental slice, completely surrounded by oceanic crust, and located northwest of continental India. Palaeocene collision between India and the Kabul block could have led to thickening of the Indian Plate prior to initiation of India-Asia collision (Badshah et.al, 2000).

The structural and tectonic development of Afghanistan interrelating crustal blocks as defined by Sborsschckikov, et al. (1973) is summarized by Afghanistan Geological Survey as under:

North Afghanistan

The Tadjik block of northern Afghanistan formed the southern margin of the Eurasian continental plate during Permo-Triassic times. The Palaeozoic basement was intruded by Triassic granitoids as a result of subduction related to the first stages of the closure of the Tethys Ocean during the Cimmeride Orogeny. Subsequent to this, a Jurassic clastic sequence was deposited, which changes upwards to Cretaceous carbonate platform sedimentation. This area is now the prime target for hydrocarbon exploration, although the exposed granitoids in the northeast of the block are prospective particularly for precious (and base) metal mineralisation, and further exploration of the occurrences identified to date is warranted.

The Cimmeride Orogeny

During the Triassic, parts of the northern edge of the Gondwanaland supercontinent broke away and began drifting north, before colliding with the Tadjik block, resulting in the Cimmeride Orogeny. The orogeny is marked by two distinct collisions which brought Himalaya at first the Farad block against the Tadjik block, followed closely by the Helmand block against the Farad block. The Herat Fault system marks the suture line of this first collision, which was finished by

the beginning of the Cretaceous, and the Panjao Suture marks the line of the second collision that was complete by early Cretaceous times. Both suture zones are ophiolite bearing, and the Herat Fault system in particular has had a long history of sedimentation and igneous activity up to the present. The Farad block was subsequently overlain by Upper Jurassic-Cretaceous sediments and the Helmand block by Cretaceous sediments only. During this period the Pamir and West Nuristan blocks of northeast Afghanistan were also accreted onto Eurasia. These four blocks, together with the Tadjik block, are collectively known as the Afghan Block. Due to processes discussed below, the southeastern margin of this Block is considered prospective for precious and base metal mineralisation, as well as rare metals in the numerous pegmatite fields.

The Himalayan Orogeny

Following a brief period of quiescence, tectonic activity began once again as India drifted north, away from Gondwanaland and towards the enlarged Eurasian plate with the Afghan block at its southern margin. The first evidence of this is preserved as the Kandahar volcanics, which marked the beginning of the development of a volcanic arc on the margins of the Eurasian plate. These were intruded by subduction-related, 'I-type' granitoids in the Helmand and West Nuristan blocks (during the Cretaceous to early Tertiary). This geological setting is highly prospective for a number of different mineralisation styles, and the large number of mineral discoveries to date only reinforces the potential of the east-central Afghanistan region. Igneous activity was not confined to this region, with younger (Oligocene) alkaline intrusions and basaltic extrusions in the Farad Block and the sedimentary basins within the Herat Fault Zone. The chemistry of these rocks suggests derivation from a mantle source beneath a zone of continental extension (within an overall setting of dextral transtension). Oligocene granitoids were also intruded into the thickened continental crust of northeast Afghanistan. By the start of the Tertiary, the widespread marine sedimentation that had preceded the Himalayan Orogeny had become restricted to the Tadjik Block and by Neogene times even this had become localised as the collision of India began to raise the area above sea level. Himalayan deformation of the Afghan Block resulted in the reactivation of many of the internal block boundaries including the Herat Fault system (as discussed above, but not active since the Miocene) and the Chaman Fault system (which marks the southeast edge of the Afghan Block and is still active to the present day). Folding and thrusting of the Mesozoic sediments also led to basin inversion and imbrication with the Palaeozoic basement.

East Afghanistan

To the east of the Afghan Block is a complex collage of tectonic units that marks the collision zone with the Indian plate. During the Cretaceous period, the East Nuristan volcanic arc was accreted to the margin of Eurasia (although magmatism continued into the Eocene). This was followed by the docking of the Kabul Block. The Kabul Block is somewhat of an enigma in Afghan geology. It includes, to the west and east, the Kabul and Khost ophiolites respectively, but is itself formed of Lower Palaeozoic basement overlain by Mesozoic sediments. It is now believed that the Block was a sliver of continental crust, separated from the Indian and Afghan blocks by oceanic crust that got caught up in the collision and was accreted to the edge of the Afghan Block before final collision with India. The Kabul Block is particularly prospective for

sediment-hosted copper in its basement sediments and chromite in the ophiolites. The final block in the Afghanistan jigsaw is the Katawaz Basin in Southeast Afghanistan. This is interpreted as a flexural basin on the western margin of the Indian Plate where subsidence synchronous with sedimentation resulted in the deposition of more than 10 km of Tertiary sediments before shortening and inversion in the late Tertiary as India finally collided with Afghanistan. Sedimentation across the country since this time has been continental, with large areas of Quaternary deposits particularly across the very north and south of the country.

Early in the Mesozoic, Pangaea began to break apart into Laurasia to the north of the Tethys Sea and Gondwana to the south. Smaller landmasses split off from Gondwana into the Tethys Sea. During the Cretaceous, central Afghanistan south of the Hari Rud fault was sutured against Eurasian Plate. India was another one of these landmasses, migrating during the Cretaceous and Paleocene across the Tethys; by the middle Eocene, it had begun to collide with Eurasian Plate northeast of Afghanistan, forming the beginning of the Himalayan orogeny. A tongue of the Tethys Sea remained between Afghanistan and India until the Pliocene. Upon this remnant of oceanic crust marine sediments were deposited. With the subduction of oceanic crust westward beneath Afghanistan, igneous activity increased along the eastern margin of Afghanistan that is now west of the Chaman fault. This sea also contained another small landmass that now surrounds Kabul; it collided with Laurasia and then India collided with it. Today, the Kabul landmass is encircled by suture zones. The marine sediments of the Katawaz basin folded as the ocean crust disappeared in the Pliocene time. Afghanistan is a complex juxtaposition of geologic units: Colliding landmasses formed crustal sutures at their boundaries that have rejuvenated and multiplied into abundant lateral and thrust faults that in turn are compensating for continued crustal displacement. Geologic maps of Afghanistan illustrate this composition with many slivers of very different lithologies and ages bounded by faults.

GEOTHERMAL POTENTIALS

3.2 Potential of the Hindu Kush Geothermal Province

As stated earlier the Herat-Panjshir fault is a deep seated strike-slip fault dipping as deep as up to 700 kilometer into the mantle is the result of colliding fragments of Gondwana onto Eurasian Plate (Saba et. al, 2004). Along this plane the Hindu Kush was uplifted since the end of the Cretaceous (Tapponnier, et al., 1981). This major structural fault and the subsequent Neotectonic movements produced fracture system in the area which are considered to provide excellent seepage of water into the superheated zones in the crust to produce geothermal fluids (Saba et al. 2004). Along these features wide spread occurrences of hot springs have been found indicating active geothermal areas in Afghanistan (**Figure 3.2**).

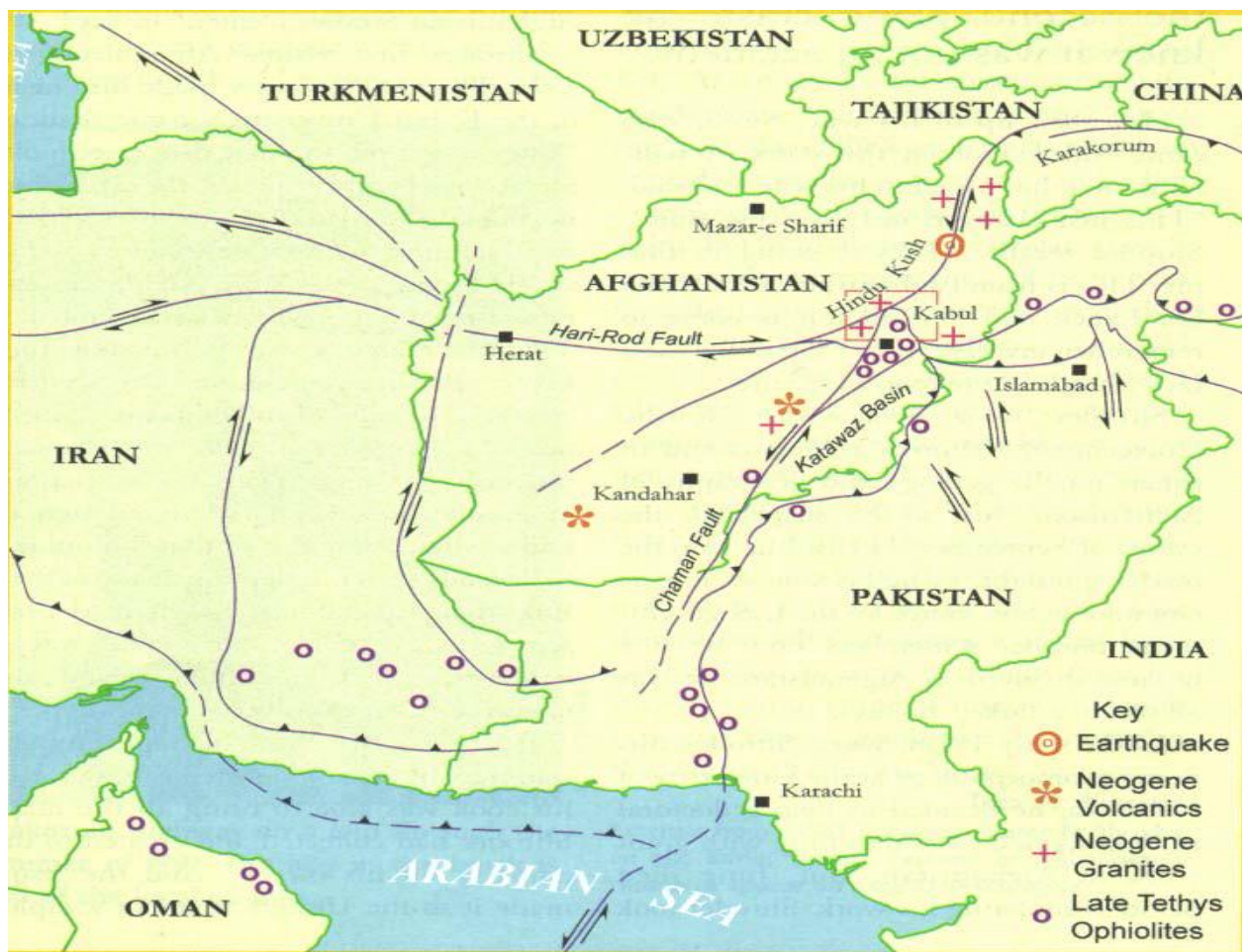


Figure 3.2: Major Structural Features of Afghanistan (After Saba et al., 2004; Schindler, 2002)

Likewise hot springs associated with the Chaman-Moqor fault and associated secondary faults indicate geothermal energy resources associated with them (**Figure 3.2** and **Figure 3.3**).

Saba and Avasia (1995a) noted that since end of the Cretaceous neotectonic movements generated by collisional and uplifting of the Hindu Kush mountain ranges divided Afghanistan into northern and southern structural components. The dynamic characters of the resulting structures indicate north-south compression and east-west extension. In addition, neotectonic movements show strong vertical uplifting, total rising and differential tilting. Seismic activities in Afghanistan show a decreasing tendency from east to west, with the strongest seismic activity occurring in the northeaster Badakhshan province, where the most active structures of the country are located (**Figure 3.3**).

Recent tectonic movements are characterized by seismic and geothermal activities in Afghanistan. Active geothermal systems are generally located in the main axis areas along the Herat fault system of the Hindu Kush, extending from Herat in the west to the Wakhan area in the Afghan Pamirs (**Figure 3.3**). This structure marks the plate boundary of the Eurasian plate and the Gondwana fragments. Although the collision along these plates in Afghanistan appears to end approximately at the beginning of Palaeogene (Beck, et al., 1995), but the geo-structural components of Afghanistan are still under enormous stress from the south, exerted upon them

by the ongoing movement of the Indian plate northwards (Saba and Avasia, 1995b). This process produces enormous frictional seismic and heat energy in the crust of this region, particularly along the geosutures, faults and fracture zones.

As mentioned earlier that the geothermal occurrences in Afghanistan are closely associated with the fault and fracture networks, seismic activity and young magmatism encountered at the plate boundary and its associated branching fault systems.

Prospects of low to medium temperature geothermal resources are widespread all over Afghanistan. These resources has tremendous potential for direct-use applications, such as in the food processing, fruit drying, refrigeration, fish hatchery and farming, carpet and wool processing, recreation and tourism, and many other possible small-scale local industries.

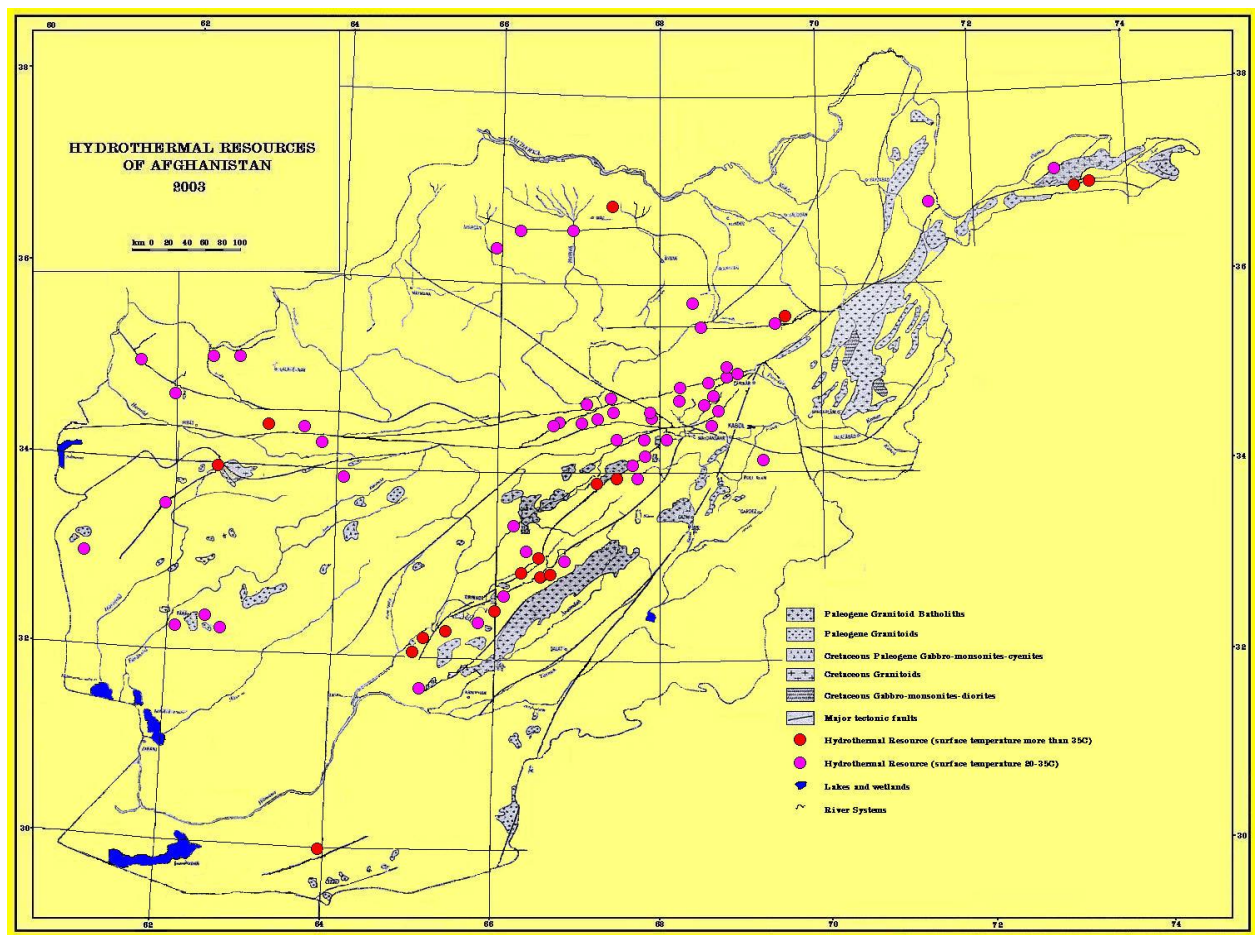


Figure 3.3: Occurrences of Geothermal Springs (After Saba et al. 2004)

Saba et al. (2004) consider that geothermal activities in Afghanistan are closely associated with active terrains. Due to the collision of many Gondwana micro plates moving northwards onto the southern margin of Eurasian plate, the strongest Neotectonic movements and intensive associated hydrothermal activities are evidenced south of the Hindu Kush main axis or the Herat-Panjshir geosuture. Thus, major geothermal manifestations are located along the Herat-Panjshir geosuture and the Chaman-Moqor fault systems in central Afghanistan active terrain

(Figure 3.4). The neotectonic activity results in uplift and displacement of the crust in central Afghanistan.

Geothermal occurrences in these areas are mostly located in the fracture systems of active faults, within basins and linear faulted valleys or wide valleys of the southern structural component of Afghanistan.



Figure 3.4: Neotectonic Activity in the Hindu Kush Resulting in Uplift and Displacement of the Crust (Photo of the Bande-Azhdar, Bamiyan), (After Saba et al., 2004)

3.3 Potential of Active Magmatic and Volcanic Geothermal Province

Shareq, et al., (1980) has reported widespread continental volcanism of Palaeogene, Neogene and Quaternary periods in Central, and Southwestern Afghanistan, where more than 50 dormant volcanic cones together form a volcanic zone with two distinct belts. A variety of magmatic intrusive rocks ranging in age from Precambrian era to Quaternary period covers approximately eight percent of the total surface area of the Afghanistan (Musazai, 1994).

Most of the geothermal indicators in Northeastern, Central, Western and Southwestern Afghanistan are found in the form of linear magmatic structures associated with the Palaeogene-Neogene magmatic formations. In these geothermal fields, the energy source of geothermal activity is controlled by magma chambers, which are located in shallow and intermediate depths with various intrusion periods, depths and volumes.

Almost all thermal indicators in Afghanistan are located in close contacts with young granitic massifs, which are void of pegmatitic or aplitic vein formations. This implies that the permeability in these rocks is controlled by fractures, which are already sealed by pegmatite-aplite bearing mineralization and the successive hydrothermal alteration minerals, reducing the overall permeability of reservoir rocks.

Geothermal fields associated with intrusive margins generally exhibit laterally continuous permeability zones and turnout more easily predicted continuous targets (Bogie and Lawless, 2000). The prospect of geothermal energy is much higher in association with intrusive contacts of such magmatic terrains, which occupy the core of the Hindu Kush mountain system, extending from northeastern extensions of the ranges towards central, southern, and southwestern Afghanistan.

These include magmatic complexes such as the Wakhan with a surface area of 300km², Baghe Aareq with a surface area of 2,500km², and Shiva, with multiple sub-complexes of up to 300km² each, in the northeast; the Baraky, with multiple sub-complexes of up to 35km² each, the Helmand, which has not been fully exposed on the surface, but exhibit multiple sub-complexes of up to 50km², and the Arghandab complex with a surface exposure area of 15000km² in central Afghanistan. Without exception, all of these complexes are of Palaeogene-Neogene ages, forming granitoid plutons in multiple temporal phases, exhibiting linear and extended structures with northeast-southwest strikes (Musazai, 1994).

The volcanic-subvolcanic complexes of the Nawor desert to the west of the city of Ghazni have dacite-andesitic compositions, forming volcanic cones with basal diameters of 100-500m, and sometimes up to 1.5 km. The conical subvolcanic carbonatite complex in Khan-Nashin to the left flank of the Helmand River, which is the most recent volcanic activity in Afghanistan (Quaternary), has a diameter of 7km with a very shallow carbonatitic cover. Similarly, the Malek-Dukan carbonatite conical volcanic complex, located in the Rigestan desert on the foothills of the Chagai-e mountain range in the southwestern corner of Afghanistan, has a basal diameter of 3.6 km, with the carbonatitic cover thickness reaching 500-800m. All volcanic-subvolcanic complexes of Afghanistan, including those in the upstream of the Farahrud in the province of Farah, have young ages that extend from Late Neogene into the Quaternary period (Shareq, et al., 1980).

Some of these geothermal prospect fields may be void of adequate groundwater resources as a heat transport medium, but dry hot rock is also a source of geothermal energy. By definition, dry hot rocks are naturally heated unmelted crustal rocks, which lie beneath the surface in areas where the geothermal gradients are two to three times greater than normal. Dry hot rocks are absolutely certainly present in volcanic and active magmatic regions in shallow depths. The temperature in dry hot rocks hovers around 177°C in shallower depths, while at a depth of many kilometers, the heat may increase to up to 760°C (Tester, and Smith (1978/79). Since the rocks are bone dry, there is no medium to transport the heat energy to the surface. The process of artificially making a geothermal reservoir within hot buried rocks is difficult and expensive, but if successful, the potential is enormous. The technology to tap this resource is already in existence in developed countries, but it is yet to be developed into commercially viable means for tapping this resource.

In the view of the authors of this report, considering the recent volcanic activities in south-southwestern structural blocks in Afghanistan, the prospect of these volcanic regions for geothermal energy is very promising. Other prospects associated with the young magmatic

complexes of Afghanistan, particularly in the vicinity of fault and fracture systems are as promising and interesting in regards to their potential geothermal energy reserves.

3.4 Geopressured Prospect

These very high-pressured geothermal energy prospects are associated with the hydrocarbon-bearing strata of northern Afghanistan. Geopressured thermal zones are deposits of water trapped and buried under thousands of feet of rocks and clay. This kind of water is very old, perhaps a million year or more, which is under abnormally high pressure, and is hot, with temperatures at times as high as 296°C. In these zones, which generally lay some 3-8km below the surface, the heat is trapped and insulated by encircling layers of sand, clay, and shale. The Geopressured zones are a dual source of heat and methane at the same time (Holt, 1977). Indications of this type of prospects are recorded in the oil and gas fields of the Jozjan and Balkh provinces of northern Afghanistan (Kurenov and Belianin, 1969).

3.5 Potential of Harirud-Badakhshan Geothermal Province

The geosuture structural zone of central Afghanistan including the deep-seated fault system of Harirud and the central Badakhshan faults with their associated fracture system form the main and axial component of the geothermal activity in the country (**Figure 3.3**). The zone extends eastward, beginning from Herat in western Afghanistan, to Panjao, Ghorband, Panjshir, Badakhshan, and up to the Pamirs to the most northeasterly corner of the country.

Of major hydrothermal indications in the western extensions of this field are the nitrogen-bearing siliceous hot springs in the Obe district of Herat province, 120 km to the east of Herat city, and 8km to northwest of the Obe township, as well as the Safed-Koh hot spring with surface temperatures of 48-52°C as measured in September 2003 (**Figure 3.5**). In Panjao-Bande Amir region of central Afghanistan, many CO₂ bearing thermal springs with carbonate-chloride-calcium-sodium salts are recorded to have surface temperatures of 24-35°C and a TDS of up to 3 gram/liter. The pH in these waters is controlled by the amount of CO₂ (up to 4 gram/liter), which ranges from 6.1-6.5. Geochemical elements in these waters include Be, Ge, Ba, Sr, Ti, V, As, Ga, Ni, Co, Fe, and traces of Rb, Cs, Cu, Pb, P. (Belianin, et al., 1970).



Figure 3.5: The Obe Shefa Hot Spring, Obe Township, 120 km to the East of Herat City, with a Surface Temperature of 52°C and a Very Hot Ground in a Granitic Contact Zone. (After Saba et. al 2004)

The hot springs in the Kalu and Ghorband valleys, as well as Khwaja Qeech, and Ghorghauri hot springs in central Afghanistan are examples from the central portions of the Harirud-Badakhshan geothermal field. Generally, these waters with chloride-bicarbonate-sodium or chloride-sodium compositions are having high concentrations of elements such as Ge, Be, B, Fe, Ag, Zn, Pb, Ba, Li, Rb, Sr, and Sc (Kurenov and Belianin, 1969).

High mineralizations in these thermal waters could be attributed to the higher amounts of CO₂ in the metamorphic hydro-geochemical environment, which facilitates the release of microelements from the surrounding country rocks into the solution. Of these springs, those in the Kalu Valley (**Figure 3.6**), which is located 20 km to the east of the Bamiyan township, have promising potentials for balneological applications and tourist attraction, as well as the development of a small scale geothermal power plant, probably in the range of up to 10MW, in the immediate future.

In the eastern extensions of this field, in the Andarab-Panjshir region, as well as in the Badakhshan and the Pamirs, fewer hydrothermal manifestations are exposed on the surface. These are mainly of the nitrogen-bearing category, e.g., the Qala-e Saraab hot springs in Andarab, and Bobe-Tangi and Sarghaliyan hot springs in the Wakhan and Badakhshan regions, respectively. In comparison to the more westerly hot springs, these are having lower concentrations of geochemical elements. The Bobe-Tangi and Sarghaliyan also contains some amounts of hydrogen sulfide in their solutions.



Figure 3.6: Southern View of the Kalu Valley with Hot Spring
(After Saba et. al 2004)

3.6 Potential of Helmand-Arghandab Geothermal Province

With mainly CO₂ and nitrogen-bearing waters, hydrothermal activities in this geothermal field are associated with the Helmand-Arghandab granitoid massifs, connecting to the main geothermal axis through southern extensions of the fault and fracture systems of central Afghanistan. The deep-seated Chaman-Moqor fault system and other groups of secondary faults are the main structural factors in the formation of this geothermal field, which covers regions such as Helmand, Moqor, and Tirin-Azhdar in south-central Afghanistan. The latter having thermal springs with the highest water discharges in the country. Hydrothermal activity here is mostly characterized by categories of CO₂ and nitrogen-bearing springs, which are normally rich in silicic acid and many solid minerals as micro-components in the solution.

The main areas of activity in this field are those in the vicinities of the Chaman-Moqor fault system, which is characterized with many CO₂-bearing thermal springs, rich in alkali and rare earth elements. In the Helmand fault and fractures system, thermal springs are more similar in their hydrogeochemical composition to those of the Panjao-Bande Amir hot springs. Geothermal activity in the vicinity of Helmand-Arghandab granitoid complex in the Tirin-Aajar area is very typical, in the sense that in southeasterly direction from the main Helmand fault system, the content of CO₂ decreases as the amount of nitrogen and nitric acid increases.

3.7 Potential of Farahrud Geothermal Province

This field is located in the Farahrud structural depression to the southwest of the main geothermal axis in southwestern Afghanistan. Geothermal activity in the form of hydrothermal springs in this field is associated with Pasaband deep-seated fault and fracture system. In its southwestern extension, it joins the nitrogen-bearing hydrothermal system of the Helmand-

Arghandab geothermal field. Bicarbonate-calcium nitrogen-bearing thermal waters rich in silica and void of CO₂ are the norm in this geothermal field.

3.8 Potential of Baluchistan Geothermal Province

To the extreme southwestern corner of Afghanistan lies the volcanic terrain of Chagai-e in Baluchistan, with lots of hydrothermal activity, mainly of brine nature, rich in CO₂ and calcium. Two types of brine waters are typical for this field: thermal chloride-sodium rich pressured waters with a pH level of 6-6.6 that release high amounts of gases from the solution at the surface, leaving behind travertine and halite deposits; and chloride thermal waters with little or no gas in the solution, having a pH level of 7.8-8. These hydrothermal activities are suggested to be associated with carbonatitic post-volcanic processes in this region, resulting in the deposits of beautiful onyx marbles.

3.9 Surface Indications of Geothermal Potentials

The average geothermal gradient of producing wells of the North Afghanistan is about 34.6 °C/km. Assuming that the geothermal gradient has been stable since Early Tertiary in the entire country, it appears that: 1) Hot Water Fields can be expected from 2km to 2.5 km depth in all the basinal areas; 2) the Wet Steam Fields can be expected from a depth of 3km depth in the thermal gas window zone in the deeper parts of the Afghan-Tajik sub-basin.

3.10 Hydrogeochemistry of Thermal Waters

Reservoir fluids are usually complex mixtures of various chemicals exhibiting a wide range of compositions and concentrations of solutes that generally increases with the temperature of the associated geothermal systems.

There are a diversity of thermal water types in Afghanistan, i.e., bicarbonate, chloride, sulphate, and sodium-chloride, all produced by complex geological, metamorphic and metasomatic processes in a variety of geochemical and hydrogeological conditions. Many categories of thermal waters are distinguished in Afghanistan, such as carbon dioxide rich, which in some instances having viable amounts of REE (Rare Earth Elements) contents, nitrogen-bearing, hydrogen sulfide-bearing, Fe-Al-bearing, and brine. All these categories of thermal waters are originating from three major hydro-geochemical environments: metamorphic, reducing, and oxidizing (Kurenov and Belianin, 1969).

CO₂ is the dominant gas phase constituent in the main geothermal axis of the Hindukush. Carbon dioxide and CO₂-nitrogen-bearing waters are mostly originating from metamorphic environments associated with granitoid complexes. In this case, they are mainly characterized with high surface temperatures (>37°C), high pH levels (>7.5), and low solid mineral contents in the solution (1-2.5 gm/lit). Such geothermal systems are located in the areas of higher CO₂ flux, resulting from their peculiar geological structures that give origin to the geothermal reservoirs of these systems. As a matter of fact, a larger amount of natural CO₂ is produced at depth, mainly by thermo-metamorphism of marine carbonate rocks. This CO₂ is usually trapped in deep

structures, saturates the deep aquifers and is discharged with hydrothermal activities at the surface in the form of carbonated thermal waters.

The Geological Survey of Afghanistan surveyed a number of thermal springs with high CO₂ reactivity in the Kalu, Ghorband, Dara-e-Soof, and Istalif valleys in 1968-69. It was found that many of these are comparable with some therapeutically famous thermal waters of Russia, with many of them exhibiting high to moderate concentrations of REE elements (Kurenov and Belianin, 1969), which are of extreme value in balneological applications.

Spatially, in some instances, nitrogen-bearing hydrothermal activities are also associated with the same structures that exhibit carbonated hydrothermal activities. Most of the times, these two types of waters coexist in single systems, thus creating a spatial transition in between their typology. Carbonated waters are a characteristic of the central portions of the main geothermal axis, and are closely related with deep-seated faults. As the distance from the main axis increases towards the peripheries, the nitrogen-bearing waters are becoming more typical of the hydrothermal activities, to the extent that at the peripheries of the main axis, the nitrogen gas becomes the dominant gas species.

Hot water springs associated with the contact zones of granitoid batholiths generally contain Nitrogen-bearing waters originating from reducing geochemical environments and having high surface temperatures (>37°C), considerable water discharges (1-10 lit/sec), and high pH levels (>7.5). These kind of hydrothermal activities are normally rich in silicic acid (1-100 mg/liter). Their geochemistry is reflective of their host rocks, mainly those of granitoid affinity. They include chemical elements such as Mo, W, Sn, Be, Li, Ge, etc., in the solution as reported by GSA (Kurenov and Belianin, 1969). Though having higher surface temperatures, nitrogen-bearing thermal waters are generally poor in their microelement contents comparing to carbon dioxide-rich thermal waters, which are normally having higher amounts of Li, Rb, Cs, Ge, B, and Sr in their solutions.

The hydrogen-sulfide-bearing thermal waters are basically associated with reducing hydro-geochemical environments. These are mainly observed in association with hydrocarbon-bearing structures of northern Afghanistan, and probably would be found in similar strata in southeastern Afghanistan. Example of this type could be the “Chahe Gandzh” geopressed system in Sheberghan province, in which the surface temperature is recorded to be 51°C.

Hydrogen-sulfide-bearing category of thermal water is also found in the areas of contacts with granitoid batholiths in central as well as northwestern Afghanistan, associated with oxidizing environments in the vicinity of the main geothermal axis of the Hindu Kush. Emission of hydrogen sulfide is a characteristic of such springs, which are also sometimes rich in silica, nitrogen and CO₂. In the Arghandab district of southwestern Afghanistan, thermal water springs in oxidation environments are characterized by their high discharge volumes, low pH levels, and richness in sulfides. Chemical elements such as Li, Ga, Ti, Cr, Se, Be, Ba, Pb, Zn, Ag, and As, are the defining microelements in these waters, where sometimes they reach industrial

proportions, e.g., the amount of Li up to 10mg/liter in some of these springs is not unusual (Kurenov and Belianin, 1969).

Oxidizing hydro-geochemical environment in Afghanistan also produces brine waters associated with Mesozoic and Cenozoic evaporites (a mixture of salt and anhydrate) strata of the country. Low temperature, iron-aluminum-bearing acidic springs are also produced in this environment. In this case, they are associated with the oxidation zones of the sulfide deposits, such as in the Aynak area, which exhibit a surface temperature of 18°C.

3.11 Dynamics of Hydrothermal Activities

Heat transport from magma and geothermal fluids is a relatively fast process driving the high temperature geothermal systems encountered in young volcanic and in seismic areas at the boundaries of tectonic plates, such as in the Hindu Kush. On the other hand, thermal conduction in a geological setting is a relatively slow process, where a time constant of the order of hundreds of years is needed to characterize the system. In this process, heat is transferred from the earth's interior towards the surface mostly by the conduction process, causing the temperatures to rise with increasing depth by an average of 25-30°C per kilometer of depth. Dry hot rock geothermal systems are associated with such thermal conduction.

The water that comes from the rain and snow seeps into the ground. It will reach impermeable rock layers. There it will spread along the lines of least resistance until it comes to a system of fault and fractures in the surrounding structure. Down the cracks of this system, it will flow to the aquifer or the porous rocks that permits water to flow through it. If the aquifer is deep enough, it may rest on the impermeable rock layer that is in contact with superhot magma. Such an aquifer will be very hot, soaking up heat and circulating it through its structural components.

The heat from the superhot magma moves up through the impermeable rock layers into the aquifers and heats the water. If the heated water encounters some fracture leading upward, it expands, becomes less dense and more buoyant, and consequently rises to the surface as hot water or steam. The rising water is then replaced with denser cold water seeping into the aquifer. Hot-water deposits though abundant, but do not always announce their location in the form of hot springs or geysers. They are often hidden in volcanic and earthquake regions, and in some sedimentary areas. Thus, knowing the geology and the structure of the geothermal fields will facilitate the delineation of favorable prospects.

In Afghanistan, it is suggested that one of the main controlling factors in the formation of thermal water systems is continuous Neotectonic activity that facilitate the creation of passageways through fault and fracture zones in the lithosphere of this region. A structural analysis indicates that hydrothermal activities in Afghanistan are closely associated with major faults that divide the country into smaller structural blocks (see **Figure 3.1**, **Figure 3.2** and **Figure 3.3**).

Comparatively, plentiful reserves of thermal waters are associated with the structures located in the junction areas of fault systems, e.g., where the Herat-Panjshir deep-seated fault system intersects with the Moqor and the Panjao fault systems, respectively. Such intersections form

fracture networks that cover vast areas in central Afghanistan, controlling the permeability of the reservoirs of geothermal systems in these fields. It is along these networks that the geothermal fluids move to the surface and forms the geothermal prospects of the country. A second and determining factor in hydrothermal activity is young magmatism of the Hindu Kush, which provides the thermal energy for percolating underground reservoirs in the vicinity of granitic intrusive complexes throughout the country.

Infiltration dynamics, particularly the altitude of the watershed, also play a determining role, as most of the hydrothermal activity depends on the amount of atmospheric water that could feed the hydrothermal systems. At high altitude and latitude the atmospheric precipitation contains lighter isotopes than in the lowlands. The isotopic analyses of water samples from springs and wells gives information about the origin of the field discharges, their age and possible underground mixing processes between different waters, about water-rock interaction and about steam separation processes (Nuti, 1991). Oxygen isotope analysis of five representative samples from thermal waters in Afghanistan reveals a value of δO^{18} (a deviation in parts per thousand of the sample from standards mean ocean water) in the range of -10.5 to -11.7 (Belianin, et al., 1970). This implies that the major volumes of thermal waters in Afghanistan are of meteoric origin, derived mainly from recharged water, rather than juvenile.

All the aforementioned factors contribute to the formation of a single hydrothermal system in Afghanistan, in which the high hydrostatic pressure forces the cold meteoric waters downward towards hot magmatic chambers that define the basic hydro-geochemical composition of the thermal fluids in the source region. The heated water, which is rich in dissolved gases, particularly CO_2 , is much lighter than colder incoming water, thus moving upward through fractures and pores in different strata, picking many other elements into the solution en route to the surface.

Considering the complex geotectonic structure and endogenic processes in Afghanistan, the most potential prospects of geothermal reserves are suggested to be associated with the junctions of major fault systems, as well as the currently dormant volcanoes. A general trend in hydro-geochemical categories of thermal waters could be established, such as the changes in the category and types of water. For example, as the system gets closer to the main geothermal axis, it becomes richer in its CO_2 and total dissolved solid (TDS) mineral contents. In the contrary, as the system gets farther away from the main geothermal axis, the surface temperature of water increases and the water becomes richer in its nitrogen and silica contents, with an overall lower TDS contents of less than 1gram/liter.

Saba et al., (2004) are of the view that geothermal fields in Afghanistan are mainly water-dominated systems, where liquid water at high temperature and under high hydrostatic pressure is the pressure-controlling medium, filling the fractured and porous rocks. Thus, major faults and fracture zones provide the initial structural components of these hydrothermal systems, based on which the following interconnected geothermal fields could be distinguished in the country: the Harirud-Badakhshan, the Helmand-Arghandab, the Farahrud, and the Baluchistan geothermal fields.

3.12 Conclusions and Recommendations

The tectonics, magmatic, and metamorphic events in Afghanistan exhibit colossal potential of geothermal energy in this country. Hot springs occurrences along with some blind potential along the Herat-Panjshir and Chaman-Moqor fault systems are the most promising prospects for geothermal exploration and characterization of known and hidden reservoirs are in regions.

For industrial exploitation, these potentials need systematic geological, geochemical and geophysical exploration including fluid inclusion geothermometry, stable isotope analysis, electrical resistivity surveys, self-potential (SP) surveys (Ross, et al., 1995). Seismic survey of limited areas may also be undertaken to locate the blind reservoirs and delineate shallow producing geothermal fields to accurately identify depth of hot water reservoirs and for exploratory drilling. Thus, a major exploration effort is needed to characterize geothermal reservoirs and build the inventory of prospective geothermal areas for further development.

Considering the benefits of geothermal resources and their wide spread occurrences, it is recommended that programs including exploration research, development of these resources and their marketing to meet the energy requirements may be undertaken by the Government of Afghanistan.

A thorough assessment of the country's geothermal resource potential for use in electrical power generation, district heating, cooling of homes and buildings, food processing, green house industry, fish farming and hatchery, refrigeration, recreation and tourism, and a myriad of other industries may be undertaken. To facilitate the accomplishment of these goals, policies and regulations that promote investment in development of geothermal resources has to be worked out.

It is suggested that the United Nations, World Bank, Asian Developing Bank, and other interested global institutions should include strong geothermal energy components in their developing programs in Afghanistan, and encourage geothermal industries and agencies worldwide to help in the development of geothermal resources of this country as a component of the international cooperation in the rebuilding of Afghanistan.

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CHAPTER – 4

GEOTHERMAL RESOURCES OF BANGLADESH

4.1 Geological Framework

This part is mainly derived from the Banglapedia (2006). The Geology of Bangladesh is affected by the country's location, as Bangladesh is a rivine country. It is the eastern two-thirds of the Ganges and Brahmaputra River delta plain stretching to the north from the Bay of Bengal. While the eastern part of Bangladesh is the continuation of the frontal belt of the Indo-Burma Range.

Bengal delta is one of the largest deltas in the world. Geological evolution of Bengal delta is related to the uplift of the Himalaya due to collision of Indian and Asian plates. The Bengal delta is characterized by enormous sediment supply from Himalaya, rapid sedimentation and subsidence resulting in huge thickness of siliciclastic deltaic sediments. This process is ongoing into the present Bay of Bengal.

Tectonically Bangladesh lies in the northeastern Indian Plate near the edge of the Indian craton. Stable Pre-Cambrian Platform and a huge geosynclinal basin in the southeast are dominating tectonic features of Bangladesh which are separated by a narrow northeast-southwest trending hinge zone, currently known as palaeo continental slope (Salt et al, 1986, Banglapedia, 2003).

Stable Pre-Cambrian Platform covers the country to the west and northwest of the hinge zone and is divided into three major zones: Rangpur Saddle, Bogra slope and Dinajpur slope (**Figure 4.1**). It is composed of continental crust overlain by Cretaceous to Recent clastic sediment along with Eocene Limestone. However, Permo-Carboniferous sediments with coal seams of considerable thickness and extent are deposited in isolated depressions on the stable shelf. The thickness of sedimentary column on the stable shelf of Bengal Basin varies from less than 200m to 8,000m (Banglapedia, 2006).

Rangpur Saddle connects the Indian Shield with the Shillong and the Mikir Hills Massif resulting in uplifted basement with thin cover of sedimentary rocks. In Madhyapara area the basement is encountered at 130m depth and overlain by Plio-Pliocene sediments. The northern and southern slopes of Rangpur Saddle are quite gentle and the basement plunges gently from Madhyapara towards the southeast up to the Hinge Zone. It separates the Bengal Fore deep and the Himalayan Fore deep. The Northern Slope of Rangpur Saddle is also recognized as Dinajpur Slope, and gently slopes towards the Sub-Himalayan Fore deep.

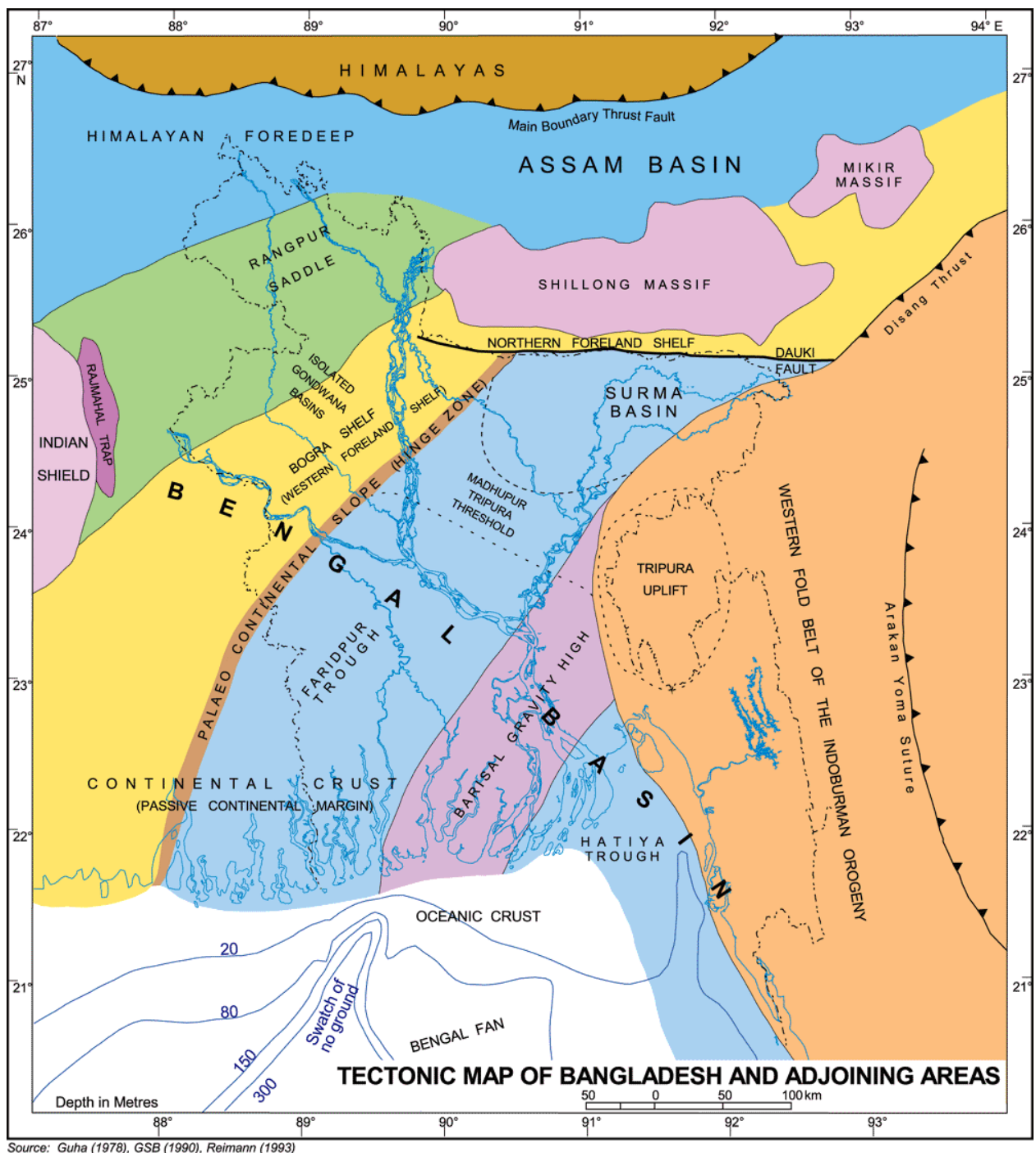


Figure 4.1: Tectonic Map of Bangladesh and Adjoining Areas (After Banglapeedia, 2006)

Bogra Shelf is in continuation of the southern slope of Rangpur Saddle and also marks the transition between the Rangpur Saddle and the Bengal Fore deep. The width of Bogra Shelf varies from 60 km in north to 125 km in the southeast with progressive increase in thickness of the sedimentary sequence. The area is traversed by a number of NE-SW trending faults of which Bogra Fault being the most prominent.

The Hinge Zone or palaeo continental slope is the reflection of Calcutta-Mymen singh Gravity High. The Hinge Zone is a narrow strip of about 25 km wide complex flexure zone, which

separates the Bengal Fore deep from the shelf. This zone is characterized by the sharp change in the dip of the basement rocks associated with deep-seated displacements in faults and is reflected on the gravity and magnetic anomalies.

The southeastern part of Bangladesh is covered by the geosynclinal basin characterized by the huge thickness (maximum of about 20km near the basin centre) of Tertiary age clastic sedimentary rocks (Banglapedia, 2006). The huge thickness of sediments in the basin is a result of tectonic mobility or instability of the areas causing rapid subsidence and sedimentation in a relatively short span of geologic time.

The geosynclinal basin is subdivided into fold belt in the east and Bengal fore deep to the west. Bengal Foredeep occupies the vast area between Hinge Line and fold belt of Arakan Yoma Folded System. It comprises a platform region in the west and a folded region in the east. The western platform flank is characterized by several highs and lows namely Faridpur Trough, Barisal-Chandpur High, Hatiya Trough, Madhupur High and Sylhet Trough.

Folded Belt represents the most prominent tectonic element of Bengal Fore deep with general sub-meridional trending hills parallel to the Arakan Yoma Folded System. A large number of narrow, elongated N-S trending folds of the eastern part of Bangladesh occupy the Folded Belt west of the Arakan Yoma Folded System. The folds are en-echelon and are forming box-like structures having high amplitude with variable width. Some of the structures are thrust showing increase in the intensity of folding gradually from west to east.

Stratigraphy of Bangladesh is controlled by its major tectonic elements. A thin veneer of sedimentary sequence ranging in age from Permian to Recent covers crystalline basement in the Precambrian platform area. Likewise the geosynclinal basin, received huge clastic sediment pile of mostly Tertiary age. The geological map of Bangladesh (**Figure 4.2**) illustrates the distribution of exposed sedimentary and igneous sequences in the country.

The Precambrian basement, which forms the base of all sedimentary rock units, is dominantly composed of granite, granodiorite and gneiss. The basement occurs at a shallowest depth of 130m below the surface in the Rangpur area and dips towards southeast with increasing sedimentary cover ranging in age from Permian (Gondwana group) to Holocene deposits.

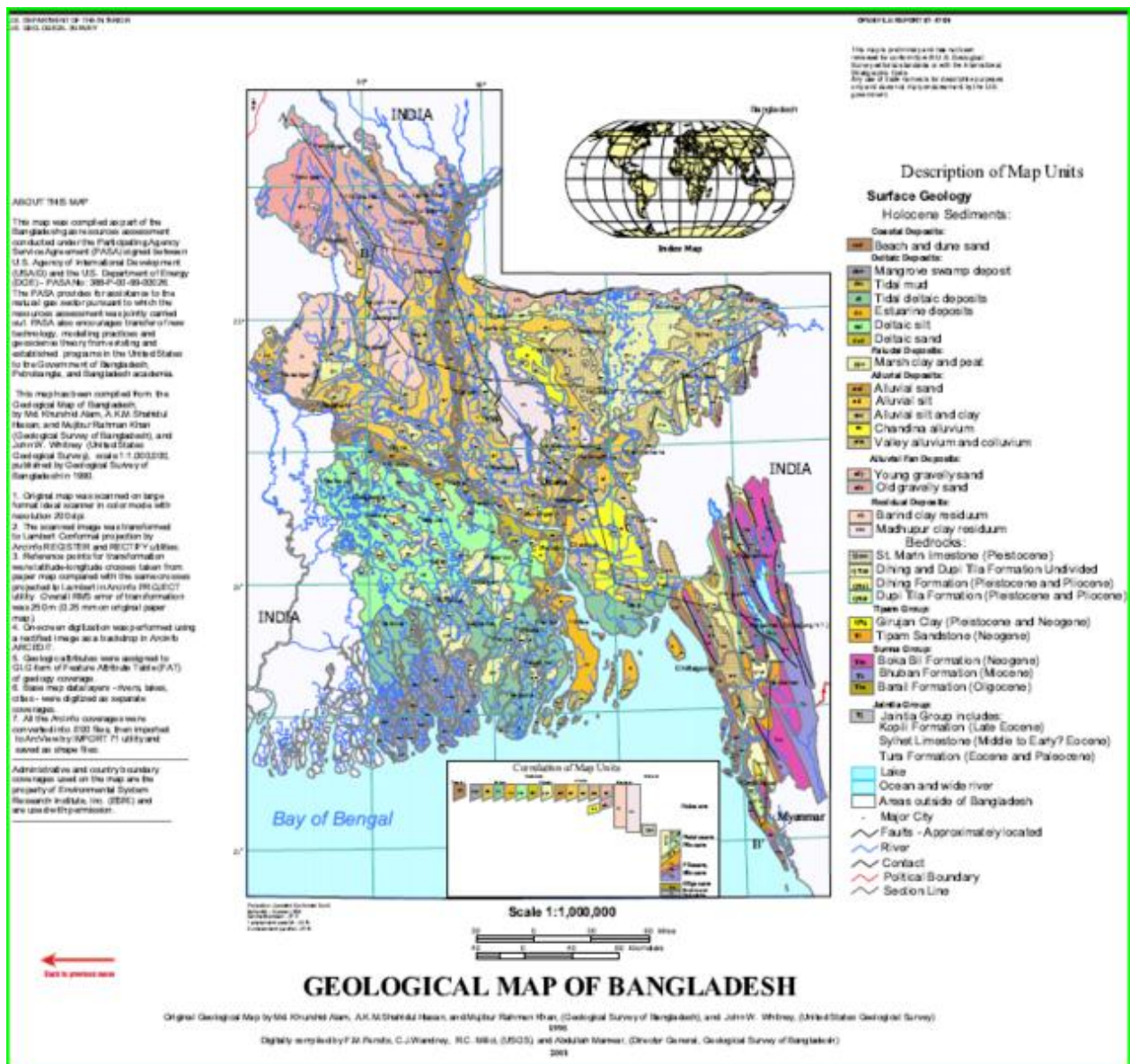


Figure 4.2: Geological Map of Bangladesh showing Extent of Sedimentary and Igneous Rocks

The Gondwana group unconformably rests on the Precambrian crystalline basement and is dominantly composed of sandstone with some coal seams and shale horizons. The stratigraphy of the country is illustrated in **Table 4.1** which shows the overlying successive units, their thickness and generalized litho logic composition.

Table 4.1: The Generalized Stratigraphy of the Bengal Basin

AGE	Group	Formation	Thickness (m)	Lithology
Holocene	Alluvium			
Pleistocene	Dihing	Dihing	129	Yellow and gray, medium-grained, occasionally pebbly sandstone
Pliocene	Dupi Tila	Dupi Tila Sandstone	2,393	Medium-to coarse-grained, gray to yellow sandstone with clay balls.
		Girujan Clay		Red, brown, and purple mottled clay with sand lenses.
Miocene	Tipam	Tipam Sandstone	3,500	Gray to brown, coarse-grained, cross-bedded, massive sandstone
	Surma	Boka Bil	3,100	Alternating shale, siltstone and sandstone.
		Bhuban		Sandstone, siltstone, clayey sandstone, clays and lenticular conglomerate.
Oligocene	Barail	Renji	800-1,600	Coarse-grained sandstone, carbonaceous shale and lenses of coal
		Jenam		Dark gray silty and sandy shale
Eocene to Paleocene	Jaintia	Kopili Shale	15-150	Alternating dark-gray calcareous shale, with thin limestones
		Sylhet Limestone	148	Gray to dark gray, highly fossiliferous limestone
Pre-Paleocene	Undifferentiated sedimentary rock	Tura/Cherra Sandstone	240	White, pink to brown, coarse-grained, cross-bedded, carbonaceous sandstone
Cretaceous		Shibganj Trap wash formation		Volcanic, Red ferruginous sandstone and mudstone
Jurassic		Rajmahal Trap formation	500	Volcanic basalt
Permian	Gondwana group		1,000	Hard sandstone with some coal and shale
Precambrian igneous and metamorphic rocks				Mainly of granite, granodiorite and gneiss.

4.2 Surface Indicators of Geothermal Activity

Surface indicators of geothermal activity are often present above blind or concealed geothermal systems, but their expressions are sometimes subtle. When mapped in detail, these indicators yield valuable information on the location, structural controls, and potential subsurface reservoir temperatures of geothermal fluids (After Guha et al., 2010).

Listed below are the surface manifestations of geothermal activity, which are needed to be studied in more detailed to demarcated prospective areas for geothermal energy in Bangladesh.

4.2.1 Warm Ground

Warm ground represents a low level of geothermal activity. The ground temperature is raised at 1 m depth but not at the surface. Warm ground is not visible on infrared images but changes to vegetation can be identified. The Gondwana sandstone sequence below the coal seams in Barakupuria coal mine has a temperature of 50°C at a depth of 400m.

4.2.2 Hot Steaming Ground

Hot ground is the result of underground thermal conduction. Hot vapours rise near the surface but are not actually discharged. The vapours condense and drain away without being released to the atmosphere. A thin layer of steam may condense under moist air conditions. If the air is dry then no steam is observed.

4.2.3 Hot Pools

Hot pools are the result of hot water or steam heating a pool of groundwater. Hot pools may be calm, ebulliant (effervescent) or boiling. Guha et al (2010) has mentioned that warm water, up to 36°C, has been observed in irrigation wells at depths of 80m at Thakurgaon.

4.2.4 Hot Lakes

These lakes fill hydrothermal depressions in geothermal areas. They are a subclass of volcanic lakes.

4.2.5 Hot Springs

Hot springs are the most common type of geothermal activity. They are located where water from a geothermal system reaches the surface. Some springs in Iceland pulsate and release water in cycles. Hot springs have been observed at Barbarkund and Gobaniya Chara in the Sitakund anticline with temperatures of up to 35°C. (Guha and Henkel 2005).

4.2.6 Fumaroles

A fumarole is a steam discharge from a hydrothermal or volcanic system. A solfatara contains sulfur emissions. Solfioni emit boric acid. Fumaroles can burn, so be careful when approaching them.

4.2.7 Geysers

A geyser is a vent from which hot water and steam are violently emitted. They are very rare but well known and extensively studied. Requirements for geyser formation include fractured rocks and boiling water at a shallow depth.

4.2.8 Hydrothermal Eruptions

Hydrothermal eruptions are caused by catastrophic discharges of water close to the boiling point. It is a phreatic eruption. No ash, incandescence, or clasts are erupted. Hydrothermal eruptions may be caused by a reduction in the overlying pressure.

4.2.9 Geothermal Seepages

A seepage is a general term which describes any subsurface discharge of warm fluids from a geothermal area. Seepages may occur into rivers or lakes. A river seepage may be identified by differing non reactive constituents above and below the seepage outlet.

4.3 Geothermal Gradients

Thermal methods for geothermal exploration involve the measurement of subsurface temperature at specified depths in exploratory boreholes. Using temperature-depth measurements, geothermal gradient can be determined and (when coupled with other down-hole data) heat flow. These down-hole temperature measurements comprise the only geothermal exploration method for direct detection of geothermal resources. Temperature logs of boreholes are made by lowering a sensitive thermostat probe -- capable of measuring temperature differences of about 0.01°C on a conductor cable, recording probe resistance, and converting resistance data to temperatures at specified depths in the borehole. All data in this report were obtained from the logs of exploratory wells drilled in various tectonic zones of Bangal Basin. Temperatures in the range of 100-120°C at depths of 2100-2500m and these temperatures could be used for generating electricity using a binary power plant technology

Till 2002 fifty-two onshore and twelve offshore exploration wells were drilled in Bangladesh, twenty-two of which have been reported successful in locating oil and gas fields (Imam and Hussain, 2002). **Figure 4.3** shows the well locations in various parts of sedimentary basin of Bangladesh. Of these only a few wells have been drilled in NE part of the basin.

The majority of the wells drilled so far in eastern fold belts and foreland basin areas of the Bengal basin encountered overpressure zones in the Lower Miocene Bhuvan Formation (Surma Group) at depths ranging from between less than 1 km at Patharia-5 to 4.5 km at Muladi-1 (Imam and Hussain, 2002). It seems probable that the overpressure zones are caused by compactional disequilibria of thick shale sequences in the Bhuvan Formation (Imam and Hussain, 2002). It may be noted that rapid burial with high geothermal gradients favours the most rapid volume change and produces the high overpressure zones.

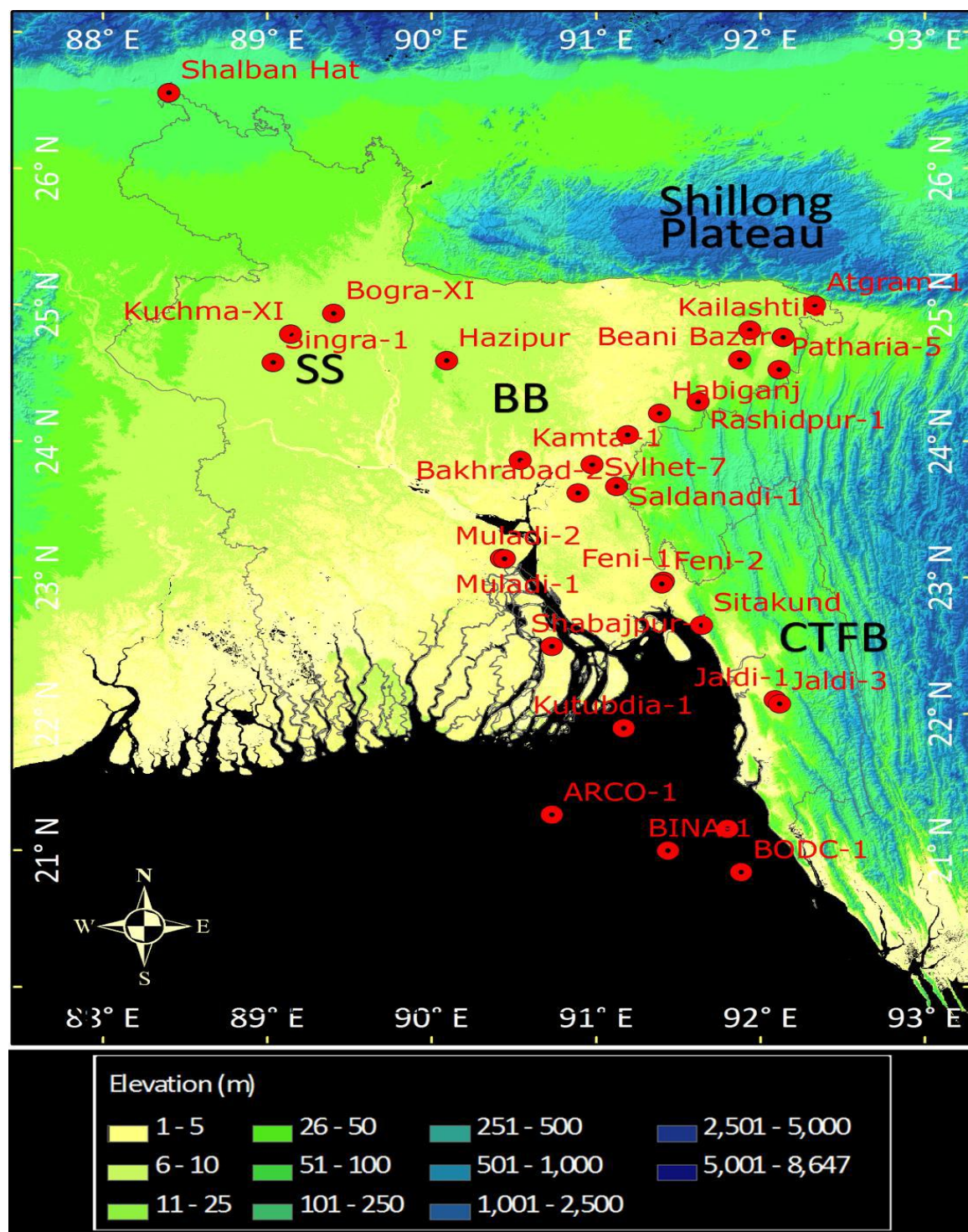


Figure 4.3: Locations of Exploratory Wells Used in this Study

(After Hossain, M. S., 2009)

The deeper parts of the Bengal basin covering central, eastern, and southern Bangladesh has an average geothermal gradient of about 21.3°C/km (**Figure 4.5**). However, data from a total of 62 wells drilled in the deeper part of the Bengal basin indicate significant variations in geothermal gradient across the basin. In the deeper part of the basin, depths of the petroleum

exploratory wells range from 2,100m to 4,977m. The geothermal gradient of these wells ranges from 15.8°C/km to 30°C/km.

In the stable shelf area, temperature data from deep exploratory wells show higher geothermal gradients than the deep basin area to the southeast. Sedimentary thickness in the stable shelf varies from 130 m (Rangpur saddle) to 7 km (Bogra shelf) above a granitic Precambrian basement (Bakhtine, 1966). The geothermal gradient calculated for stable shelf area varies from 21.1°C/km to 31.6°C/km (**Figure 4.5**). In Maddhyapara hard rock mine (near Barapukuria coal mine), the 130-meter-thick sedimentary section above the Precambrian basement has a geothermal gradient of 13.3°C/km, whereas the geothermal gradient increases to 32°C/km in the basement rocks.

A temperature–depth profile was constructed for the Bengal basin by adding new data to Matin et al. (1982) diagram (**Figure 4.6**). A linear trend line suggests that the average temperature gradient for the selected wells is 30.35°C/km (**Figure 4.6**).

Based on the above data Hussain (2010) and Guha et al (2010) established geothermal gradients for various basinal areas of Bangladesh (Figure 4.3, **Figure 4.4** and **Figure 4.5**). The variance in geothermal gradients from deep basin wells (example: Rashidpur-1), wells in the Fold Belt (Example: Siltakund-5), and Singra-1 at the Bogra Shelf is evident. The different attitudes of the thermal gradient are related to the thermal conductivity of the local lithologies at depth. The proceeding information presented in this chapter has been mainly derived from Guha et al. (2010).

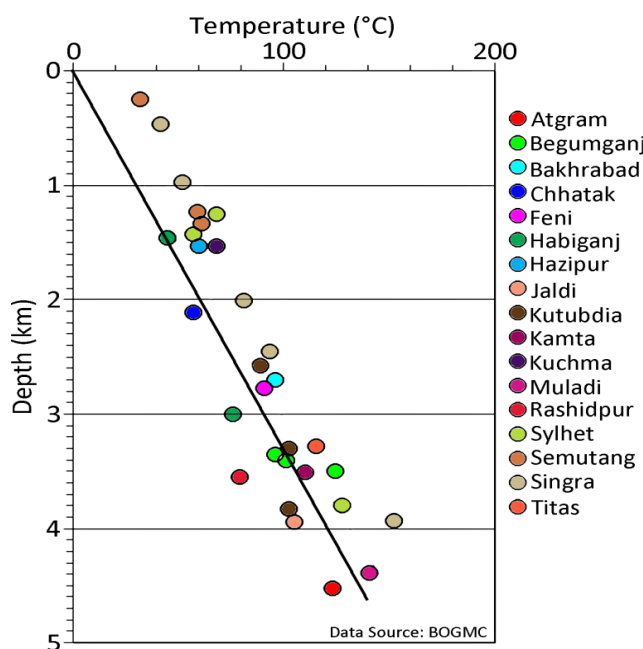


Figure 4.4: Average Geothermal Gradient in Bengal Basin(BAPEX, and Matin et al., 1982)

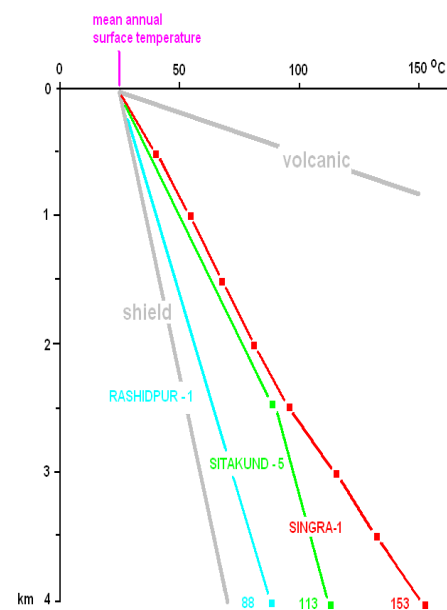


Figure 4.5: Characteristics Geothermal of Basinal Areas (After BAPEX and Matin et al., 1982)

The geothermal gradients calculated from bottom hole temperatures in the well logs of 62 wells have been utilized by Guha et al (2010) to develop a geothermal map of Bangladesh. The map shows distribution of temperatures at three km depth.

The map (**Figure 4.6**) shows that deep wells in the Bogra Shelf are the primary target for further investigations of their geothermal energy potential and establishing geothermal power plant. The following details of geothermal energy in different parts of Bangladesh have been derived from Guha et al., 2010.

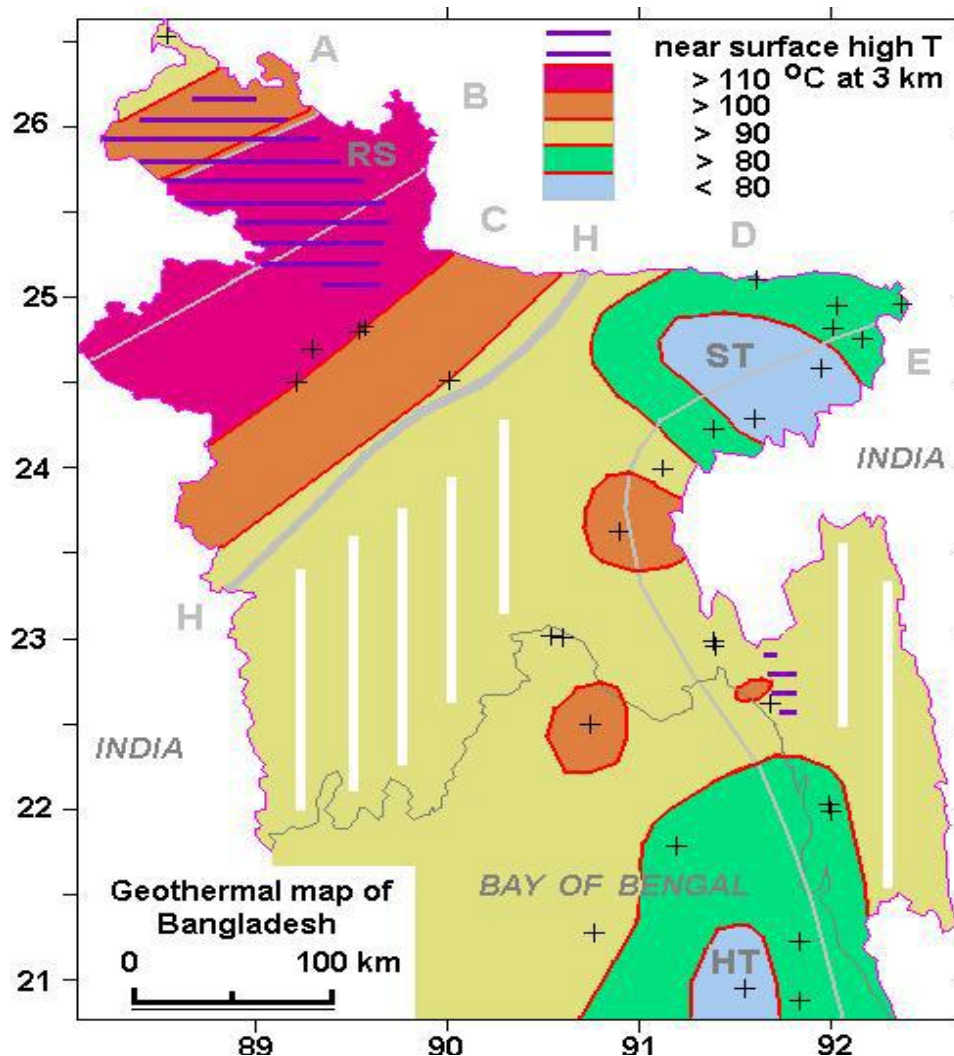


Figure 4.6: Geothermal Map of Bangladesh at 3 km Depth. (After Guha et al., 2010)

4.4 Geothermal Prospects of Sub-himalayan Foredeep

The Himalayan Foredeep lies south of the Main Boundary Thrust (MBT) all along the foothills of the Himalayas. In this area at the NW tip of Bangladesh the basement occurs at 2,500m depth as encountered in Salbanhat-1 well. At this depth 79°C bottom hole temperature is recorded. The Neocene of the Siwaliks are well developed in the Himalayan Foredeep and attains

As there are no deep wells in the region, the temperatures at depth in the crystalline basement are unknown. To establish a representative temperature profile, a test drill hole depth would be required. To assess the geothermal potential of the region in addition permeability tests are required for the basement rocks.

The Rajmahal Traps are similar to the Deccan traps in composition and vary from dolerite to basalt in texture. The Traps extend to the east and south east below the Gangetic plain. The sequence comprises of 500-700m of bedded basalts or dolerites with 35m thick inter-stratified sedimentary beds (inter- trappean beds) of siliceous and carbonaceous clays and sandstones. The shales have turned procellanoid-like due to heat while in contact with the basalt flows. Basaltic volcanic rocks of Rajmahal Traps have been penetrated in boreholes at Kansat, Patnitola, Singra (68m) and Kuchma (70m), also signify high paleo-temperatures in the region.

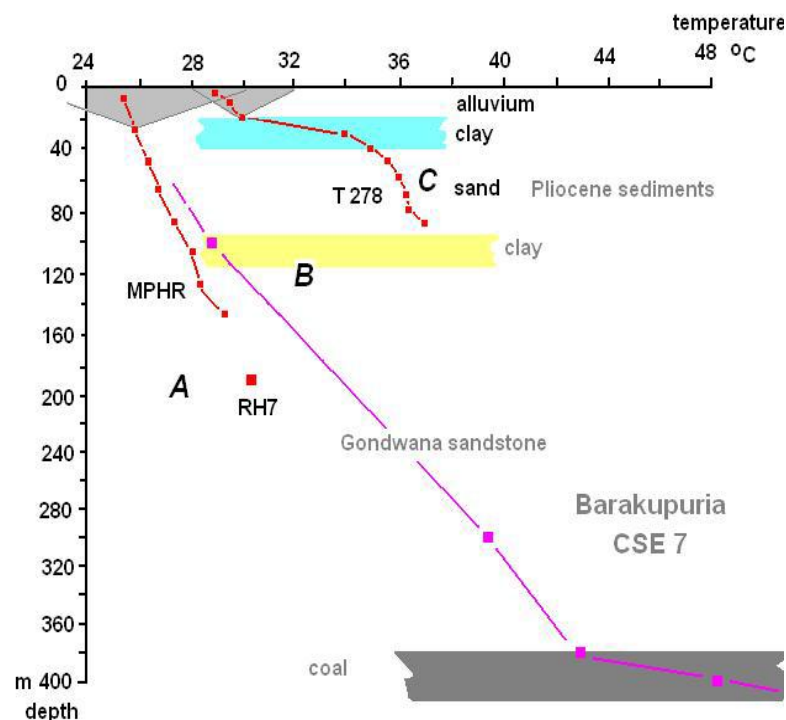


Figure 4.8: Near surface temperature profiles in: **A)** Madhyapara (alluvium, clay, sandstone, hard rock, not shown), **B)** Barakupuria (Pliocene sediments (clay yellow), Gondwana sandstone and coal beds (dark gray)), and **C)** Thakurgaon (alluvium, clay (blue), sand, that illustrate the high near surface temperature regime in the Rangpur Saddle (After Guha et al., 2010). It may be noted that the Geological Survey of Bangladesh drilled a well at Thakurgaon in 2011 up to the depth of 561m and recorded 44.75°C temperature at 560m depth.

4.6 Geothermal Prospects of Bogra Shelf

The Bogra Shelf represents the southern slope of the Rangpur Saddle. It is a regional monocline plunging gently towards south east towards the Hinge zone and marks the transition between the Rangpur Saddle and the Bengal Foredeep from depositional as well as structural point of view. The width of Bogra Shelf varies from 60- 125km up to the Hinge Zone and the thickness of the sedimentary sequence increases towards the Southeast. Stanvac Oil Company (SVOC)

carried out aero-magnetic and seismic surveys in the mid-fifties followed by drilling two wells at Kutchma and Bogra. Four deep wells have been drilled in the Bogra slope at distances of 22 – 26km: Singra to the southwest, Bogra to the northeast and Kuchma in between. The litho-stratigraphic correlation between these wells is shown in **Figure 4.9**.

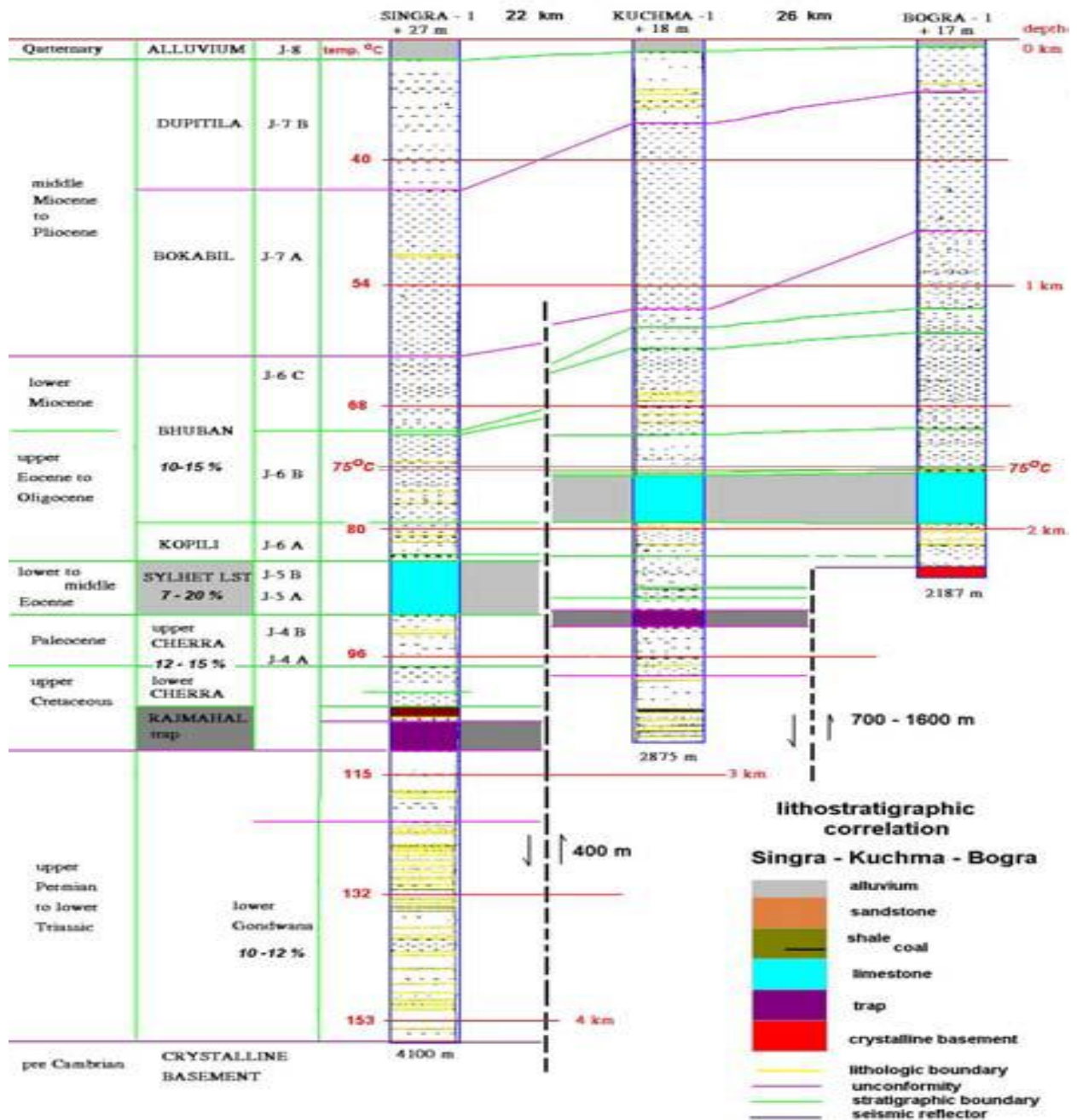


Figure 4.9 : Litho-stratigraphic correlation between the wells Singra, Kuchma and Bogra, showing vertical displacements related to faulting and the occurrence of potentially permeable lithologies at depth where temperatures are above the minimum required for electricity production. (After Guha et al, 2010).

Geothermal gradient in the Kutchma well (TD 2,875m) has been calculated at 27°C/km indicating temperature of more than 100°C at 3 km depth. The Bogra-1 well (TD 2,187m)

showed the bottom hole temperature and interpreted geothermal gradient 30°C/km. The Singrawell (TD 4100m and geothermal gradient 30°C/km) drilled by Petrobangla in 1981 is the deepest well ended at the top of the basement. Borehole EDH-4 at Jaipurhat penetrated basement (11m) on which laid younger stratigraphic succession. The litho-stratigraphic columns show that faulting took place in the Singra – Kuchma – Bogra area with vertical displacements of about 400 m between Singra and Kuchma occur with respect Sylhet limestone marker horizon. Rajmahal Trap is absent in Bogra while it occurs in Kuchma at a depth of 2.3 km and here the vertical displacement between Kuchma and Bogra is about 700m, restricted to the stratigraphy below the Sylhet Limestone and Cherra formation.

The geothermal gradients observed at Singra, Kuchma and Bogra are very similar and reach up to 31 °C/km (see **Figure 4.5** and **Table 4.2**). In this region, potential geothermal energy resources are in the Sylhet Limestone, the Cherra and Gondwana sequences.

Table 4.2: Temperature Data Collected from Exploration Wells Located in the Eastern Bengal Basin

Well Name	Longitude	Latitude	Estimated Temperature at				Geothermal Gradient (°C/km)
			1 km	2 km	3 km	4 km	
ARCO-1	90.72861	21.25748	45.7	68.9	91.5	115.0	23.1
Atgram-1	92.32978	24.99588	41.8	61.0	80.5	100.2	19.5
Bakhrabad-2	90.88885	23.61639	54.0	84.0	114.0	144.0	30.0
Beani Bazar	92.13679	24.75859	43.0	62.5	81.8	101.0	19.3
BINA-1	91.43665	20.99455	42.2	56.4	73.0	89.5	15.8
BODC-1	91.88177	20.83720	44.0	64.0	84.0	104.0	20.0
Bogra-XI	89.40175	24.93491	52.0	82.0	112.0	142.0	30.0
Cox's Bazar	91.79688	21.15396	47.0	70.0	93.0	116.0	23.0
Fenchuganj-2	91.87305	24.59348	39.5	57.5	75.5	93.5	18.0
Feni-1	91.40912	22.97042	47.5	71.0	95.0	119.0	23.8
Feni-2	91.39715	22.95150	45.0	66.0	87.0	108.0	21.0
Habiganj	91.38514	24.20239	44.0	64.0	84.4	104.4	20.1
Hazipur	90.08885	24.58864	43.5	66.2	89.5	112.2	22.9
Jaldi-1	92.08836	22.09958	44.0	64.0	84.0	104.0	20.0
Jaldi-3	92.11399	22.07280	46.5	69.0	89.8	114.3	22.6
Kailashtila	91.93514	24.81257	43.0	61.0	79.5	98.0	18.3
Kuchma-XI	89.14137	24.78355	54.0	81.0	109.0	136.0	27.3
Kutubdia-1	91.16751	21.89365	43.0	62.5	81.5	101.0	19.3
Muladi-1	90.42365	23.13880	47.0	67.8	88.0	108.8	20.6
Muladi-2	90.44021	23.13604	47.0	67.8	88.0	108.8	20.6

Well Name	Longitude	Latitude	Estimated Temperature at				Geothermal Gradient (°C/km)
			1 km	2 km	3 km	4 km	
Patharia-5	92.11238	24.52117	44.0	64.5	85.0	105.0	20.3
Rashidpur-1	91.61837	24.28692	39.9	56.0	72.2	90.4	16.8
Saldanadi-1	91.12409	23.66647	54.0	81.0	109.0	137.0	27.7
Shabajpur-1	90.73006	22.49287	48.5	78.5	108.5	138.5	30.0
Shalban Hat	88.40022	26.55273	47.8	68.5	90.0	111.0	21.1
Singra-1	89.03430	24.57387	53.0	85.0	116.0	147.8	31.6
Sitakund	91.64103	22.64745	49.0	72.0	95.5	118.0	23.0
SyLesser Himalayaet-7	90.97508	23.82465	44.0	63.0	83.5	103.0	19.7
Titas-11	91.18971	24.04294	48.5	72.5	97.0	122.0	24.5

Source: BAPEX (After Hossain, M.S.2009)

Table 4.3: Temperature Data Collected from Exploration Wells

Well Name	TD (m)	Geothermal Gradient (°C/km)
Hazipur	3,816	30,9
Bakhrabad- 1	2,837	25,0
Kamta	3,614	30,7
Titas -1	3,758	30,1
Habigonj-1	3,509	31,6
Rashidpur 1	3,861	26,8
Fenchugonj 1	2,439	28,3
Patharia 5	3,356	34,6
Biani Bazar 1	4,107	28,7
Kailas Tila 1	4,139	27,8
Atgram	4,959	27,8
SyLesser Himalayaet 1	2,377	31,1
Chhatak 1	2,133	33,8
Jaldi 3	4.500	28,0
Semutang 1	4.088	30,3
Muladi 1	4.732	25,1
Begamganj 1	3.656	31,7
Feni 1	3.200	35,6
Lalmai 2	4.115	30,1
Patiya 1	3.104	37,4

Source: BAPEX (After Guha, et. al. 2005)

4.7 Geothermal Prospects of Deep Sedimentary 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 trending SSW-NNE from Sylhet-Mymensingh-Pabna. It is bound by the Bogra Shelf (or south slope of the Rangpur Saddle) by the seismic depth of 3500 m to the top of the Eocene Sylhet Limestone. The seismic depth of 5000m of the Sylhet Limestone is the south-eastern boundary of the Hinge Zone, also known as the Hinge Line. The dips increase from 3-5° in the shelf monocline to 15-20° in the Hinge Zone as evident from Sylhet Limestone. The Hinge Zone is possibly tectonically related to a deep seated basement fault that probably started with the breakup of the eastern Gondwana continent. The Sylhet Limestone reflector can be traced into the basin clearly up to 6500m depth and flattens below 5000m depth. In the northeast, Hinge Zone is connected with the Dauki Fault by a series of west-east trending faults.

The Faridpur Trough situated adjacent to Hinge Zone and is characterized by a general gravity low and the development of Neogene sequences. The Sylhet Limestone is at 6500m depth in area south of the confluence of the Padma and the Jamuna rivers. The Barisal-Chandpur High is a tectonic zone of uplift. Located between the Faridpur Trough and the Hatiya Trough of the Bengal foredeep, the Barisal-Chandpur High is characterized by general gravity maxima with SW-NE trend. The width of the zone is about 60km and corresponds to an uplift of the sedimentary cover.

The Hatiya Trough represents the deepest trough of the Bengal Basin and has received the highest accumulation of clastic sediments. The axis of the Bengal Foredeep runs through the apex of the Hatiya Trough. Shahbazpur (Bhola), Kutubdia, Sangu and a number off-shore anticlinal structures are located here, of which Sangu is under hydrocarbon production while Shahbazpur and Kutubdia are awaiting development.

The Madhupur High is a Pleistocene terrace separating the Faridpur Trough from the Sylhet Trough (Surma Basin). Here the basement is relatively uplifted as evident from gravity and aeromagnetic data. Morphological studies reveal a pronounced recent morphological upheaval east of Madhupur. The Nagarpur dome and the Nandina high are regarded as protrusions from the basement without deforming the sedimentary sequence overlying these features.

In the deep sedimentary basin the average geothermal gradient is about 20°C /km, and less, which is rather low and therefore of limited interest for geothermal resources, unless the abandoned wells are extremely deep.

4.8 Geothermal Prospects of Folded Belt

The Folded Belt (or the folded eastern flank of Bengal Foredeep) represents the most prominent tectonic element of the Bengal Foredeep, with general sub-meridional trending hills parallel to the Arakan Yoma Folded System. The Folded belt extends S-N within Bangladesh for 450 km and is about 150km wide, covering an area of 35 000 square km of on-shore area. The folds are characterized by ridges, box-like in cross section with variable width and high amplitude,

oriented enechelon with the adjacent structures. The elevation of these elongated anticline folds ranges from 100 to 1,000m in Bangladesh. Some of the structures are faulted and thrust and the intensity of folding increases gradually from west to east. Consequently the structures of the eastern part are tightly folded, faulted and thrust with narrower synclines between them. The Neogene sedimentary sequence developed here are largely un-fossiliferous and consists mainly of the alteration of shales, clays, clay stones, siltstones and sandstones with occasional intra-formational conglomerates which can be subdivided into 9 formations on the basis of lithology (Kitovani and Guha 1965).

The Paleocene sediments are subsided to greater depths and have not been encountered in any well except in Atgram IX (Reiman 1986). The depth of basement is not known but can be of the range of ca 20 km. The Folded Belt is sub-divided into a *Western Zone* and an *Eastern Zone* according to the intensity of folding and other structural features. The *Western Zone* consists of a large number of relatively simple anticline structures with 27 known structures in Bangladesh (ten in adjacent regions of India and 3 in Myanmar). The Western Zone is the most important and prospective oil and gas province of Bangladesh with 12 fields from Kailas Tila in the north to Semutang in the south.

Hot springs have been observed at Barbarkund and Gobaniya Chara in the Sitakund anticline with temperatures of up to 35°C. (Guha and Henkel 2005). In the Sitakund well 5, the geothermal gradient is 25°C per km. In the sedimentary sequence to 2.3 km depth, consisting of mainly shales, the gradient is slightly higher, indicating a lower thermal conductivity and hence an insulating effect to warmer and deeper formations. In the Bakhrabad well 1, the geothermal gradient has been found at 30°C per km-1 (Kabir 2008). The geothermal gradient for Sitakund-5 is seen in **Figure 4.5**.

The Eastern Zone includes 11 more steep folded and faulted anticline structures in Bangladesh. The anticline structures can turn out to be of significance geothermal energy prospects as there are many deep dry wells with high temperatures.

4.9 Conclusions and Recommendations

Bangladesh is facing an acute energy scarcity which is hampering its industrial growth and economic progress. Setting up of new power plants is inevitably dependent on import of highly volatile fossil fuels. Thus, it is essential to tackle the energy crisis through judicious utilization of abundant renewable energy resources, such as biomass, solar, wind and geothermal. Bangladesh is heavily dependent on fossil fuels for its energy needs. Most of the power generation is carried out by coal and mineral oil-based power plants which contribute heavily to greenhouse gases emission.

Geothermal studies so far carried out in Bangladesh indicate that the country is ideally suited for further detailed studies to tap the geothermal energy by carrying concentrated effort to fully explore the potential of the country particularly in Bogra Shelf and Rangpur Saddle areas.

Guha et al. (2005) have suggested utilization of deep abandoned oil and gas wells for production of geothermal electricity for meeting the requirements of rural population of Bangladesh (**Table 4.3**). Accordingly they have also recommended use of efficient pumps for cooling the buildings and heating for warm water production.

Considering the economic conditions of the country, there is need for transition from petroleum-based energy systems to one based on renewable resources in general and geothermal in particular. This would help to decrease reliance on depleting reserves of fossil fuels and to mitigate climate change. In addition, geothermal energy has the potential to create many employment opportunities at all levels, especially in rural areas. An emphasis on presenting the real picture of geothermal energy potential, it would be possible to attract foreign investments.

Exploration of geothermal energy resource should be given emphasis as it is environmental friendly, continuously available, independent of weather variations. The geothermal exploration cost be reduced by using the existing/abandoned on-shore dry wells where the geothermal gradient is sufficiently high (like over 30°C/km) and where porous and permeable reservoir sandstones are penetrated.

The tectonic and geothermal maps of Bangladesh clearly demonstrate a pattern of geothermal conditions in Bangladesh. Accordingly the work of Guha et al (2010) suggests occurrence of geothermal potential of the various tectonic element by using the data of available information derived from deep abandoned exploratory wells.

The Sub-Himalayan foredeep in NW Bangladesh is barely feasible to explore for geothermal energy due to limited data from one deep drill hole exhibiting relatively low thermal gradients.

The Rangpur saddle. This area is characterized by relatively high surface temperatures reported from some irrigation wells, in coal bearing graben structures and underground hard rocks mine. The geothermal resource is likely located within the uplifted basement and would require hydraulic fracturing methods to create permeability at depth with sufficient high temperature for present technology of electricity generation. As fairly high temperatures may be reached at reasonable drilling depth, further study of the region is recommended by pilot drill holes to ca 1 km depth to establish a proper geothermal gradient.

The Bogra Shelf, with the deep wells at Singra, Kuchma and Bogra potentially offers such favorable conditions for geothermal energy. The Singra well with over 150 °C bottom hole temperature is the most promising of the three areas and a feasibility study is part of the ongoing project. The porosity of Bhuban sandstone, Sylhet limestone, Cherra sandstone and Gondwana sandstone varies from 7-20%. The permeability needs to be ascertained from cores of the Singra well regarding the Lower Bhuban to Gondwana sandstones. Similar studies should also be done for the cores of the Kutchma and Bogra wells. Additional reflection seismic lines may also needed in the Singra and Kuchma areas for the assessment of available volumes for geothermal energy.

The Deep Basin areas are continuously loaded with cool sediments and the geothermal gradients are very low. Despite some deep drill holes, they are barely feasible to explore for geothermal energy with present technology for electricity generation.

Further mapping of the margin of the Folded Belt may be rewarding as local tectonic structures, occurrence of hot springs, and relatively high geothermal gradients indicate suitable conditions for geothermal energy exploration.

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CHAPTER – 5

GEOTHERMAL RESOURCES OF BHUTAN

5.1 Geological Framework

The fundamental geological appraisal of Bhutan carried out by Gansser (1983) paved way for some interesting researches by a number of professionals from all over the world. Among lot of the geogists worth mentioning are Long, S.P., McQuarrie, N., Tobgay, T., Grujic, D., and Hollister, L, Whynot, N. M.P. Searle, J.M. Cottle, M.J. Streule, and D.J. Waters etc (See references).The details on the stratigraphic and Structural description of Bhutan has been extracted from the paper entitled “Preliminary stratigraphic and structural architecture of Bhutan: Implications for the along strike architecture of the Himalayan system” by Nadine McQuarrie, Delores Robinson, Sean Long, Tobgay Tobgay, Djordje Grujic, George Gehrels, Mihai Ducea.

5.1.1 Bhutan Stratigraphy

The stratigraphy of Bhutan is explained in term of the following tectonostratigraphic units.

Sub-Himalaya

The Sub-Himalaya of Bhutan (**Figure 5.1**) is characterized by the discontinuity of the Siwalik Group along strike. Consequently the map pattern of synorogenic sediments is patchy, with 20–40 km portions of the belt either covered by Quaternary sediments, or overridden by the Main Boundary thrust (MBT) or apparently never deposited (Gansser, 1983). The most complete Siwalik Group section is in eastern Bhutan where It is 4-6km thick and dips consistently northward at 30–40°. The entire package is generally coarsening upward sequence from clays and silts in the lowest portions of the section exposed just north of the Main Frontal thrust (MFT), to fluvial siltstone and sandstone in the middle sections grading to sandstones and gravelly braided river deposits in the upper sections.

Mapping from Gansser (1983), Gokul (1983), Bhargava (1995), Hollister and Grujic (2006), and McQuarrie et al, 2008. Dolomite lenses (grey) are from Gansser (1983) and indicate presence of the Baxa Group. Location of Diuri formation to the west of ransect is from Bhargava (1995). The folded Shumar thrust is inferred from Bhargava (1995) and Gokul (1983). Strike and dip symbols indicate mapping and blue dots are sample locations discussed in text; Greater Himalayan Sequence, MCT, ain Central thrust, MBT, Main Boundary thrust, MFT, Main Frontal thrust. (After McQuarrie et al, 2008).



Figure 5.1: Geological Map of the Bhutan Himalaya (after Gansser 1983)

Lesser Himalaya

Lesser Himalayan rocks in Bhutan have historically been divided into four units (Gansser, 1983; Bhargava, 1995; Gokul, 1983). Although lack of fossils and radiometric age dates have led to confusion regarding the exact stratigraphic order (Gansser, 1983; Bhargava, 1995), recently conducted field studies as well as preliminary geochronology and isotope geochemistry data allowed to delineate the relative ages of the Lesser Himalaya from following oldest to youngest groups (McQuarrie et al., 2008).

Daling–Shumar Group

The Daling–Shumar Group was named by Gansser (1983) correlating with phyllitic Daling Formation identified in Sikkim–Darjeeling (Sengupta and Raina, 1978) and the quartzite rich Shumar Formation in eastern Bhutan (Jangpangi, 1974, 1978). McQuarrie et al., 2008 divided the Shumar–Daling Group in Bhutan into 2 distinct formations, the Shumar Formation quartzite and the overlying Daling Formation phyllite. An entire Shumar–Daling Group section is exposed in the Kuru Chu valley (**Figure 5.2**).

The basal unit of the Lesser Himalaya in Bhutan is the Shumar Formation quartzite of varying thickness from west to east Bhutan with maximum thickness of 6 km in the Kuru Chu valley. It is a well-bedded, medium to thickly bedded, white to greenish grey, fine-grained, re-crystallized quartzite with thin to 3 m thick interbeds of phyllite or schist. The Shumar Formation often forms several-hundred-meter-high cliffs.

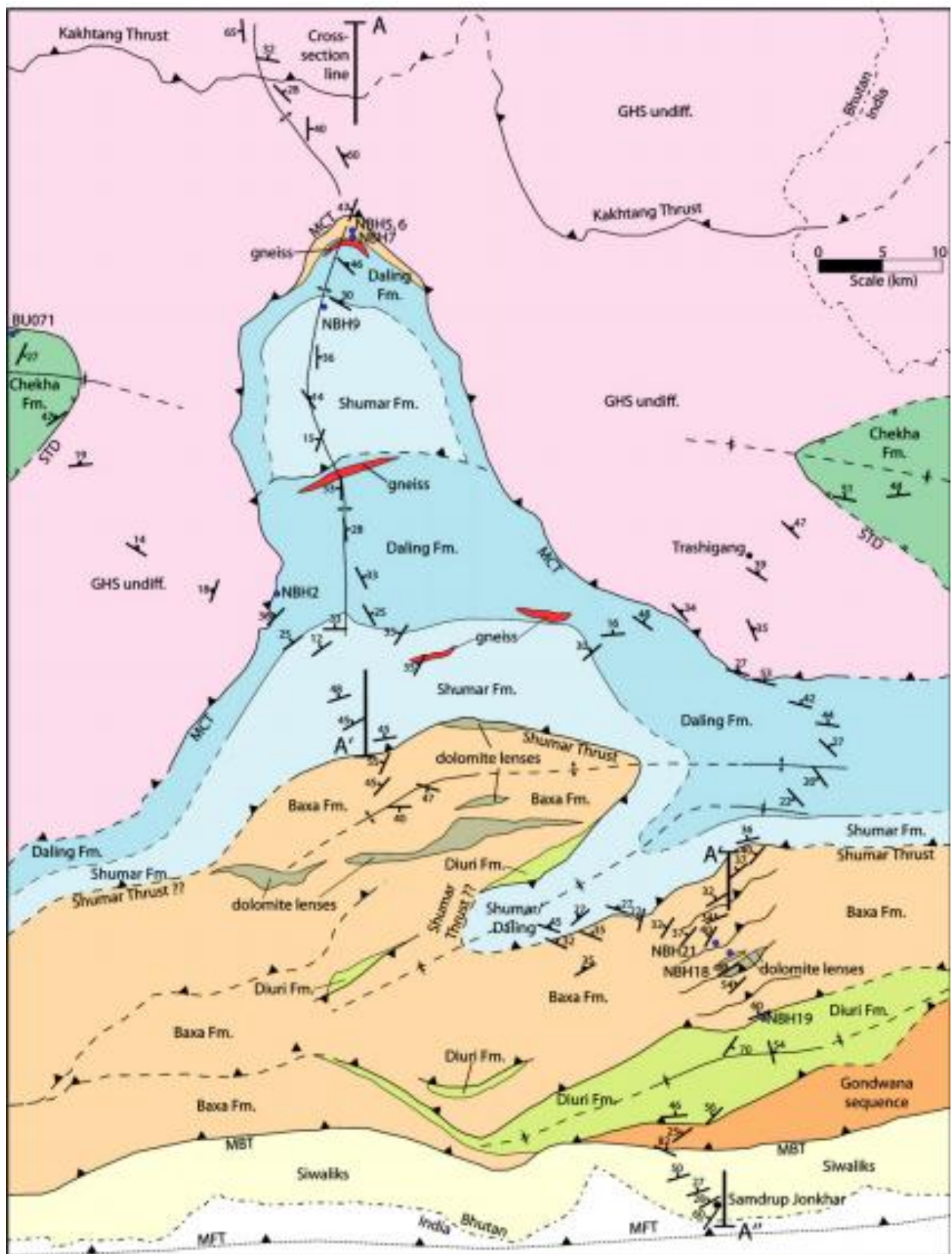


Figure 5.2: Geological Map of the Kuru Chu Valley, Bhutan

The Daling Formation overlying the Shumar Formation with a transitional contact is 4km thick dominantly chloritic to sericitic schist (in the north) and becomes more phyllitic to the south.

Intercalated quartzite beds, common especially near the base of the unit, range from a clean, white, fine-grained rock with 5–10cm thick lithic-rich beds. Sedimentary structures include ripple marks and planar cross-beds. The schist and phyllite display irregular and scaly foliation with common quartz veins and blebs. The Daling Formation rarely forms cliffs but rather has a characteristic blocky weathering.

Baxa Group

The Baxa Group is broadly comprised of white to buff, gritty to pebbly quartzite, meta-siltstone, greenish grey to grey slate, and massive to bedded, grey to yellow dolomite and limestone (Tangri, 1995a). Tangri (1995a) divided the Baxa Group into 4 formations (Pangsari, Phuntsoling, Manas and Jainti Formations) with the various formations most likely representing significant lateral variations during deposition. For simplicity, the Baxa Group nomenclature is used to refer to all Baxa formations. In the Kuru Chu valley, the Baxa Group is primarily a massive cliff forming quartzite. It is a fine- to medium-grained gritty quartzite, locally pebbly to conglomeratic and contains distinct clasts of jasper and rose quartz. Intercalations of light to dark grey phyllitic slate and non-persistent limestone–dolomite horizons are common. Dolomite horizons are lenticular in map view and may represent patch reefs deposited in a deltaic environment. Quartzite beds are lenticular, often separated by thin beds of shale and display ubiquitous trough cross bedding. The road from Trashigang to Sandrup Jonkhar exposes an 11 km thick consistently northward dipping section of Baxa Group rock. We propose that the minimum thickness of the Baxa Group is 2.5 km, but is tectonically repeated along 5 thrust faults.

Diuri Formation

The Diuri Formation is ~2–2.5km thick diamictite with interbedded slates which overlies the Baxa Group (Gansser, 1983; Jangpangi, 1974; Tangri, 1995b). The Diuri Formation contains pebbly shale, slate and minor sandstone. Pebbles vary from 0.5 to 5 cm and are sub angular to well-rounded. Clast types include white and dark grey quartzite, white vein quartz and yellowish dolomite. Groundmass shows clear schistosity.

Gondwana Sequence

This sequence of Feldspathic sandstone, siltstone, shale, coal lenses and plant fossils was initially designated as the Damuda Formation and later correlated to the Gondwana Super group (Lakshminarayana, 1995). In Bhutan both the northern and southern boundaries of the Gondwana sequence are faulted making its initial relationship to older units uncertain. However, the stratigraphic age of the unit is Permian (Lakshminarayana, 1995). Along the road to Sandrup Jonkhar the Gondwana Sequence contains finely-laminated, dark, salt-and-pepper sandstone and quartzite, coal seams and carbonaceous shale and slate. Sandstone and quartzite have thick- to massive-bedding. Total thickness of the Gondwana sequence is ~2 km.

Greater Himalaya

Much of Bhutan is dominated by exposed Greater Himalayan rock, which crops out over a north–south width of 60–100 km between the STD and the MCT (**Figure 5.1**). Greater Himalaya

rocks in Bhutan are composed of paragneiss, orthogneiss, (increasingly migmatitic in the higher structural levels) schist, quartzite, Miocene age leucogranites, and less common marble and amphibolite layers. In the Kuru Chu valley, the MCT places Greater Himalaya augen gneiss (with leucosomes) over Lesser Himalaya quartzite and pelitic schist (2 mica +quartz+lithics +/-garnet) in the footwall. Within Greater Himalaya rocks, paragneiss and quartzite become more common up-section until the Kakhtang thrust which places migmatite over garnet-staurolite schists (Davidson et al., 1997; Grujic et al., 2002; Daniel et al., 2003).

5.1.2 Structural Geology

Lesser Himalaya from the MCT to the MBT provides the first order structural framework of this portion of the eastern Himalayan orogen. To help interpret the structures a composite balanced cross-section (Figure 5.3) and geologic maps (**Figure 5.1** and **Figure 5.2**) compiled by Gansser (1983), Gokul (1983) and Bhargava (1995). The cross-section is line-length balanced (Dahlstrom, 1969), without incorporating small-scale deformation that characterizes some of the stratigraphic units and brittle and ductile deformation with Greater Himalaya rocks. No subsurface data are available for this region except the deep crustal reflection seismic profile of IN-DEPTH (Hauck et al., 1998) and broad-band telesesimic data (Mitra et al., 2005) which broadly constrains the dip of the Main Himalayan decollement. As is typical through most of the Himalaya, the hanging wall cut-offs of the thrust sheets are not preserved. However, the southward extent of Greater Himalaya over lower Lesser Himalaya rock and the southward extent of lower Lesser Himalaya (Daling–Shumar) over upper Lesser Himalaya rock (Baxa Group) limit the magnitude of slip that can be proposed for this region on faults below the MCT. With these considerations, the cross-section (**Figure 5.3**) should be viewed as initial attempt that will undoubtedly be changed as new data become available.

5.1.3. (i). Siwalik Group

The Siwalik Group outcropping immediately north of Samdrup Jonkhar is an ~8 km north–south exposure of northward dipping rocks with dips varying between 25° and 65° with most dips clustering between 30° and 40° northwest. The section is not repeated by faults although some meso-scale folds with gently west plunging fold hinges are present in the finer-grained units near the base of the section. The Siwalik Group was interpreted as a continuous 6 km thick section uplifted by motion along the MFT. The magnitude of slip (9 km) is the minimum required to move the hanging wall cut-off (which, if exposed, would be southward dipping rocks) through the erosion surface (**Figure 5.3**).

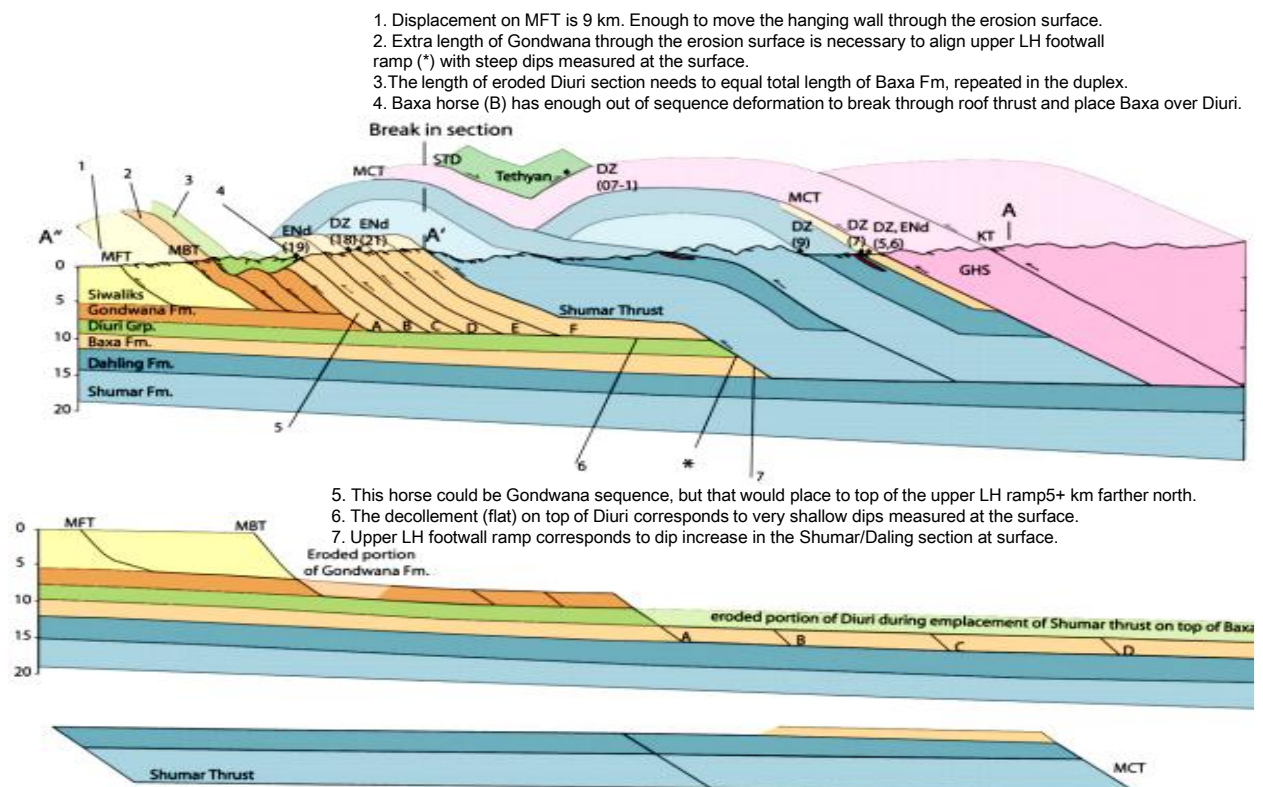


Figure 5.3: Balanced Cross-section of the Kuru Chu Region, Bhutan

Note: MFT: Main Frontal Thrust; MBT: Main Boundary Thrust; MCT: Main Central Thrust
STD: South Tibetan Detachment, KT: Kakhtang Thrust

5.1. 3. (ii). Upper Lesser Himalaya

In the hanging wall of the MBT, a 2.5 km wide surface exposure of steeply northward dipping (40°–86°) Gondwana sequence rocks is followed northward by a 9 km wide exposure of gently folded Diuri Formation. The extra length of the Gondwana sequence shown above the erosion surface (**Figure 5.3**, #2) is needed to align footwall ramps in the upper Lesser Himalaya with a change in apparent dips measured at the surface from very shallow dips ~10° to N30° (footwall ramp identified on the cross-section with a symbol of □). The two thrust sheets of Gondwana sequence rocks shown in the cross-section fill space between Diuri Formation exposed at the surface and its projected location in the subsurface as well as provide a mechanism for passively folding the Diuri Formation. The broadly synclinal nature of the exposed Diuri Formation implies that much of the original section of Diuri (a length equal to the cumulative length of Baxa Group to the north) has been removed by erosion (**Figure 5.3**). It was proposed that the last thrust sheet underneath the Diuri syncline is composed of Baxa Group rock, because making that thrust sheet Gondwana sequence rock would push the footwall cut-offs of the upper Lesser Himalaya 5+ km to the north, which is in compatible with the surface geology (**Figure 5.3**, #4). An 11 km thick section of consistently northward dipping Baxa Group was mapped (**Figure 5.2**). This is unreasonably thick for a simple stratigraphic section. We use field observations of a ~2.5 km thick section of Baxa Group in each limb of an anticline immediately south of the Shumar thrust (**Figure 5.2**) and prominent ENE to WNW valleys and

saddles spaced ~3 km apart along the Trashigang–Samdrup Jongkhar road to support dividing the Baxa Group into 5 additional thrust repeated sections.

5.1. 3. (iii). Lower Lesser Himalaya

The sedimentary package of Shumar–Daling Group with augen gneiss intrusions in the upper Daling Formation is repeated once along the upper Kuru Chu valley (**Figure 5.2** & **Figure 5.3**). Both thrust sheets carry an ~8–11 km thick section, comparable to the Lesser Himalaya thickness in the Arun River valley of eastern Nepal (Schelling and Arita, 1991). Apparent dips along the line of section describe northward dipping rocks (~45°) adjacent to the southern Baxa Group contact and then a long section (~30 km) where the apparent dips are very flat (~5°–10°) before significant northward dips are measured again, close to the northern Shumar–Daling Formation contact (**Figure 5.2** and **Figure 5.3**). This pattern of dips defines a ramp–flat–ramp geometry, where the southern ramp is related to the Baxa Group duplex system, the regional flat is above the Diuri Formation and the northern ramp is the regional ramp through upper Lesser Himalaya rock (**Figure 5.3**, #5). Maps of Bhutan (Gansser, 1983; Bhargava, 1995; Gokul, 1983) show lower Lesser Himalaya rock extending ~30 km farther south along the Kuru Chu valley (**Figure 5.2**). One explanation for this map pattern is a folded roof thrust of lower Lesser Himalaya rock (similar to the Ramgarh thrust identified in Nepal) (i.e. Pearson and DeCelles, 2005) over an upper Lesser Himalaya rock duplex system (**Figure 5.3**). The southern extent of the Daling–Shumar Group was used to the west to N (**Figure 5.3**). Balanced cross-section of the Kuru Chu region, Bhutan supports the extension of the Shumar thrust over the Baxa Group duplex. Black diamonds are sample locations with sample numbers. DZ is detrital zircon sample location, END is an $\epsilon\text{Nd}(0)$ sample location, MFT (Main Frontal thrust), MBT (Main Boundary thrust), MCT (Main Central thrust), STD (South Tibetan Detachment), KT (Kakhtang thrust). See Figure for location. Displacements on each of the thrusts in the lower Lesser Himalaya rocks are 35 km (northern thrust) and 56 km (southern thrust). All of the measured cross-beds in the Daling–Shumar Group indicate that strata are right side up from immediately in the footwall of the MCT to the Shumar thrust. These data combined with structural observations suggest that there is no large scale, tight to isoclinal folding of Lesser Himalaya rock near the MCT. Based on our DZ and ϵNd data, we suggest that there are upper Lesser Himalaya rocks stratigraphically above lower Lesser Himalaya rocks in the footwall of the MCT. The thickness of this unit is ~2 km. Comparing the stratigraphy of lower Lesser Himalaya rock from western Nepal (3–4.5 km (Robinson et al., 2006) to Eastern Nepal (11 km (Schelling and Arita, 1991)) and Bhutan (~8–11 km) initially suggests that a first order change exists in the stratigraphic thickness, which may result in shortening variations between the central and eastern Himalaya.

5.1. 3. (iv). Greater Himalaya

Pervasive ductile fabrics through the MCT in conjunction with mineral assemblages, thermo barometric datasets, and the widespread presence of migmatite and leucogranite in most exposures of Greater Himalaya rocks are used to support the idea that the rocks may have flowed at midcrustal depths (Davidson et al., 1997; Ganguly et al., 2000; Daniel et al., 2003; Hollister and Grujic, 2006; Searle and Szulc, 2005; Grujic et al., 1996; Hodges et al., 2001; Searle et al., 2003). The ductile fabrics throughout Greater Himalaya rocks emphasizes that any

estimate of displacement on the MCT is a bare minimum; however, the southernmost extent of Greater Himalaya rock from east and west of our line of section can be used to determine the absolute minimum displacement estimate of ~100km. On average, throughout Bhutan, the main foliation in Greater Himalaya rocks dips gently (~20–30°) to the north; however, the foliation is affected by long wavelength, low amplitude E–W and N–S trending folds. The interference of the two fold sets produces gentle basin and dome structures seen in the map patterns of the region (**Figure 5.1**). The Kuru Chu valley is the topographic expression of one of the prominent N–S trending antiforms in Bhutan. Normal fault bounded klippen of the TH Chekha Formation (Grujic et al., 2002) exposed east and west of the Kuru Chu valley, are preserved in the core of a prominent E–W trending synform (**Figure 5.1** and **Figure 5.2**). It was proposed that many of these map scale folds preserved in Greater Himalaya rocks are a result of duplexing of Lesser Himalaya rock at depth. That the Lesser Himalaya strata immediately below the MCT contains 500Ma zircon grains and Chekha Formation directly above the Greater Himalaya only contains grains as young as ~850 suggests that the MCT must have first been emplaced as a thrust over Baxa Group equivalents and that MCT displacement must be greater than STD displacement by ~100 km. North of the MCT the Kakhtang thrust places sillimanite bearing migmatite over lower grade paragneiss (Grujic et al., 2002; Daniel et al., 2003). It also cuts across penetrative fabrics and metamorphic isograds (Davidson et al., 1997). Like the MCT the minimum magnitude of displacement on the Kakhtang thrust it could be estimated. Assuming the Kakhtang thrust roots into the Main Himalayan thrust (Nelson et al., 1996), and that the hanging wall cut-off is immediately above the erosion surface, the minimum amount of displacement on the Kakhtang thrust is 33km (**Figure 5.3**).

location, MFT, Main Frontal thrust, MBT, Main Boundary thrust, MCT, Main Central thrust, STD, South Tibetan Detachment, KT, Kakhtang thrust. See (**Figure 5.2**) for location (after McQuarrie et al, 2008).

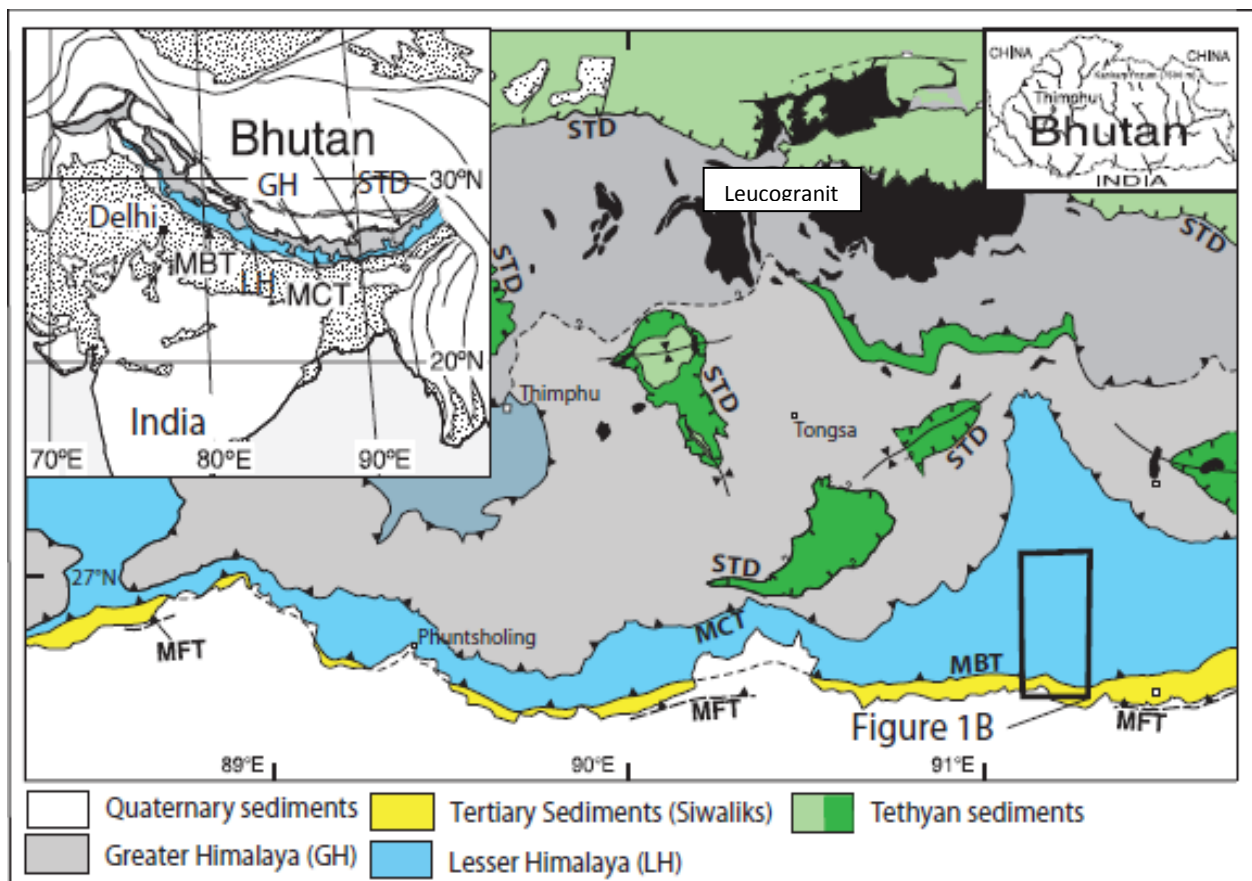


Figure 5.4: Simplified Geological Map of Bhutan Showing Occurrence of Leucogranite in the Greater Himalayan Sequence (After Grujic et al., 2002)

5.2 Surface Indications of Geothermal Energy

Occurrence of leucogranite in eastern part of Himalaya indicates metamorphic history of Bhutan. Earlier researchers believed in the intrusive origin of some igneous rocks, such as granite, which were believed to have been injected, in a molten state, into previously existing rocks; Further studies (Hallam 1983) led M.P. Searle (2010) to deduce the thermal history of the Himalaya involving following four stages during part of a 50 m.y. continuum

1. During initial stage of crustal subduction of leading edge of Indian Plate at > 100 km depth and 720-770°C at 46.4 Ma.
2. Crustal thickening resulted in 550-680°C at ca. 37-30 Ma
3. Wide spread metamorphism attaining temperature 620-770°C accompanied by partial melting and leucogranite formation at ca. 23-16 Ma.
4. Burial and thickening followed by heating, decomposition, partial melting and rapid exhumation and cooling.

As such leucogranites were generated during the Early Miocene along the entire 2200 km length of Greater Himalaya. Crustal melting occurred at relatively shallow depths of ca. 15-20 km depth (Searle et al, 2010).

Hot springs known as Tshachus in local language are found in most places in Bhutan and have been used for centuries to cure the Bhutanese of various ailments. Since long time it is a tradition for the Bhutanese to visit the hot springs during winter months.



Figure 5.5: Road Map of Bhutan Showing Important Locations in Bhutan

Potential of Punakha Area

Gasa dzongkhagis famous for its hot springs (tshachhu) known for their healing powers. In fact it's about the only attraction the country's remotest and poorest district can boast of. The hot spring at Gasa in western Bhutan is situated close to the banks of the Mo Chu River. Getting to Gasa hot spring is about ten hours trek from Punakha district or one can choose to travel half way by vehicle till a village called Damji. From Damji is about six hours trek till Gasa hot spring through beautiful hills of pine, bamboo and oak forests and small streams. On reaching a pass one can see a beautiful view of Gasa dzong (fortress) seated below snow covered mountain.

Located about two hours walk downhill from the dzong, beside the Mochhu River, Gasashachhu is believed to cure rheumatism, arthritis, ulcers, indigestion, skin diseases, even tuberculosis and other ailments. Results come if one soaks for more days.

The healing water attracts more than 7,000 visitors a year, most visit the hot springs in winter. Bhutanese, old and young, from far and near, with weeks' rations, converge at the Gasa tshachhu to seek the curative powers. The few houses around the tshachhu are occupied to the full and many pitch tents that sometimes number as much as 60. Some visitors stay for months. Experts say that the tshachhu is rich in sodium, potassium, calcium chloride and several other minerals.

Gasa Hot Spring has four main ponds of about three feet deep, of concrete and rock, all roofed, and each meant for different ailments. One pond can hold about 12 people each. There is also a pond to wash up before dipping. Regular visitors say that the Gasa tshachhu is cleaner than before.

The other well-known hot spring in Punakha area is the Chubu tshachu. It is located at 2,930m above sea level by the banks of the Pho Chu River. The hot spring is reported to contain water at 43-45 °C temperature. It can be reached within a day's journey from Punakha town. Chhubu hot spring can also be reached by a vehicle upto Walathang road head from where it takes two hours walk. The mountain trail gently passes through a chir pine forest into the cool, temperate mixed forest.

The hot springs at Nye in Kurtoe, Koma and Chuphu in Punakha and Dunbang in Zhemgang are also known to occur in the north western part of Bhutan but there are no details available.

Bumthang Area

In central eastern Bhutan in Bumthang area two hot springs have been reported. The Dur Tshachu is located in the village of Dur. These are considered to be the most beautiful natural hot springs in the Himalayas. The Duer Hot Spring Trek is a demanding nine day trek along the same route as the finishing of the Snowman Trek. As shown at **Figure 5.6** that some part of the track is motor able while from Gorsum upto the Duer Hot Springs it involves four long days with steep and long ascents.

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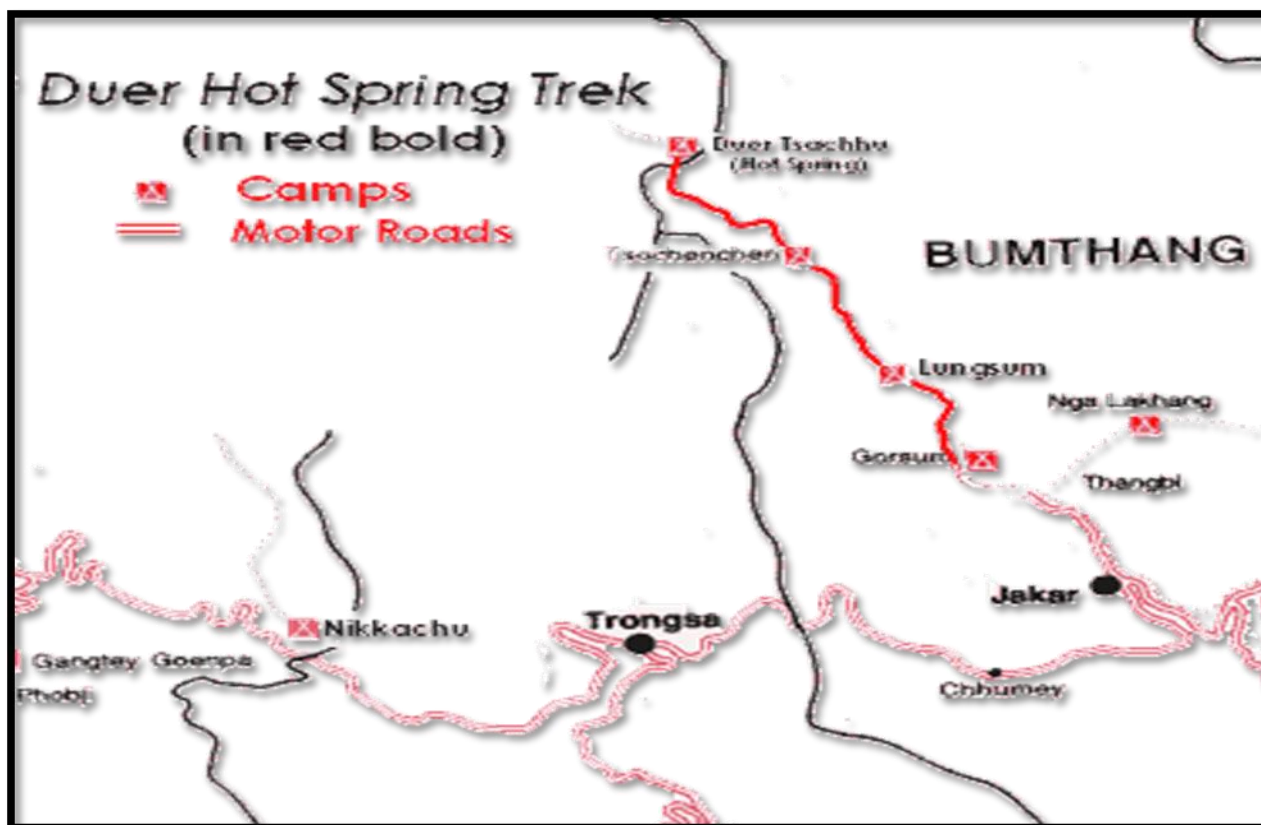


Figure 5.6: Route of Trekking for Duer Hot Spring

This tshachu also has been used for its medicinal value and are known to cure body aches. Then we have the Duenmang tshachu in Zhemgang. Situated by the banks of Mangde Chu River, Duenmang tshachu is also being frequented by the Khengpas and the rest of the Bhutanese population.

Gelephu Area

In southern Bhutan, hot spring is located near a stream in the foothills at distance of 15km from Gelephu the Tsachu is located. There are four proper ponds which are used as bath tubs for soaking by the people. The tshachu is mostly frequented by the local residents and in winter by the other Bhutanese people that take trips to get cure themselves of diseases. The Tsachu gets crowded from December to February every year. People from Trashiyangtse, Trashigang, Lesser Himalayautentse, Bumthang, Trongsa, Zhemgang and Thimphu alongwith people from eastern and western districts.

The following photograph shows the belief of the common Bhutanese about the medicinal values of the hot springs. It can also be deduced that the temperature of these springs is bearable for human body.



Figure 5.7: People Taking Bath in Hot Springs for Health Benefits

5.3 Conclusions

Although Bhutan has ample resources for development of its energy base through hydroelectricity, wind, solar and biomass, the use of geothermal may be utilized in the energy mix as most of the occurrences of geothermal are located in far flung and remote areas.

In this connection a scientific study is necessary for detailed evaluation of all the geothermal springs. As mentioned earlier that occurrences of leucogranites indicate that crustal melting occurred at relatively shallow depths of ca. 15-20 km depth during Early Miocene at about 15-20 km depth (Searle et al, 2010). These magmatic rocks are considered to generate sufficient heat energy for disseminating at shallow depths at places of their occurrence in Bhutan.

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CHAPTER – 6

GEOTHERMAL RESOURCES OF INDIA

6.1 Geological Framework of India

Geology of India is as diverse as its geography and people. It contains rocks covering almost the entire spectrum of the Geological Time Scale. The Indian craton was once part of the supercontinent of Pangaea and was attached to Madagascar and southern Africa on the south west coast and Australia along the east coast. During the Jurassic Period, rifting caused Pangaea to break apart into two supercontinents namely, Gondwana in the south and Laurasia to the north (International Commission on Stratigraphy; ICS 2004). The Indian craton remained attached to Gondwana, until the supercontinent began to drift apart about in the early Cretaceous (ICS 2004). The Indian Plate then drifted northward toward the Eurasian Plate, at a pace that is the fastest movement of any known plate. It is generally believed that the Indian plate separated from Madagascar about 90 Ma (ICS 2004), however some biogeographical and geological evidence suggests that the connection between Madagascar and Africa was retained at the time when the Indian plate collided with the Eurasian Plate about 50 Ma (ICS 2004). This orogeny, which is continuing today, is related to closure of the Tethys. The closure of this ocean created Himalaya and the Plateau in South Asia. The current orogenic event is causing parts of the Asian continent to deform westward and eastward on either side of the orogeny. India's geographical land area can be classified into Deccan trap, Gondwana and Vindhyan regions.

Geological studies indicate that the Deccan Trap was formed as result of sub-aerial volcanic activity associated with the continental deviation during the Mesozoic era (Chandrasekharam and Parthasarathy, 1978). During its northward drift after breaking off from the rest of Gondwana, the Indian Plate passed over a geologic hotspot, which caused extensive melting underneath the Indian craton. The melting broke through the surface of the craton in a massive flood basalt event, creating what is known as the Deccan Traps. It is also thought that the Reunion hotspot caused the separation of Madagascar and India. The Gondwana and Vindhyan include within fold parts of India. The Gondwana Super group forms a unique sequence of fluvial rocks deposited in Permo- Carboniferous time.

6.1.1 Tectonic Evolution

Due to continental, the India Plate split from Madagascar and collided with the Plate resulting in the formation of the Himalayas. The earliest phase of tectonic evolution was marked by the cooling and solidification of the upper crust of the earth surface in the Archaean era (prior to 2.5 billion years) which is represented by the exposure of gneisses and granites especially on the Peninsula. These form the core of the Indian. The Aravalli Range is the remnant of an early Proterozoic orogen called the Aravali-Delhi orogen that joined the two older segments that make up the Indian craton (Figure 6.1). It extends approximately 500 kilometers from its northern end to isolated hills and rocky ridges into Haryana, ending near Delhi. Minor igneous intrusions, deformation (folding and faulting) and subsequent metamorphism of the Aravalli Mountains

represent the main phase of orogenesis. The erosion of the mountains and further deformation of the sediments of the Dharwaian group (Bijawars) marks the second phase. The volcanic activities and intrusions, associated with this second phase are recorded in composition of these sediments.

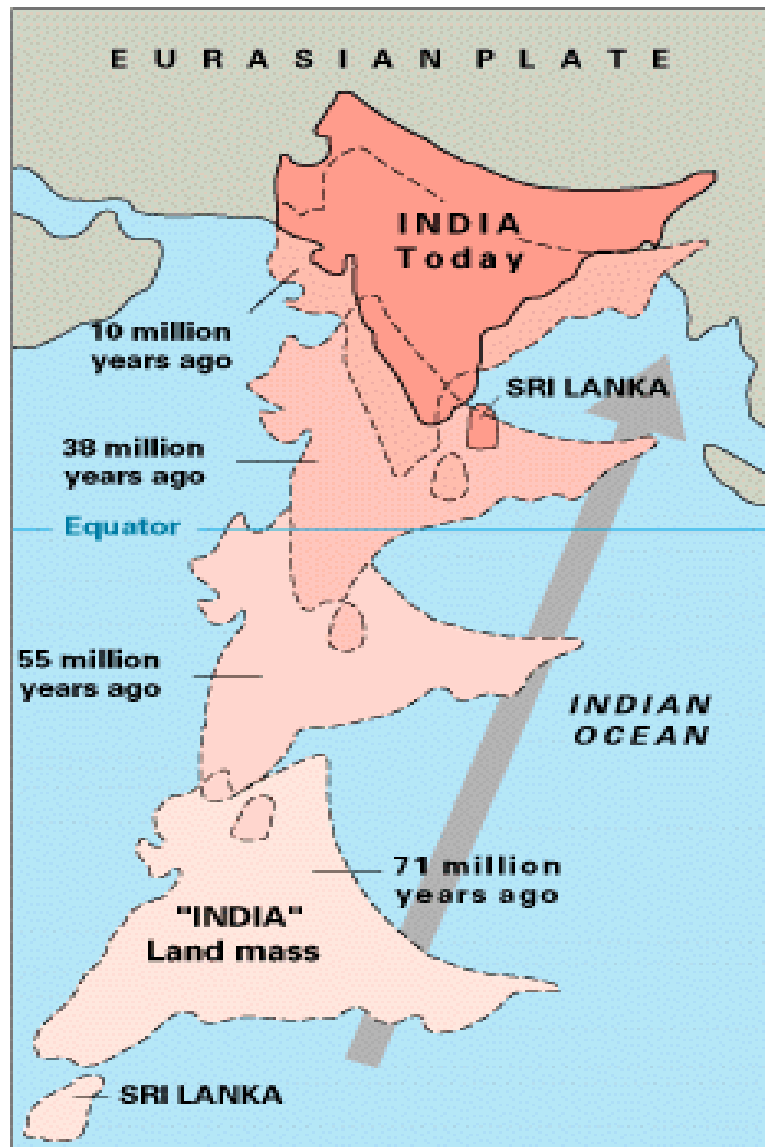


Figure 6.1: Northward Flight of the Indian Plate

Early to Late Proterozoic calcareous and arenaceous deposits, which correspond to humid and semi-arid climatic regimes, were deposited in the Cuddapah and Vindhyan basins. These basins, which border or lie within the existing crystalline basement, were uplifted during the Cambrian (ICS 2004). The sediments are generally underformed and have in many places preserved their original horizontal stratification. The Vindhyan is believed to have been deposited between ~1700 and 650 Ma (ICS 2004). Early Paleozoic rocks are found in the Himalayas and consist of

southerly derived sediments eroded from the crystalline craton and deposited on the Indian platform.

In the Late Paleozoic, Permo-Carboniferous glaciations left extensive glacio-fluvial deposits across central India, in new basins created by sag/normal faulting. These tillites and glacially derived sediments are designated the Gondwanas series. The sediments are overlain by rocks resulting from a Permian marine transgression around 270 Ma (ICS 2004)).

The late Paleozoic coincided with the deformation and drift of the Gondwana supercontinent. To this drift, the uplift of the Vindhyan sediments and the deposition of northern peripheral sediments in the Himalayan Sea can be attributed.

During the Jurassic, as Pangea began to drift apart, large grabens formed in central India filling with Upper Jurassic and Lower Cretaceous sandstones and conglomerates.

By the Late Cretaceous India had separated from Australia and Africa and was moving northward towards Asia. At this time, prior to the Deccan eruptions, uplift in southern India resulted in sedimentation in the adjacent nascent Indian Ocean. Exposures of these rocks occur along the south Indian coast at Pondicherry and in Tamil Nadu.

At the close of the Mesozoic one of the greatest volcanic eruptions in earth's history resulted the Deccan covering more than 500,000 square kilometers area. These mark the final break from Gondwana.

In the early Tertiary, the first phase of the Himalayan orogeny, the Karakoram phase occurred. The Himalayan orogeny has continued to the present day.

6.2 Stratigraphy

6.2.1 Precambrian Super-eon

A considerable area of peninsular India is covered by the Indian and consists of Precambrian rocks. It has been classified into two systems, namely the Dharwar system and the Archaean system (Wikipedia, 2011).

6.2.2 The Dharwar System

The rocks of the Dharwar system are mainly sedimentary in origin, and occur in narrow elongated synclines resting on the gneisses found in Bellary district, Mysore and the Aravalis of Rajputana (**Figure 6.2**). These rocks are enriched in Manganese and ore which represents a significant resource of these metals. They are also extensively mineralized with gold most notably the mines located in Kolar. In the north and west of India, the Vaikrita system, which occurs in Hundes, Kumaon and Spiti areas, the Dailing series in Sikkim and the Shillong series in Assam are believed to be of the same age as the Dharwar system (Wikipedia, 2011).

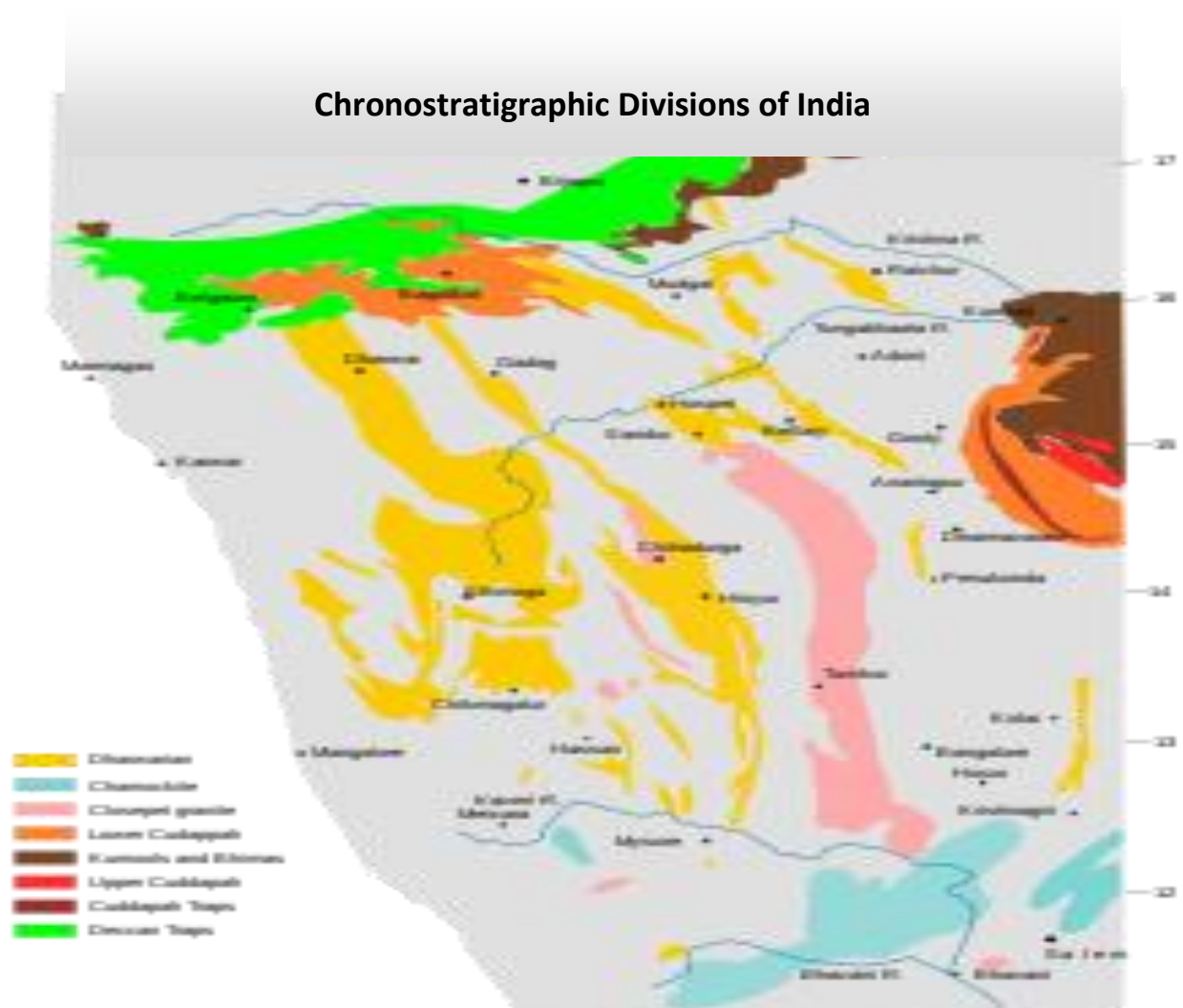


Figure 6.2: Distribution of Dharawars System in India

The metamorphic basement consists of gneisses which are further classified into the Bengal gneiss, the Bundelkh and gneiss and the Nilgirigneiss. The Nilgiri system comprises Charnockites ranging from granites to gabbros (Wikipedia, 2011).

6.2.3 The Archean System

Archean System covering pensular India consists of crystalline, gneisses and schistose rocks which are considered oldest rocks form an enormous extent of the surface of India. By far the largest part of the Peninsula is occupied by this ancient crystalline complex. In the extra-Peninsula, gneisses and crystalline rocks are exposed along the whole length of the Himalayas, building all their highest ranges and forming the core of the mountain-system.

6.2.4 Palaeozoic

Lower Paleozoic Rocks of the earliest Cambrian period are found in the Salt range in Punjab and the Spiti area in central Himalayas and consist of a thick sequence of fossiliferous sediments. In the Salt range, the stratigraphy starts with the Salt Pseudomorph zone, which has a thickness of 137m and consists of dolomites and sandstones. It is overlain by magnesian sandstones with a thickness of 76m, similar to the underlying dolomites. These sandstones have very few fossils. Overlying the sandstones is the Neobolus Shale, which is composed of dark shales with a thickness of 30m. Finally there is a zone consisting of red or purple sandstones having a thickness of 76m to 122m called the Purple Sandstone. These are unfossiliferous and show sun-cracks and worm burrows which are typical of sub aerial weathering. The deposits in Spiti are known as Haimanta system and they consist of Slates, micaceous quartzite and dolomitic lime stones. The Ordovician rocks comprise flaggy shales, limestones, red quartzites, quartzites, sandstones and conglomerates. Siliceous limestones belonging to the Silurian overlie the Ordovician rocks. These limestones are in turn overlain by white quartzite and this is known as Muth quartzite (Wikipedia, 2011).

Upper Paleozoic-Devonian fossils and corals are found in grey limestone in the central Himalayas and in black limestone in the Chitral area. The Carboniferous is composed of two distinct sequences, the Upper Carboniferous, and the Lower Carboniferous Lipak. Fossils of Brachiopods and some Trilobites are found in the calcareous and sandy rocks of the Lipak series. The Po series overlies the Lipak series, and the Fenestella shales are interbedded within a sequence of quartzites and dark shales. In many places Carboniferous strata are overlaid by grey agglomeratic slates, believed to be of volcanic origin. Many genera of productids are found in the limestones of the Permo - Triassic, which has led to these rocks being referred to as "productus limestone". This limestone is of marine origin and is divided into three distinct litho-stratigraphic units based on the productus chronology: the Late Permian Chideru, which contains many ammonites, the Late - Middle Permian Virgal, and the Middle Permian Amb unit.

6.2.5 Mesozoic

In the Triassic the Ceratite beds consist of arenaceous limestones, calcareous sandstones and marls. The Jurassic consists of two distinct units. The Kioto limestone extends from the lower to the middle Jurassic with a thickness 610m to 914m. The Upper Jurassic is represented by the Spiti black shales, and stretches from the Karakoram to Sikkim. Cretaceous rocks cover an extensive area in India. In South India, the sedimentary rocks are divided into four stages; the Niniyur, the Ariyalur, the Trichinopoly, and the Utatur stages. In the central provinces, the well developed beds of Lameta contain fossil records which are helpful in estimating the age of the Deccan Traps. This sequence of basaltic rocks was formed near the end of the Cretaceous period due to volcanic activity. These lava flows occupy an area of 520,000 sq. km. These rocks are a source of high quality building stone and also provide a very fertile clayey loam, particularly suited to cotton cultivation (Wikipedia, 2011).

6.2.6 Cenozoic

Tertiary period- In this period the Himalayan orogeny began, and the volcanism associated with the Deccan Traps continued. Further north the rocks found in the Simla area are divided into three series, the Sabathu series consisting of grey and red shales, the Dagshai series comprising bright red clays and the Kasauli series comprising sandstones. Towards the east in Assam, Nummulitic limestone is found in the Khasi hills. Along the foothills of the Himalayas the Siwalik molasse is composed of sandstones, conglomerates and shales with thicknesses of 4,877m to 6,096m and ranging from Eocene to Pliocene. These rocks are famous for their rich fossil vertebrate fauna including many fossil hominoids. Quaternary period- The alluvium which is found in the Indo-Gangetic plain belongs to this era.

6.3 History of Geothermal Studies

Ninety-nine well-known thermal springs were documented in India as early as 1864. Subsequently R. D. Oldham published the monumental work of his father T. Oldham (1882) which included an inventory of three hundred thermal springs covering the entire country. La Taiche published a list of mineral springs in 1918. Further studies on the hot springs were carried out by various workers including Heim and Ganssar (1938), Ghosh (1954), Chatterjee and Guha (1964) and Guha (1986). The Ministry of Power and Irrigation constituted a committee on 'Hot Springs' in the year 1963 to explore the commercial utilization potential of thermal springs in India. The committee inducted members from the GSI, NGRI and Jadavpur University, Kolkata. All the thermal springs of India were classified on the basis of their geotectonic setup and grouped into six Geothermal Provinces as follows:

I. Himalayan Province comprising Tertiary Orogenic Active belt with Tertiary magmatism. There are about 100 thermal springs with surface temperatures as high as 90°C discharging more than 190 tones/h of thermal water. Post Tertiary granite intrusives are responsible for the high temperature gradient ($> 100\text{ }^{\circ}\text{C/km}$) and heat flow ($> 468\text{ mW/m}^2$) recorded in the 500 m drill-hole in this province (Chandrasekharam, 2010). Geothermal reservoir between depths 1 and 3 km was delineated from magneto-telluric recordings (Singh and Nabetani, 1995). The first and the last pilot binary 5 kW power plant using R 113 binary fluid was successfully operated by the Geological Survey of India at Manikaran which proved the power producing capability of this province. Presence of epidote in drill-cuttings recovered from 500m drill-holes support estimated reservoir temperature of 260°C. Space heating experiments were also successfully conducted using thermal discharge by the Geological Survey of India (Chandrasekharam, 2010).

II. Areas of faulted blocks comprising Aravalli belt, Naga-Lushi, West coast regions and Son-Narmada lineament.

This province extending from Cambay in the west to Bakreswar in the east is an area with very high heat flow and geothermal gradient and encloses the well known Tattapani geothermal province spreading over an area of about 204,800 sq km (

Figure 6.3). The Tattapani province encloses 23 thermal discharge sites with surface temperatures varying between 60 and 95°C and flow rate greater than 4000 l/m. Nine thermal springs are discharging waters at 90°C. These waters, compared to those of west coast, are low in Chlorine (Cl) content (60-70 ppm) and the chemical composition of the thermal discharge is controlled by water-rock interaction. Based on thermal gradient and experimental results, estimated reservoir temperatures are as high as 217°C at 3km depth. (Chandrasekharam and Antu, 1995). In certain bore holes drilled by the Geological Survey of India, thermal discharge was not encountered but the recorded thermal gradient in these bore holes exceed 100 °C/km (G.S.I, 1991). Such sites are best suited for experimenting Hot Dry Rock (HDR) projects (Chandrasekharam, 1996). GSI drilled five production wells of 6 inches diameter to commission a pilot power plant of 3.17 MW capacity. The pressure of the thermal discharge is 5 kg/cm² and the estimated life of the reservoir is about 20 years (Pitale et al., 1995). It is not yet confirmed that the proposed power plant at Tattapani is commissioned or not.

Unapdeo and Nazardeo, the two thermal provinces located between Tattapani and Cambay and enclosed by the Tapi rift within the SONATA, discharge 59°C thermal waters. Though these springs issue through Deccan basalts, chemical signature of the springs indicate that they are in chemical equilibrium with underlying Na-rich granites, recorded through magneto-telluric surveys (Rao, et.al., 1995). Estimated reservoir temperatures are 105°C and 133°C respectively (Chandrasekharam and Prasad, 1998).

Bakreswar-Tantloi thermal area falls in Bengal and Bihar districts and marks the junction between SONATA and Singbhum shear zone (

Figure 6.3). High Helium (He) gas is encountered in all the thermal discharges (water and gases) and it is proposed to install a pilot plant to recover Helium (He) from the thermal manifestation of this region. The Helium discharge is 4 l/h (Nagar et.al., 1996).

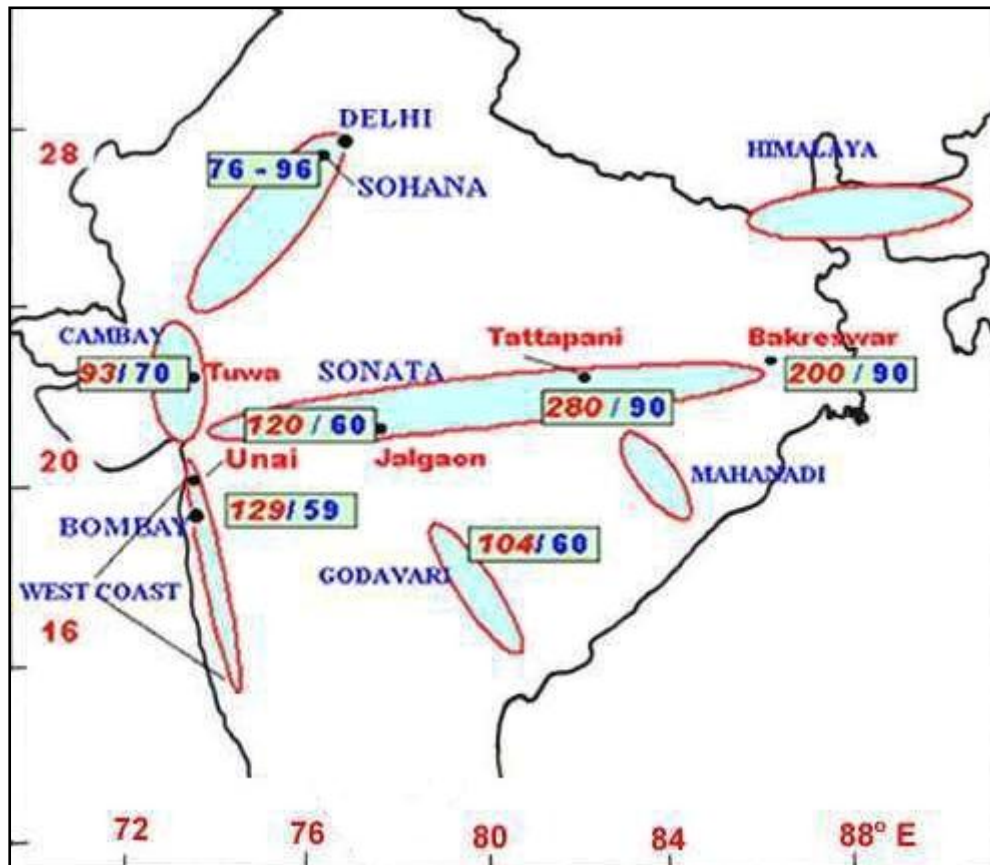
Godavari valley in Andhra Pradesh is a northwest-southeast trending graben filled with Gondwana sedimentary formations. The rocks of lower Gondwana group exposed towards the southwestern part of the graben consist of sandstone, shale and clays and hosts 13 thermal discharges with surface temperature varying from 50 to 60°C. This graben falls within zone II (100 - 180 mWm²) on the heat flow map of India and has a thermal gradient of 60°C/km (Ravi, 1988). Two thermal springs, Bugga and Manuguru, discharging 1000 l/m of water, were studied in detail. Talchir sandstone, which forms a unit in the lower Gondwana group, is the reservoir rock with an effective porosity of 35%. The storage capacity of the Talchir sandstone is 35 x 10⁶m³ which is expected to yield thermal discharge for about 75 years. Geochemical thermometers indicate reservoir temperatures in the range of 175 to 215°C. The reservoir is reported to be at a depth of 2.5 km. It has been estimated that 38 MW power can be generated from this province (Chandrasekharam and Jayaprakash, 1996). A 1-6 shell and tube heat exchanger to suite the thermal discharge conditions has been designed to dehydrate 10,000 lb/hr of onions with an air volume of 20,000 m³ (Chandrasekharam et.al., 1996).

The west coast Area is located within the Deccan flood basalts region of Cretaceous age. Attenuation and foundering of the continental crust prior to the out pouring of the large volume of lavas along the coast (Chandrasekharam and Parthasarathy, 1978) resulted in the development of several faults and graben structures (Chandrasekharam, 1985) which are channeling thermal waters. This province enjoys a thin lithosphere of 18 km thickness (Pande et.al., 1984) thereby rendering this province as one of the most promising sites for exploitation. The thermal discharges are saline with Cl content varying from 800 ppm to little over 1500 ppm (Ramanathan, 1993). Hence, geothermometers may not indicate the true reservoir temperatures. About 1% saline component has been estimated in these thermal discharges. The reservoir temperatures calculated, after making necessary correction for 1% saline component, are between 102 and 137°C (Chandrasekharam et.al., 1989). One thermal discharge, located at Rajapur, within the Deccan basalts along the coast is an exception to the other thermal discharges mentioned above. The thermal reservoir of this discharge is located within the Precambrian formation, like the Puttur thermal waters, with reservoir temperatures varying between 120 and 200°C (Ramanatha and Chandrasekharam, 1997).

III. Volcanic arc comprising Andaman and Nicobar arc.

The Andaman - Nicobar island chain in the Bay of Bengal and is located 116 km ENE of Port Blair. Recent volcanic activity was recorded in 1991 which resulted in the appearance of high temperature steaming ground and thermal discharges. Fumarolic discharge recorded temperatures varying between 100 and 500°C. Detailed exploration work needs to be commissioned in this province.

IV. Deep sedimentary basin of Tertiary age such as Cambay basin in Gujarat. Situated in a failed arm of a rift (Sheth and Chandrasekharam, 1997), this province forms a part of the Cambay basin with > 500 m of post Cretaceous sedimentary formation overlying the well known Deccan basalts. Besides deep seated faults, which brackets the basin, older (~955 Ma) granite intrusives (Gopalan et. al., 1979), such as those at Tuwa and Miocene- Pliocene basic intrusives, contribute partly to the high thermal gradient (>60°C) and heat flow value (>80 mW/m²) of this basin. More than 15 thermal discharge sites are located in this province with surface temperatures varying from 40-90°C. Steam discharge in certain oil wells were recorded with



rates exceeding 3,000 m³/d. Reservoir temperatures estimated at two sites (Tuwa and Tulsi Shyam) are greater than 150°C (Kamble, 1994). V. Radioactive Province - Surajkund, Hazaribagh, Jharkhand. VI. Cratonic province - Peninsular India. The

Figure 6.3 illustrates the geographic distribution of geothermal provinces of India

Figure 6.3: Geothermal Regions in Central India (After Chandrasekharam, 2000)

6.4 Geothermal Resources of India

There are some 340 hot springs spread all over India. Of this, 62 are distributed along the northwest Himalaya, Himachal Pradesh and Uttarakhand. They are found concentrated along a 30-50-km wide thermal band mostly along the river valleys. Naga-Lusai and West Coast Provinces manifest a series of thermal springs. Andaman and Nicobar arc is the only place in

India where volcanic activity has been reported. Some of the islands like Barren are still active. The area is in the continuation of the Indonesian geothermal fields and can be good potential sites for geothermal energy. Cambay graben geothermal belt is 200 km long and 50 km wide with Tertiary sediments. Thermal springs have been reported from the belt although they are not of very high temperature and discharge. The area contains oil and gas at considerable depths. High subsurface temperature and thermal fluid have been reported in deep drill wells in depth ranges of 1.7 to 1.9 km. Steam blowout have also been reported in the drill holes in depth range of 1.5 to 3.4 km. The thermal springs in the peninsular region are more related to the faults, which allow down circulation of meteoric water to considerable depths. The circulating water acquires heat from the normal thermal gradient in the area, and depending upon local condition, emerges out at suitable localities. The area includes Aravalli range, Son-Narmada-Tapti lineament, Godavari and Mahanadi valleys and South Cratonic Belts. Some of the important geothermal fields of India are described as follows (G.S.I., 1991; Chandrasekharam, 2000).

6.5 Potential of Beas and Parbati Valley Geothermal Province

Beas and Parbati valleys are well known for their hot springs in Kulu district, Himachal Pradesh. The springs lie between altitude of 1,300 m and 3,000 m. The famous thermal springs in the Beas valley are Bashist, Kalath, Rampur and Kulu, whereas in the Parbati valley, the springs are at Jan, Kasol, Manikaran, Pulga and Khirganga. The rocks in the area belong to Proterozoic age and are classified in Vaikrita, Kulu and Rampur Groups. The temperature of springs ranges from 22°C to 59°C in Beas and 21°C to 96°C (96°C being the boiling point at the altitude) in Parbati valley, respectively.

In the Parbati valley, the thermal springs and drill holes contain low TDS water, which rarely exceeds 1000 mg/l in the Beas valley, except at Kulu where it goes up to 4094 mg/l. The pH varies from neutral to slightly alkaline. Classification of thermal water has been made on Shoeller and Giggenbach diagrams, which indicate water is bicarbonate type and has gone shallow subsurface circulation. The water has meteoric origin and is of peripheral nature. The shallow circulation in presence of high CO₂ has converted water rich in HCO₃. The Na/K ratio in springs and drill hole is <3 or very high >22, which does not favor high temperature reservoir. Springs and drill hole plot on Na-K-Mg diagram shows that samples fall in the immature field and thus no rock-water equilibrium has taken place with respect to rock minerals in the reservoir. This supports the concept of low temperature reservoir in Beas valley. Parbati valley shows that the thermal water from springs and drill holes are again of low TDS of around 1000 mg/l. The silica content hardly exceeds 110 mg/l.

6.6 Potential of Tapoban Geothermal Province

The geothermal field falls in Dhauliganga Valley, a tributary to Alaknanda river in Chamoli district, Uttarakhand. There are several thermal springs in this part of Dhauliganga and Alaknanda Valleys in the temperature range of 25 °C to 65 °C. One of the most prominent springs is at Tapoban, located 15 km from Joshimath along Joshimath-Malari road. The exposed rocks belong to Crystalline and Garhwal Groups separated by the Main Central Thrust.

High thermal water discharge of 950 lit/min with 65 °C has been observed in the area, but the maximum temperature in free flow discharge is 92 °C with thermal fluid discharge of 800 lit/min.

The drill hole and spring water in the area is neutral to alkaline with TDS less than 1,000 mg/l. There is high SO_4 and HCO_3 content but low Cl (<20 mg/l) and silica (<120 mg/l). The Na/K ratio is either very low (<5) or high (>20). All the above chemical characters indicate that the thermal reservoir is of low to medium temperature. Further, the Na-K-Mg diagram indicates immature water for Tapoban geothermal field. The chalcedony and quartz geothermometry suggests a base temperature of the geothermal reservoir to be not more than 100 ± 10 °C, thereby bringing it in low enthalpy.

6.7 Potential of Sohana Geothermal Province

The Sohana Hot Spring is located close to Gurgaon, Haryana. The rocks of the area belong to Alwar and Ajabgarh Groups of Proterozoic age. Post intrusive in the form of pegmatite and quartz veins are of Post Delhi age. The Geological Survey of India drilled a total of 10 holes in the depth range of 90.1 to 547.2 m. Down hole measurement indicated a maximum temperature of around 56 °C. Water from drill hole is neutral to alkaline with high TDS (up to 4,818 mg/l) and Cl (1348 mg/l). Despite high Cl and TDS contents, very low silica (<49 mg/l) and high Mg (226 mg/l) do not support a high temperature environment for the geothermal field. The exacted base temperature in the area is $50^\circ\text{C} \pm 10^\circ\text{C}$, based on log SiO_2 vs log K2/Mg diagram of Giggenbach (1988).

6.8 Potential of West Coast Geothermal Province

The area has about 60 thermal springs all along the west coast of Maharashtra. The belt extends along the coast for a distance of about 350 km from Konkere in the north to Rajapur in the south with average width of 20 km. The eastern boundary is marked by NNW-SSE trending Sahyadri mountain range constituting part of the Western Ghats whose western limit is demarcated by the Arabian Sea coast line. Geologically, the area is marked by thick Deccan Basalt Flows overlying rocks of Precambrian age. The prominent thermal springs are Rajapur (42°C), Math (61°C), Sangameshwar (45°C), Rajwadi (61°C), Tural (62°C), Aravil (43 °C), Khed (35°C), Unhaver (Khed-71 °C), Unhave (Tamhane-54 °C), Vadavli (35°C), Sov (42°C), Pali (43°C), Akloli (54°C), Ganeshpuri (52°C), Sativli (58°C), Haloli (43 C), Paduspada (42°C), and Koknere (54°C). 13 exploratory holes were drilled along the coast. The spring and drill hole water are neutral to alkaline and low in TDS except at Unhaver where it is up to 2391 mg/l. The Cl content in thermal discharge is high but silica is low in amount-maximum around 100 mg/l. Water has been classified as Na-Cl type on Cl- SO_4 - HCO_3 diagram and the plots fall close to Cl apex but none is geothermally matured. The diagram also indicates mixing of thermal and seawater in the area. The Na/K ratio is very high (>70), which confirms a low temperature reservoir.

6.9 Conclusions

India has comprehensive data base on the geothermal energy occurrences in the country which shows that it has reasonably good potential for utilization of geothermal energy. It has been estimated that the potential geothermal provinces can produce 10,600 MW of power (D. Chandrasekharam, 2010). But yet geothermal power projects has not been exploited at all, owing to a variety of reasons, the chief being the availability of plentiful coal at cheap costs. However, with increasing environmental problems with coal based projects, India will need to start depending on clean and eco-friendly energy sources in future; one of which could be geothermal. However some of the fields are actively being studied in detail as given here under in **Table 6.1**.

Table 6.1: Geothermal Studies currently being undertaken in India

Geothermal Field	Estimated Min. Reservoir Temperature	Status
Puga geothermal field	240°C at 2000m	From geochemical and deep geophysical studies (MT)
Tattapani Sarguja (Chhattisgarh)	120°C - 150°C at 500 meter and 200 Cat 2000 m	Magnetotelluric survey done by NGRI
Tapoban Chamoli (Uttarakhand)	100 °C at 430 meter	Magnetotelluric survey done by NGRI
Cambay Garben (Gujrat)	160°C at 1900 meter (From Oil exploration borehole)	Steam discharge was estimated 3,000 cu meter/ day with high temprature gradient.
Badrinath Chamoli (Uttarakhand)	150°C estimated	Magneto-telluric study was done by NGRI Deep drilling required to ascertain geothermal field
Geothermal Field	Reservoir Temp (Approx)	Status
Surajkund Hazaribagh (Jharkhand)	110°C	Magneto-telluric study was done by NGRI. Heat rate 128.6 mW/m ²
Manikaran Kullu (H P)	100°C	Magneto-telluric study was done by NGRI Heat flow rate 130 mW/m ²
Kasol Kullu (H P)	110°C	Magneto-telluric study was done by NGRI

According to Sharma (2010) ONGC estimated power generating capacity of 300 KWe from the shallow secondary reservoir of Tattapani geothermal field having 105°C at a depth of up to 500m. Also on basis of the Magneto - Tellurics (MT) survey conducted by the National Geophysical Research Institute (NGRI) which revealed the presence of a vast primary reservoir of about 260°C at nearly 3 to 3.5 km at the Tattapani Geothermal Field, The National Hydroelectric Power Corporation (NHPC) technical collaboration with the ONGC and with the financial assistance Ministry of Non-Conventional Energy Sources (MNES), is developing the Tattapani Geothermal Field for tapping the electric generation for 5MWe capacity besides various direct heat applications (Sharma 2010). The project is likely to be operative in near

future. This will also lead to developing other promising geothermal sites like Puga and Manikaran.

Some companies have also taken initiative and announced to launch geothermal power plants from other geothermal fields. India's first geothermal power plant with an initial capacity of 25 mega watt (MW) is expected to come up by 2012 in the Khammam district of Andhra Pradesh (AP). It is estimated that an investment of US\$ 64.66 million will be made for the completion of the project. It will be set up by Mumbai-based Geo Syndicate Power Private Ltd, a company incubated by the Indian Institute of Technology (IIT), Bombay, which has a special focus on exploration and production of geothermal energy. It has already entered into a power purchase agreement (PPA) with Warangal-based Northern Power Distribution Company that was recently signed under the aegis of the Non-conventional Energy Development Corporation of Andhra Pradesh Limited (NEDCAP). Another company namely Avin Energy Systems Pvt Ltd has explored possibilities of setting up geothermal power projects in Gujarat. Plans are underway to set up the first 5 MW power generating plant using geothermal energy. Avin has already done most of the ground work in regard to geothermal power generation in Gujarat and in the coming future expects to set up geothermal power generating units in Gujarat in the order of 1000 MW capacity which should, in a way, feed the electricity requirements of not only the State but also the neighbouring States. Now the company is looking for financiers and investors to get the project off the ground. (avin@avinsolar.com)

With available advance technology, the geothermal resources can be developed for setting up power projects. Local and foreign entrepreneurs will be attracted in setting up power project through a liberal policy of the Government. Commissioning of at least one geothermal based power project is going to change the entire future electricity scenario of India. It is also recommended that further exploration and drilling programmes be initiated in the geothermal provinces. Data on thermal gases and geochemical investigation carried out by collaborative project between India and Italy be also made public (Minissale et al., 2000).

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CHAPTER – 7

GEOTHERMAL RESOURCES OF NEPAL

7.1 Geological Framework

Nepal occupies the central sector of Himalayan Arc. Nearly one third of the 2400km long Himalayan range lies within Nepal. Similar to other parts of the Himalaya, from south to north, Nepal can be also subdivided into the following five major tectonic zones characterized by their own lithology, tectonics, structures and geological history (After Ranjan Kumar Dahal, 2006;Figure 7.1).

- Gangetic Plain
- Sub-Himalayan (Siwalik) Zone
- Lesser Himalayan Zone
- Higher Himalayan Zone
- Tibetan-Tethys Himalayan Zone

All these tectonic zones are separated from each other by the thrust faults (**Figure 7.2**). The southernmost fault, the Main Frontal Thrust (MFT) separates the Sub-Himalayan (Siwalik) Zone from Gangetic Plains. The Main Boundary Thrust (MBT) separates the Lesser Himalayan Zone from Siwalik. The Main Central Thrust (MCT) separates the Higher Himalayan Zone from the Lesser Himalayan Zone. The South Tibetan Detachment System (STDS) marks the boundary between the Higher Himalayan Zone and the overlying fossiliferous sequence of the Tibetan-Tethys Himalayan Zone. The Indo-Tsangpo Suture Zone is the contact knot between Indian plate and Tibetan (Eurasian) Plate in terms of plate tectonics.

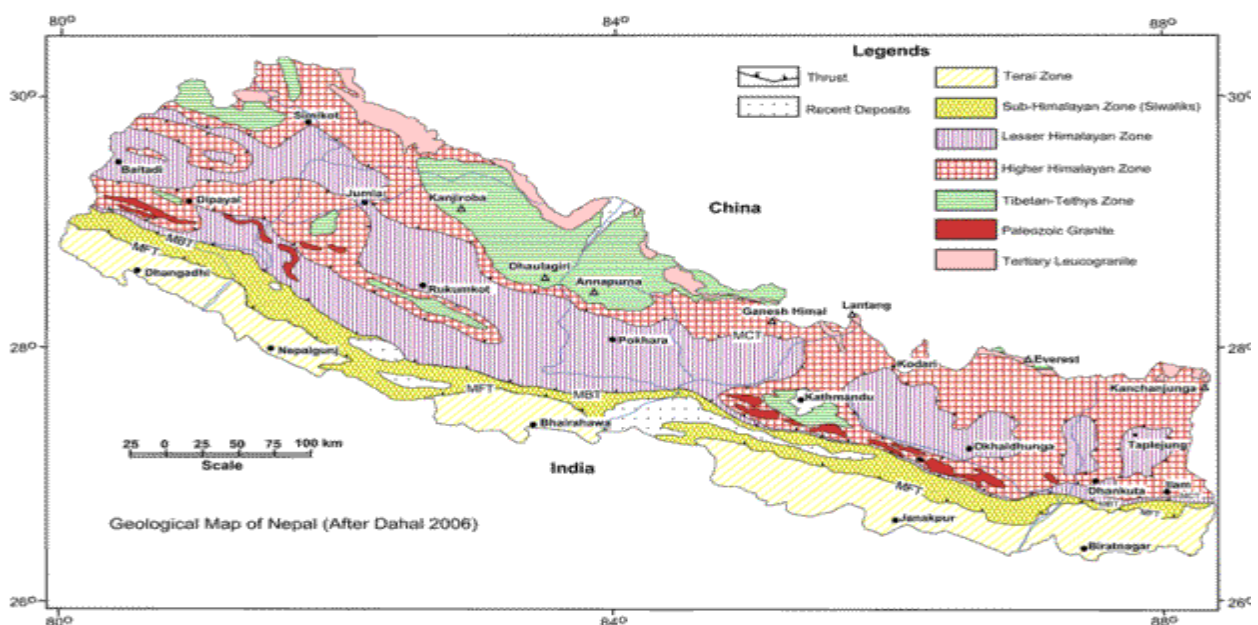


Figure 7.1: Geological Map of Nepal (Modified from Dahal, 2006)

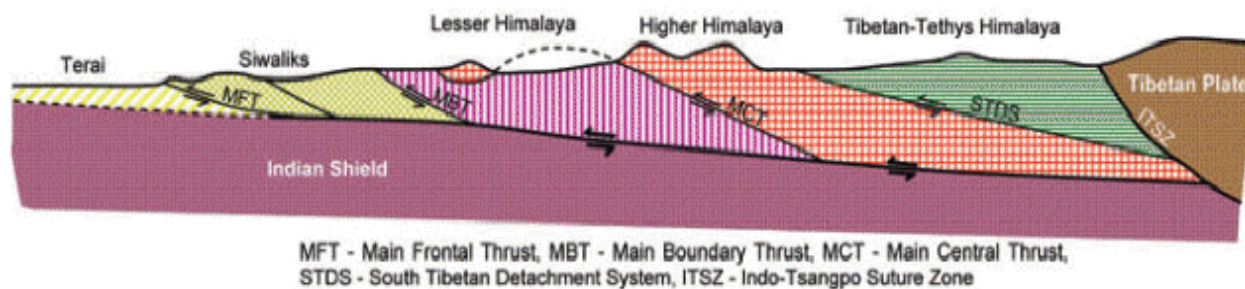


Figure 7.2: Generalized Cross Section of Himalaya (Modified After Dahal 2006)

The main geological zones of the Nepal Himalaya are described below.

7.1.1 Gangetic Plain

The Gangetic Plain is also called as Terai Zone and it is the Nepalese portion of the Gangetic Plain that extends from the Indian Shield in the South to the Sub-Himalayan (Siwalik) Zone to the North. The plain is in less than 200 meters above sea level and usually has thick (nearly 1,500 m) alluvial sediments. The alluvial sediments contain mainly boulder, gravel, silt and clay. The width of Terai Zone varies from 10 to 50 km and forms a nearly continuous belt from east to west. Exceptionally at two places, Chitwan and Rapti valleys, the Terai Zone is interrupted by Siwalik for 70 km and 80 km respectively. Terai Zone is a foreland basin and has sediment originated from peaks of Northern part. To the north, this zone is separated by an active thrust system called as the Main Frontal Thrust (MFT) with Siwalik. At some places along MFT, the Siwalik rocks are observed to rest over the recent sediments of the Terai (Dahal 2006).

A large number of borehole logs and geophysical investigation made during the groundwater investigation and petroleum exploration in Terai play a lead role to study the surface and subsurface geology of the Terai. It further helps to classify the Terai into Northern Terai or Bhabhar Zone, Middle Terai and Southern Terai.

Northern Terai (Bhabhar Zone)

The northern Terai is adjoining to the foothills of Siwalik and continues southward to a maximum width of 12 km. This part of Terai is also known as Bhabhar Zone. This zone is mainly composed of boulders, pebbles, cobbles and coarse sand derived from the rocks of Siwalik and Lesser Himalaya. These boulders, pebbles, and cobbles are mostly made up of sandstones (Figure 7.3) and the rocks from the immediate northern vicinity. Bhabhar Zone acts as a recharge zone for the groundwater of Terai. Most of the rivers lose their water while passing through this zone. In this Zone, water tables in wells show very sharp fluctuations between the summer and rainy seasons. At some places the wells become completely dry in summer. Due to the very coarse nature of the sediments, low water table and quick percolation of rainwater, this zone is particularly not productive for agriculture and therefore ideal for the development of forest resources.

Middle Terai (Marshy) Zone

This is a narrow zone of about 10-12 km wide and lying between the Northern Terai Zone and the Southern Terai Zone. This zone is characterized by pebbly and brown to grey colored unconsolidated sandy sediments with few clay partings. Clay is mostly dark grey colored and intercalated with brown colored sand layers. The medium to coarse grained sandy layers possesses good groundwater reservoir. Because of marked change in elevation from Bhabar Zone, this zone comprises marked development of spring line, natural ponds, marshland and lakes (Dahal 2006). Immediate south of spring lines, there are many artesian layers are found in depth of 25 m to 200 m. The permeability of Middle Terai Zone diminishes towards south and finally non permeable layers are encountered in boundary of the Southern Terai Zone (**Figure 7.3**).

Southern Terai Zone

Southern Terai Zone is southern most part of Terai up to Nepal-India border and also continues into India. This zone consists of main sediments of Gangetic Plain. Basically, sand, silt and clay (**Figure 7.3**) are the main sediments of this zone. This zone is composed of finer sediments than the Middle Terai Zone. To the extreme south bordering the Indian Plains, the sediments become finer and also show change of facies. The water table is about 3 m below the surface and aquifers are poor (**Figure 7.3**). Only in old river channels area north-south extending better aquifers are found. Therefore, except at the northern part and along old river channels, there are particularly no good aquifers in the lower horizons (Dahal 2006). For this reason, in the southern Terai of Nepal, the development of the groundwater also appears to be difficult by deep tube wells.

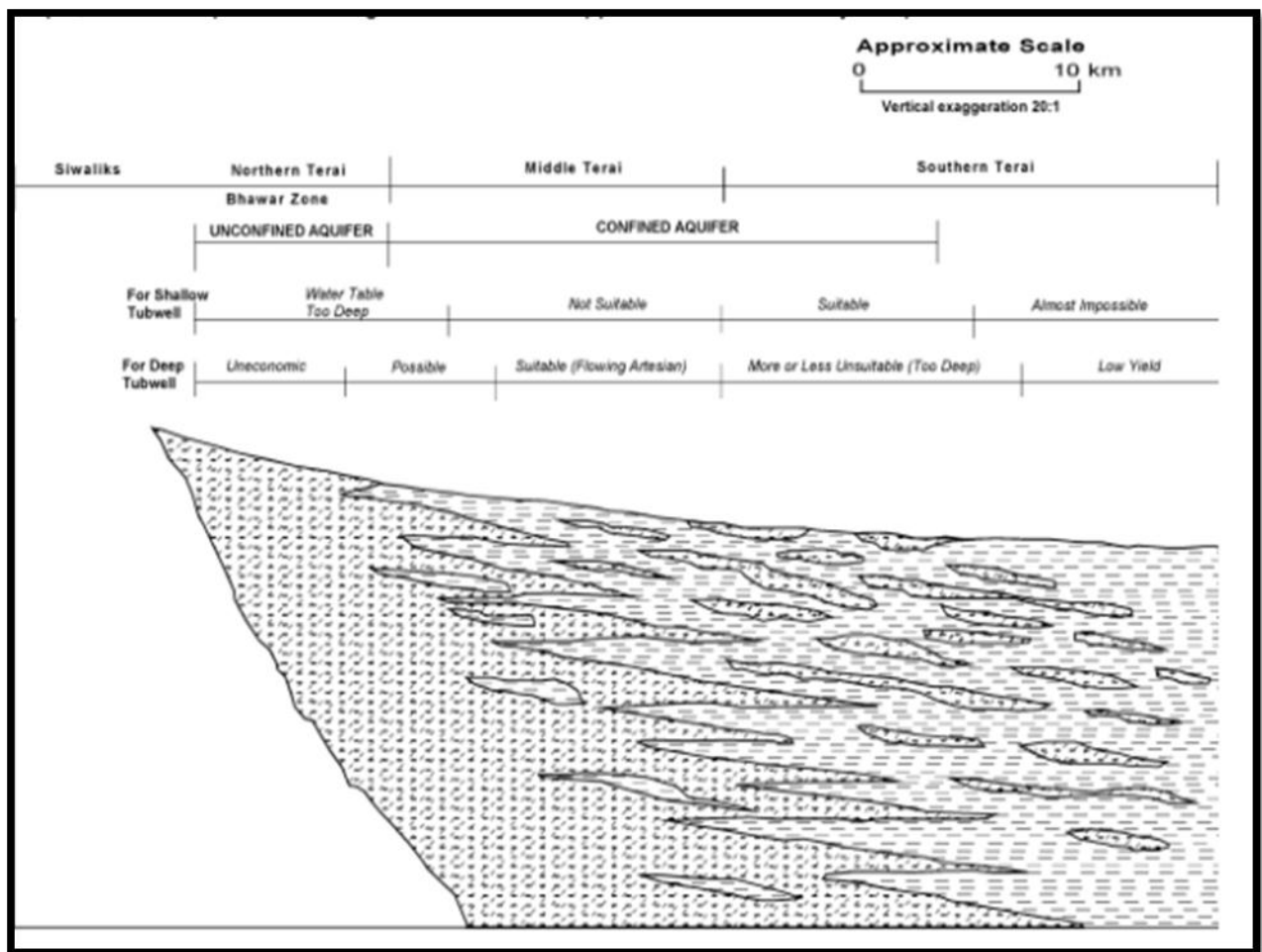


Figure 7.3: Subsurface Condition of Terai Zone of Nepal (After Daha, 2006)

7.1.2 Sub-himalayan (Siwalik) Zone

The Sub-Himalaya Zone is also called as Siwalik Zone and is delimited on the south by the Main Frontal Thrust (MFT) and on the north by the Main Boundary Thrust (MBT). It consists basically of fluvial deposits of the Neogene age (23 millions years to 1.6 millions years old). This zone extends all along the Himalaya forming the southernmost hill range with width of 8 to 50 km. The Lesser Himalayan rocks thrust southward over the rocks of Siwalik along the MBT (Dahal, 2006).

The general dip of beds of Siwalik has northward trend with varying angles and the overall strike is east-west. The Siwalik Zone has number of east-west running thrusts. Siwalik Zone is also rich with fossils. Fossils of plants, fishes, reptiles and mammals (Carnivora, Proboscidea, Artiodactyla, Rodentia and Primates) have been reported from Siwalik.

The three-fold classification of Siwalik in Potwar region of Pakistan and western Indian Himalaya was freely applied to the equivalent Siwalik of Nepal (Burbank et al., 1996) from the beginning of the geological studies in Nepal. According to three fold classification, Siwalik can be classified as follow.

- Lower Siwalik
- Middle Siwalik and
- Upper Siwalik

The example of geological map of Siwalik around Hetauda area is given in **Figure 7.4**. The map illustrates the Upper, Middle and Lower Siwalik in the Hetauda and Amalekhgunj area. The other geological names (formations) of Upper, Middle and Lower Siwalik are also provided in map as formation names.

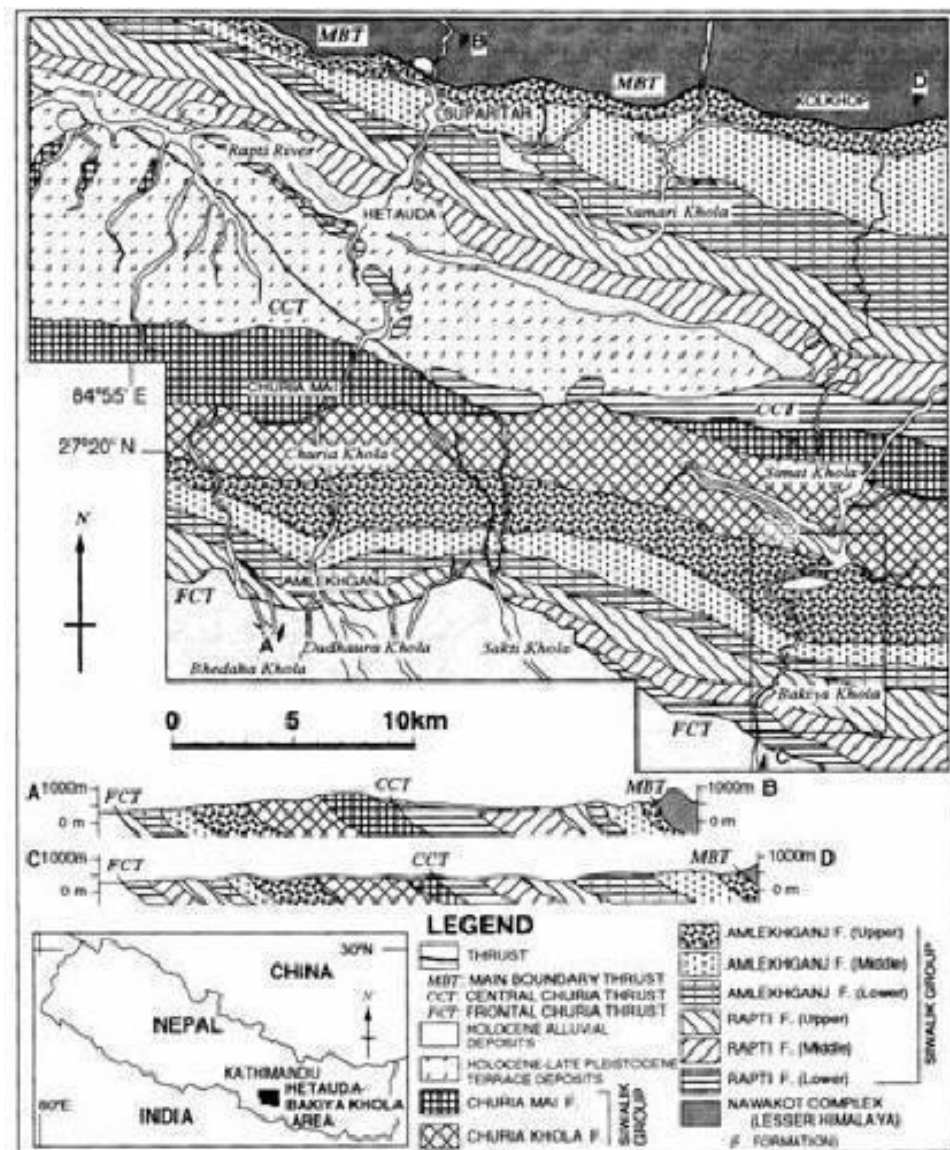


Figure 7.4: Geological Map of Hetauda-Bakiya Khola Area
(After Ulak and Nakayama, 1999)

7.1.3 Lower Siwalik

The Lower Siwalik consists of irregularly laminated beds of fine grained greenish sandstone and siltstone with mudstone. The alternating mudstone beds are thickly bedded and are variegated,

red, purple, and brown coloured. The best exposures of Lower Siwalik are found in Surainaka, Amlekhgunj, Arun Khola, Barahchhetra and Rato Khola area of Nepal.

7.1.4 Middle Siwalik

The Middle Siwalik are comprised of medium to coarse grained salt-and-pepper (looks like mixture of salt and black pepper) sandstones interbedded with mudstone (**Figure 7.5**). This is differentiated from the Lower Siwalik in lacking variegated mudstone and sandstone. In upper part of the Middle Siwalik, pebbly sandstone beds are also found. In Middle Siwalik the sandstone beds have thickness mostly ranges from 1 m to 45 m. The exposures of Middle Siwalik are found mainly in Surkhet, Surai Khola, Hetauda, and Butwal.



Figure 7.5: Interbedding Sandstone and Mudstone in Middle Siwalik, Butwal-Tansen Section of Siddhartha Highway

7.1.5 Upper Siwalik

The Upper Siwalik is comprised of conglomerate and boulder beds and subordinately sand and silt beds. The mudstone beds of the Upper Siwalik are massive and irregularly bedded and contain many invertebrate fossils including Brachiopods and Gastropods. The upper part of this sequence contains conglomerate beds, which have mostly boulder and cobble size rounded to sub angular fragments of Lesser Himalayan rocks. In Bardibas, Hetauda, Bhalubang, and Chitwan the good exposure of Upper Siwalik can be seen.

7.1.6 Lesser Himalayan Zone

The Lesser Himalayan Zone is bounded to the north by the Main Central Thrust (MCT) and to the south by Main Boundary Thrust (MBT). MBT can be traced out in entire Nepal Himalaya (**Figure 7.6** and **Figure 7.7**). The rocks of Lesser Himalayan Zone have been transported

southwards in several thrust slices. Generally two types of sequences namely autochthonous and allochthonous can be distinguished in this zone throughout the Himalayas. The both sequences of the Lesser Himalaya mainly have unfossiliferous, sedimentary, and meta sedimentary rocks such as slate, phyllite, schist, quartzite, limestone, dolomite, etc, ranging in age from Precambrian to Eocene. There are also some granitic intrusions in this zone.

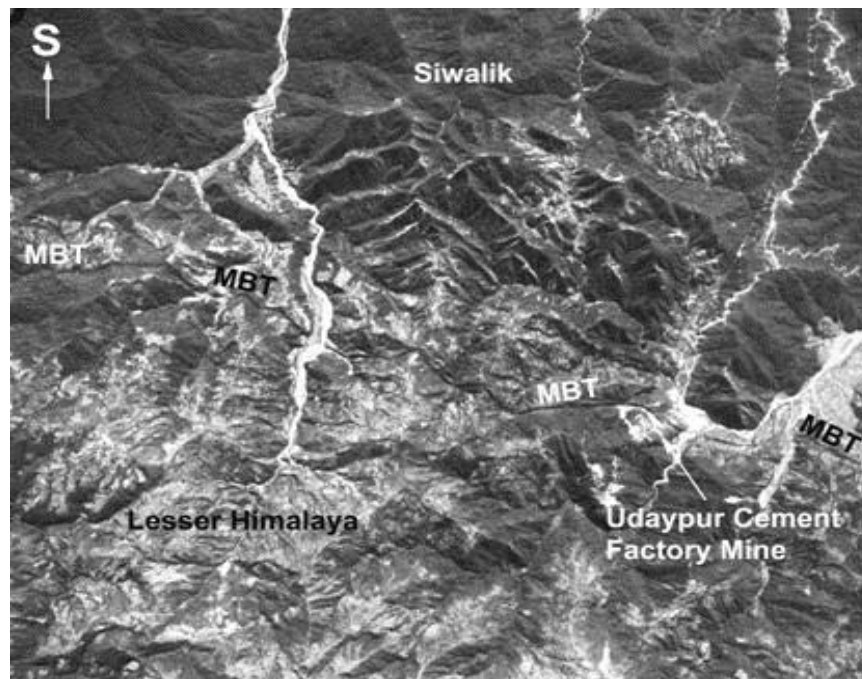


Figure 7.6: Aerial Photograph of Udaypur District (Eastern Nepal) Well Marked Main Boundary Thrust (MBT) is Passing through Middle of Photograph



Figure 7.7: MBT Observed in Butwal-Tansen Section of Siddhartha Highway

From east to west, the Lesser Himalayan Zone of Nepal varies in rock type, age, structures, and igneous rock intrusion. Eastern Nepal is characterized by the development of extensive thrust sheets (allochthonous) of high grade metamorphic rocks (gneiss and schist) which have moved southwards. Below this sequence, due to erosion, large exposure of the low-grade metamorphic rocks (autochthonous) can be seen. In Central Nepal, a large thrust sheet called the Kathmandu Nappe (allochthonous) covers a wide area around the Kathmandu region. Whereas west of Kathmandu, between the Budhi Gandaki and Bheri rivers, amount of transported high grade metamorphic rocks (allochthonous) is very low and the area is generally covered by autochthonous sequence. But in west of the Bheri River, up to the western border of Nepal (Dadeldhura-Baitadi) high-grade metamorphic rocks reappear and cover much of the terrain.

7.1.7 The Greater Himalayan Zone

The Higher Himalayan zone mainly consists of huge pile of strongly metamorphosed rocks. Geologically, the Greater Himalayan Zone includes the rocks lying north of the Main Central Thrust (MCT) and below the highly fossiliferous Tibetan-Tethys Zone. This zone is separated with Tibetan-Tethys Zone by normal fault system called as South Tibetan Detachment System (STDS). Higher Himalayan Zone consists of an approximately 10 km thick succession of strongly metamorphosed coarse grained rocks. It extends continuously along the entire length of the country as in whole Himalaya, and its width varies from place to place (see Figure 7.1). The kyanite - sillimanite minerals bearing gneisses, schists, and marbles of the zone form the basement of the Tibetan-Tethys Zones. Granites are found in the upper part of the unit.

7.1.8 The Tibetan-Tethys Zone

The Tibetan-Tethys Zone lies in northern part of the country. It begins from the top of the South Tibetan Detachment System (STDS) and extends to the north in Tibet (Figure 7.8). In Nepal, the fossiliferous rocks of the Tibetan-Tethys Zone are well-developed in Mustang, Manang and Dolpa area (Figure 7.9). In eastern part, amount of exposure of the Tibetan Tethys Zone is almost negligible and found only in top of the Mount Everest (Figure 7.1). Most of the other Great Himalayan peaks of Nepal such as Manaslu, Annapurna, and Dhaulagiri have rocks of Tibetan-Tethys Zone. This zone is composed of sedimentary rocks, such as shale, limestone, and sandstone, ranging in age from Cambrian to Eocene. This zone in some area is found as continuous deposits of Higher Himalayan Zone without normal fault.

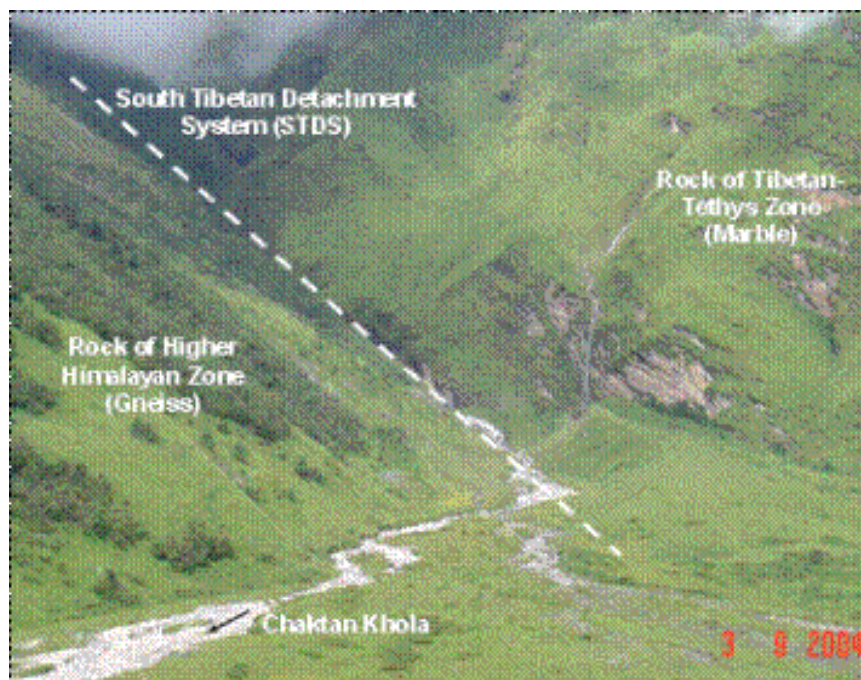


Figure 7.8: South Tibetan Detachment System Separating Higher Himalayan Zone from Tibetan - Tethys Zone, Chhaktan Khola, North West from Kokhethati, Mutang (Adopted from Dahal 2006)



Figure 7.9: Cliff of limestone belongs to Tibetan-Tethys Zone, Jomsom, Mustang (Adopted from Dahal 2006)

7.2 Physiography of the Nepal Himalaya

Physiographic division of Nepal has been in practice since 1950s. It was 1969, Tony Hagen successively divided Nepal into eight well defined physiographic provinces from south to north. These provinces are E-W running and can also be incorporated in Indian Himalayan belt. The Hagen classification is the most appropriate classification and represents all characteristic

physiographic zones of Nepal. Some geographer and geomorphologists also used fivefold classifications in the general sense namely Terai, Churai, Middle Mountain, High Mountain and High Himalaya. Nevertheless, detail physiographical provinces of Nepal are given in **Table 7.1** and **Figure 7.10**.

Table 7.1: Physiographical Divisions of the Nepal Himalaya (Modified after Upreti, 1999)

No.	Geomorphic Unit	Width (km)	Altitudes (m)	Main Rock Types	Main Processes for landform Development
1	Terai (Northern edge of the Gangetic Plain)	20-50	100-200	Alluvium: coarse gravels in the north near the foot of the mountains, gradually becoming finer southward	River deposition, erosion and tectonic upliftment
2	Churia Range (Siwaliks)	10-50	200-1,300	Sandstone, mudstone, shale and conglomerate.	Tectonic upliftment, erosion, and slope failure
3	Dun Valleys	5-30	200-300	Valleys within the Churia Hills filled up by coarse to fine alluvial sediments	River deposition, erosion and tectonic upliftment
4	Mahabharat Range	10-35	1,000-3,000	Schist, phyllite, gneiss, quartzite, granite and limestone belonging to the Lesser Himalayan Zone	Tectonic upliftment, Weathering, erosion, and slope failure
5	Midlands	40-60	300-2,000	Schist, phyllite, gneiss, quartzite, granite, limestone geologically belonging to the Lesser Himalayan Zone	Tectonic upliftment, Weathering, erosion, and slope failure
6	Fore Himalaya	20-70	2,000-5,000	Gneisses, schists, phyllites and marbles mostly belonging to the northern edge of the Lesser Himalayan Zone	Tectonic upliftment, Weathering, erosion, and slope failure
7	Higher Himalaya	10-60	>5,000	Gneisses, schists, migmatites and marbles belonging to the Higher Himalayan Zone	Tectonic upliftment, Weathering, erosion (rivers and glaciers), and slope failure
8	Inner and Trans Himalaya	5-50	2,500-4,500	Gneisses, schists and marbles of the Higher Himalayan Zone and Tethyan sediments (limestones, shale, sandstone etc.) belonging to the Tibetan-Tethys Zone	Tectonic upliftment, wind and glacial erosion, and slope degradation by rock disintegrations

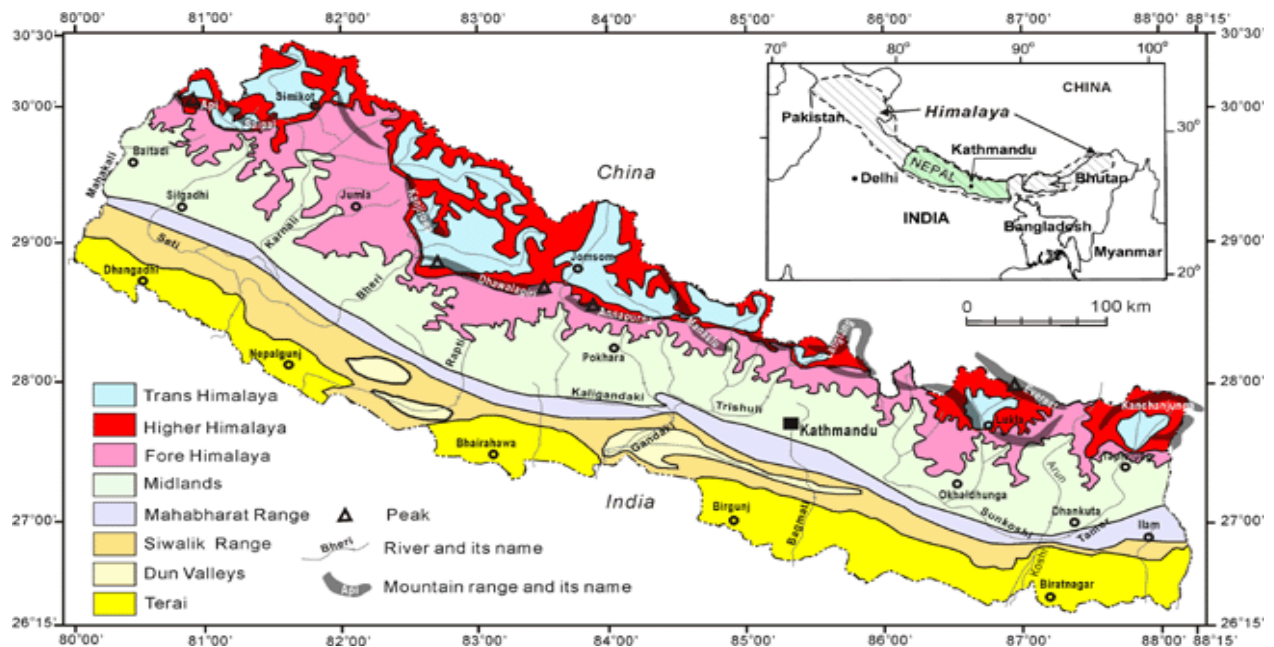


Figure 7.10: Physiography of the Nepal Himalaya (After Dahal and Hasegawa, 2008)

7.3 Surface Manifestations of Geothermal Resources

The only information on hot springs and geothermal resources of Nepal is from two papers by Ranjit (2005) and Ranjit (2010) which were published in the proceedings of World Geothermal Congress 2005 and 2010 respectively. This part of the report is mainly derived from these papers.

Surface display of geothermal energy in Nepal occurs in more than twenty-eight localities, mostly occurring along the Main Central Thrust in Lesser and Greater Himalyan Region while a few are located scattered near the Main Boundary Fault. **Figure 7.11** shows the location of the important hot springs.

7.3.1 The Darchula District Thermal Springs

It is the farthest western region which has three thermal springs located at Sina, Sribagar and Chamaliya localities. The Sina thermal springs occur in crystalline rocks located near the thrust contact between the overlying augen gneiss and the underlying sericitic schist and quartzite. The thrust is displaced by a recent fault on which many springs are aligned. The hot spring in Sribagar is located in the recent river sediments. The area is near the tectonic contact between the autochthonous metasedimentary zone and the crystalline sheet. The tectonic contact is marked by the highly crushed chlorite-sericite quartz phyllites on the ridge east of Sribagar. The Chamaliya spring issues from the recent terrace deposit and is confined to a meta sedimentary autochthonous zone composed of slates and carbonate rocks.

7.3.2 The Bajhang District Thermal Springs

The thermal springs in this district are near the major thrust between the crystalline allochthonous and meta sedimentary autochthonous zones. The purple shale and green sandstone with gritty quartzites are highly folded. The major thermal source is located near the thrust zone whereas the minor sources are either near some fault or the contact zone of different lithological units.

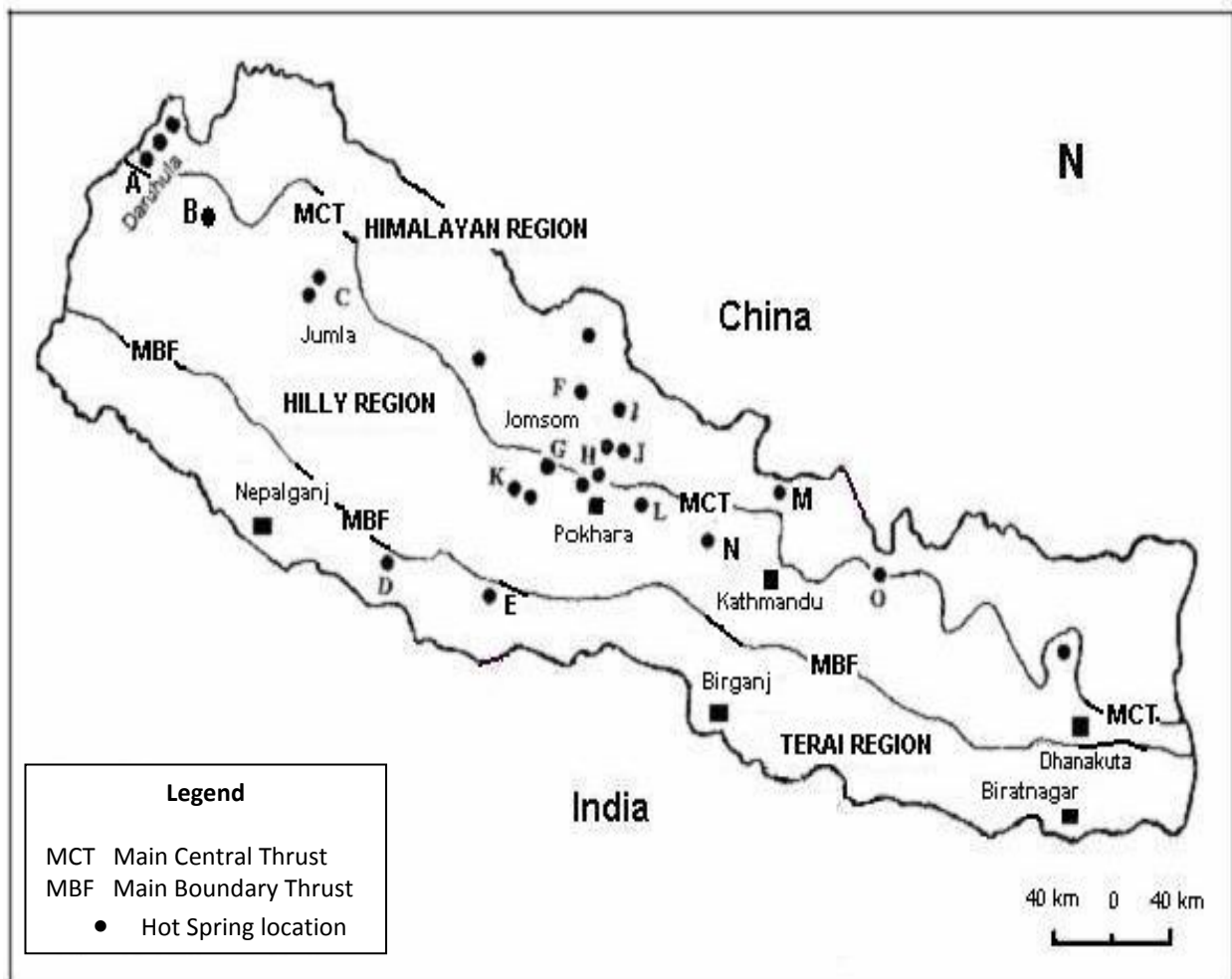


Figure 7.11: Location of Geothermal Springs in Nepal (After Ranjit 2005)

7.3.3 The Jumla District Thermal Springs

In Jumla district, the thermal springs occur mainly in Tila Nadi and Dhanchauri. The right bank of Tila Nadi accommodates a number of closely located hot springs. Gas seepage occurs in some of them in recent deposits of gravel and boulders with sandy-silty clay. Mini-folds and micro faults can be observed along the Tila Nadi valley indicating the neotectonic activity. Two seepages occur at the fracture joints in the calcareous gneiss and marble.

7.3.4 The Dhanchauri Area Thermal Springs

In Dhanchauri area the springs issue from the light-grey platy dolomite and are characterized by a thick tuffaceous deposit consisting of carbonate and silica. Three major hot springs are located here.

7.3.5 Riar Thermal Spring

It is located at the south of the Siwalik formation (a northern chain of hills reaching a height of some 1500 m and the rock in the immediate vicinity is covered by soil.

7.3.6 The Mayangdi Thermal Spring

The spring issues from the base of a cliff of poorly cemented Quaternary conglomerates. An extensive fault passes through it and carbonaceous and schist and siltstone are exposed on both sides of the fault. There are four springs in this locality.

7.3.7 Surai Khola Thermal Spring

The rocks surrounding thermal spring in this area are sandstone, siltstone and clay, belonging to the middle Siwalik. There are two discharge points in this area.

7.3.8 Thak Khola – Mustang Thermal Spring

The springs in the area are located at the foot of a berm about 100 m high on the bank of the Kali Gandaki River. Five springs are located here. However, the flow rates are extremely low and all the springs are issuing from a single source.

7.3.9 The Western Region Thermal Springs

Some other prominent geothermal springs in the Western Region are Bhurung Tatopani, Dokhola, Singha Tatopani (Myagdi district). One more thermal spring has been reported at the bank of a river near Darbang in the Myagdi District. No further specify information is available. The other occurrences of hot springs are Chhumrung and Dhadkharka (Parbat district), Dhee and Lo-Manthang (Mustang district), Chame (Manang district), Bhulbhule Khar (Lamjung district) and Khar Pani (Kaski district). Unlike most of the springs that occur along the river banks, the spring in Chilime issues on the top of a cliff. The surrounding bedrock of this thermal spring consists of quartz, biotite sandstone, graphitic argillaceous schist and siliceous limestone. In Syabru Besi, two springs can be noted in the river bank. One of them has been extensively used by the trekkers and the local hotel businessmen for cooking purposes. In the Kodari area, hot water issues at several points. The surrounding bedrock is of quartz biotite sandstone overlain by slightly graphitic argillaceous schist and underlain by siliceous limestone. The physical infrastructure of the spring area is under improvement despite continuous land slides.

7.3.10 The Eastern Region Thermal Springs

Only one thermal spring has been identified in the eastern part of Nepal. Even though this spring at Hatiya (Sankhuwasabha district) is popular among local community and the access road made more comfortable to attract increased number of visitors, no geochemical studies have been made so far.

7.4 Geothermal Potential

The updated chemical data of the thermal springs are given in **Table 7.2**. Sribagar records the maximum surface temperature (with 73.4°C) among the thermal waters in Nepal. This is followed by 71°C in Bhurung Tatopani at Myagdi district. Temperatures above 40°C were recorded for six other springs.

Table 7.2: Geothermal Localities and their Salient Features (After Ranjit 2005)

Locality	Symbol	Location		Flow Surface (l/s)	Surface Temp. (°C)	Geothermometer Temp.(°C)			Ionic Balance Diff.(%)	Discharge Enthalpy (kJ/kg)
		Lat. (E)	Long. (N)			SiO ₂	Chalce Dony	Na/K Ratio		
Darchula	A									
Sribagar		80.6°	29.9°	0.9	73	85.1	54.2	88.2	-34.3	380
Sina Tatopani		80.7°	29.9°	0.8	30	37.6	55	52.3	4.8	255
Chamaliya		80.6°	29.7°	0.3	30	55.1		100.4	1.61	158
Tapoban	B	81.2°	29.6°	0.3	31	106.9		115.3	-0.19	126
Jumla	C									
Dhanchauri-		82.3°	29.3°	0.8	24	110.6			4.52	448
Luma		82.1°	29.2°	1.3	42	50.1			-21.03	464
Tilanadi		82.7°	27.9°	1.5	33	50.3				227
Riar	D	83.3°	27.8°	1.7	36	115.4				210
Surai Khola	E	83.7°	29.8°	3	22	109.8				211
Jomsom	F	83.7°	28.5°	1.8	72	89.8				484
Bhurung Tatopani	G	115.4°	28.4°	1.5	68	91				460
Sadhu Khola	H	84.1°	28.4°	0.4	49	98.8				376
Kharpani	I	83.5°	28.4°	2	40	86.5				452
Mayangdi	J	83.3°	28.2°	6	54	96.5				386
Singha Tatopani	KL	84.2°	28.2°	1.2	34					365
Bhulbhule Khar	M	85.3°	28.3°	0.9	48					17
Chilime	N	85.2°	28.1°	0.4	34					
Syabru Besi	O									
Kodari		83.9°	27.9°	5.5	42					

The results of the chemical analyses for some thermal springs are shown in **Table 7.3**. Studies from the available chemical data of geothermal spring waters show extensive interaction with

rock at comparatively low temperatures (**Table 7.3**). The spring waters of Jomsom, Sadhu Khola, Bhurung Tatopani, Chilime, Sribagar, Dhanchauri and Tila Nadi are in equilibrium and all the other springs waters are unsaturated with the most common hydrothermal alteration minerals. The spring waters at Bhurung Tatopani and Sadhu Khola are chloride waters (relatively mature) and those of Jomsom, Dhanchauri-Luma, Mayangdi, Surai Khola and Chilime are representative of the waters with high CO₂ reactivity. Somewhat detailed chemical analyses of thermal springs including isotopic composition indicate that a large geothermal reservoir exists in the western Nepal. There also exists a good opportunity to exploit this energy resource for various direct uses in this region because of the comparatively good terrain and possibility of future road network development.

Table 7.3: Chemical Composition of Some Thermal Spring Waters (After Ranjit 2005)

Location	pH	Na	K	Mg	Ca	Cl	SO ₄	HCO ₃	SiO ₂	B	TDS
BhurungTatopani	7	370	95	27	108	583	207	370	71	14.1	1,650
Jomsom	8	60	5.6	54	113	96	249	302	14.3	2.4	850
Tila Nadi	7.3	56	0	1.2	6	45	130	0	60	0	353
Dhanchauri Luma	7	49	1.3	0.2	6.1	82	104	217	56	0	803
Mayangdi	8	460	49	17	2	351	68	430	43	0.3	1,340
Riar	9	310	4	3	4	14	70	7.9	37.5	6	788
Surai Khola	9	123	3.9	28	18	3.2	70	370	38.5	0.1	510
Sribagar	7	100	11	8.5	na	34.2	18.5	Na	35	0	516
Chamliya	7	Na	Na	Na	na	39.6	10.7	Na	10	na	1,320
Tapoban Bajhang	5	Na	22	10	na	50.1	25.9	Na	16	0	444
Sadhu Khola	7	300	12	0.6	10	286	197	78	60	0	954
Chilime	7	7.35	8.1	20.8	25.8	10	6	180	47.1	0	166
Singha Tatopani	7.2	64	1.5	1.8	6.8	51	140	10	68	0	353
Syabru Besi 1	8	73	44	84	38	66	94	848	59.7	na	620
Syabru Besi 2	7.5	7.2	12.5	90.5	75.9	12	121.4	760	35.3	na	1,300
Kodari	7.3	147	29.7	20.5	53.5	31.5	85.6	412.5	44.3	1.36	NA

One of the notable achievements in the geothermal update period is that the government has prepared 'Alternative Energy Perspective Plan' (2002-2017) which recognizes geothermal energy as one of the alternate source of energy for Nepal. The plan includes updating the geothermal data; undertake feasibility studies for direct heat use and popularization activities. The Government of Nepal initiated geothermal programmes in 2001 through Alternative Energy Promotion Centre and carried out field surveys of two popular and accessible geothermal locations (Kodari and Singha Tatopani). However, the study limited to undertaking preliminary chemical analysis of thermal water. General information of other thermal springs has been updated by Ranjit (2005).

The hot springs are presently being used for bathing activities alone. Considerable attention has been paid to make the spring areas environmentally sound with proper management and minimizing the use of solid wastes in the vicinity. This sort of awareness is growing rapidly in areas where the number of visitors is increasing. No other environmental laws, legislations or policies exist at any level in exploiting geothermal resource in Nepal because its development is still at the grass root level.

Ranjit (2010) carried out an evaluation of geothermal reservoir in Central Nepal on the basis of geochemical parameters (**Figure 7.12**). According to him the oxygen-18/16 and deuterium ratios of water samples collected from 36 hot springs have been determined in the central region. The tritium activity of 14 of them shows that the thermal waters where outflow temperatures are up to 71 °C are characterized by two features, results of stable isotope measurements fit the so-called world meteoric line and all the springs tested have tritium activity between 7 and 68 T.U. The author has combined the results of other geochemical data of the thermal water in the area with the results of the above isotope study to undertake preliminary estimation of the reservoir size.

If the tritium content is appreciable and variable with time, it means that an appreciable amount of water younger than 40 years is present and the variations imply a short circulation time of the order of a few years. Another possibility is that waters from two different sources are present: a mixture of old tritium-free water and a young water containing tritium. If the tritium content is appreciable and constant in time, the younger water is well mixed in the aquifer with old water and the size of the reservoir masks any fluctuations in recharge.

However, it has been found that the waters at Sadhu Khola, Tatopani-Mustang and Mayangdi lying in this region have relatively high chloride content suggesting that the waters are fairly mature. Variation in oxygen and hydrogen isotopes show the high possibility that waters from two different sources are mixed. Since tritium is present inappreciable quantity, younger water is well mixed in the aquifer with old water and the size of the reservoir masked any fluctuations in recharge. Hence there is possibly a large geothermal reservoir in the Sadhu Khola – Jomsom area in the central region of Nepal.

The tritium activity of 14 of them shows that the thermal waters where outflow temperatures are up to 71°C are characterized by two features, results of stable isotope measurements fit the so-called world meteoric line and all the springs tested have tritium activity between 7 and 68 T.U. (**Table 7.4** and **Figure 7.12**).

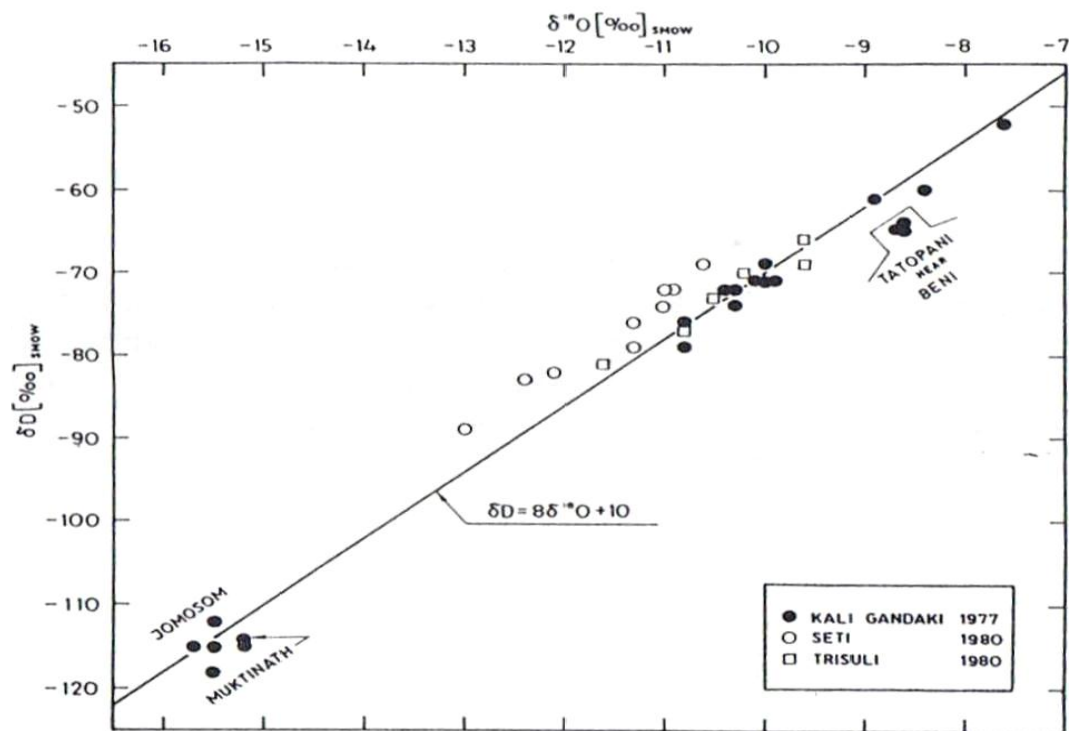


Figure 7.12: $\delta^{18}\text{O}$ - δD Correlation of Analyzed Waters (Grabczak and Kotarba, 1985)

7.5 Estimation of Reservoir

Even though the **Table 7.2** suggests that none of the springs have a huge mass flow rate, a number of springs emerging in the vicinity could have lowered the flow rate. Water containing chloride concentration less than 100 ppm in case of Jomsom and Singha Tatopani (only two springs applicable here) does not meet the mixing characteristics since their pH values do not lie between 6 and 7; calcite is either supersaturated or almost saturated in Jomsom, Mayangdi and Sadhu khola, suggesting that there is no mixing. No high concentration of silica is observed relative to discharge temperature in all the five spring waters. However, there is a variation in oxygen isotopes ranging between -7.6 and -15.7 and variation in hydrogen isotopes between -52 and -118. It leads to conclude that the waters are mixed. The waters at Sadhu Khola, Tatopani-Mustang and Mayangdi lying in this region have relatively high chloride, suggesting that the waters are fairly mature as indicated by the Giggen bach's diagram of concentrations of the major anions, Cl^- , SO_4 and HCO_3^- . Appreciable tritium content shows that the younger water is well mixed in the aquifer with old water and the size of the reservoir masked any fluctuations in recharge.

**Table 7.4: Isotopic Composition of Waters from Central Nepal
(Modified After Grabczak and Kotarba, 1985)**

Region - altitude	Spring no.	Temp. (°C)	Discharge (l/s)	TDS (g/L)	$\delta^{18}\text{O}$ (‰)	δD (‰)	Tritium (T.U.)
Tatopani – Beni - 900	B-1	35.8	1	0.46	-8.6	-65	45±2
	B-2	34.4	0.4	-	-8.6	-64	-8.6
	B-3b	52.3	-	1.68	-8.7	-65	13±1.5
Tatopani - 1250	T-1	44	0.3	1.14	-8.9	-61	33±2
	T-2c	63	0.1	-	-10	-69	-
	T-7B	61	0.2	-	-10	-71	-
	T-8	71	1.8	1.84	-10.3	-72	7±1.5
	T-10a	70	0.7	-	-10.4	-72	-
	T-10b	55	0.1	-	-10.3	-74	-
	T-16	35	0.05	-	-10.8	-76	-
	T-17b	66	0.5	-	-9.9	-71	-
	T-19c	64	1.1	-	-10.1	-71	-
	T-20	21.4	-	-	-7.6	-52	-
	T-21	25.4	3	0.98	-8.4	-60	55±2
	T-22	63.5	0.7	4.69	-10.8	-79	10±1.5
Jomsom – 2850	J-1a	20.8	4.5	-	-15.7	-115	-
	J-1b	20.7	0.2	0.89	-15.5	-112	63±3
	J1-c	20.6	3.1	0.96	-15.5	-115	68±3
	J-2	19	5	-	-15.2	-115	-
	J-3	13.8	3.5	-	-15.5	-118	-
Muktinath - 3800	M-1	6.5	0.07	0.38	-15.2	-114	67±3
Mirsa – Seti Khola Area – 1200	SK-1b	44	0.3	3.32	-10.9	-72	14±1.5
	SK-2	35.4	0.6	-	-11	-74	-
Jamaile -1500	SJ-1	30.6	0.05	-	-11.3	-79	-
Machhapuchhre base camp - 800	SM-1a	64	2.2	1.02	-13	-89	8±1.5
	SM-2	22.4	0.1	-	-11.3	-76	-
	SM-3	43	0.01	-	-12.1	-82	-
	SM-4	9.8	-	-	-10.6	-69	-
Down Batese -1900	SB-1b	44.3	0.1	0.42	-12.4	-83	-
Up Batese - 2000	SB-2	21.5	0.2	-	-11	-72	-
Syabru Besi – Trisuli area	TS-1	38	0.2	0.63	-10.2	-70	24±1.5
	TS-2	51	0.02	1.98	-9.6	-66	7±1.5
	TS-3	35.5	0.3	-	-10.8	-77	-
	TS-4	30	0.01	-	-9.6	-69	-
	TS-5	23.5	0.05	-	-10.5	-73	-
Pargang - 2600	TP-1	49	3.8	0.39	-11.6	-81	20±1.5

7.6 Conclusions

The isotopic study by Ranjit (2010) indicates possibility of a large geothermal reservoir in the Sadhu Khola–Jomsom area in the central region of Nepal. However these qualitative estimations can be ascertained by geophysical investigations.

If sufficient geothermal reservoirs at localities such as Sribagar (surface temperature 73°C), and Sadhu Khola (surface temperature 68°C) can be considered as candidate for generation of electricity. Evidently, other geothermal springs with low temperature are not technically and economically viable for the generation of electricity in Nepal.

The use of geothermal water in Nepal is still constrained by the lack of road network. The update period witnessed the opening of two trade ports in the mountainous districts viz. Kimathanka and Chid (Sankhuwasabha district) and Nechung and Lizi (Mustang district) bordering China. These ports will soon yield greater access to the adjacent geothermal areas. The on-going construction of north-south highways (Surkhet-Jumla, Baitadi-Darchula, and Baglung- Jomsom) will play significant role in connecting a number of geothermal springs upon their completion.

The concept of using low temperature water for purposes other than bathing cannot be realized in Nepal without some pilot scale demonstration projects. The efforts in this direction are needed from the government side as well research organizations and academia.

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CHAPTER – 8

GEOTHERMAL RESOURCES OF PAKISTAN

8.1 Plate Tectonics (After Wandrey, Law, and Shah, 2000)

The structural and stratigraphic features of Pakistan are derived from tectonic events associated with plate movements that occurred from latest Paleozoic time to the present. In the Late Precambrian, Pakistan was on the northern margin of Gondwana facing the Tethyan Ocean (Scotese et al., 1988). The northern margin of Gondwana was undergoing intracratonic rifting with deposition of thick clastics, marine carbonates and locally evaporite sequence. The north of the country was in a passive margin setting, while sediments to the south of that were probably laid down under partly restricted shallow marine conditions in interior rifts in intermittent connection with Tethys. Cambrian sequences of Oman, Pakistan, India and central Australia appear to be deposited on near shelf environment.

Widely separated outcrops of Ordovician, Silurian, Devonian and carboniferous rocks are present in complexly tectonized orogenic belts along the western and northern rim of Indian Plate (Gaetani, 1997). In Indus Basin, Cambrian sediments are overlain unconformably by the Permian, and it is not certain whether the intervening systems were deposited and then eroded, or whether they were ever deposited at all.

Paleogeographic setting suggest that Tethys was at its widest in the Late Permian and From Permian through Middle Jurassic time, the Indian plate, including its continental shelf was located in the southern hemisphere, between the African, Antarctic, and Australian plates which were part of southern Gondwana. A thin strip of continental fragments that now underlie Iran were separating from the Arabian Plate. Basal Permian glacial deposits on the southern part of the Indian plate and Lower Permian Tobra Formation tillites in the Kohat-Potwar area (Upper Indus Basin) indicate a cool Permian climate (Shah, 1977). Following the period of glaciation, the area that is now the Upper Indus Basin, Kohat and Potwar Plateaus, and Sulaiman-Kirthar fold belts became part of a shelf system. The shelf and shallow marine stages are reflected in the rocks of the Permian Nilawahan and Permian Zaluch Groups. More or less the same situation existed up to the Late Triassic, although a rift system had formed between the Indian Plate and the Afghanistan-Arabia-Africa Plates. In the Triassic, shelf-system strata extended to the Lower Indus Basin and are preserved in the Triassic Wulgai Formation and Jurassic Shirinab Group. A carbonate-dominated shelf environment persisted at least intermittently on the western part of the Indian plate through Late Jurassic, exemplified by the interbedded shales and thick limestones of the Springwar Formation and as much as 1,400 m of the Middle and Late Jurassic Sulaiman Limestone Group, which accumulated on the western and northern portions of the plate. The earlier shallow marine continental interior of western Pakistan was also replaced by the development of passive marginal environments. In the Early Jurassic, passive margin thermal subsidence resulted in the deposition of a thick succession of fine grained clastics in western part of Pakistan. By the Late Jurassic, the combination of widespread

passive margin conditions and tectonic quiescence resulted in the establishment of a widespread carbonate platform over much of the country.

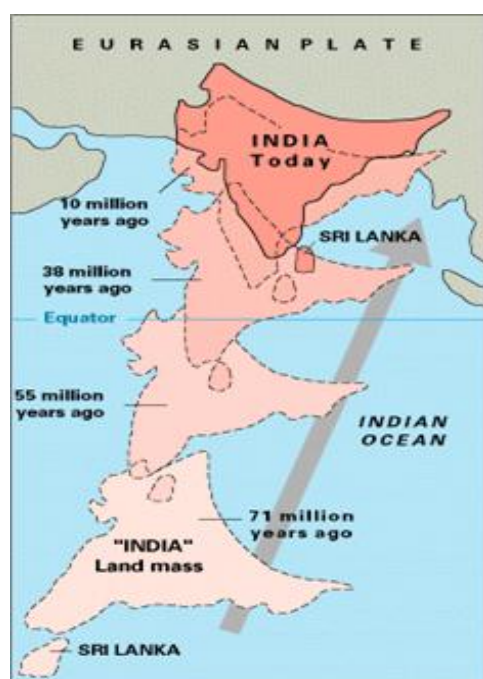
Gondwana continued break-up during the Late Jurassic to Early Cretaceous and contributed to a postulated deep-seated shear zone and horst-and-graben regime and later, a division of the greater Indus Basin into three subbasins at the Mari-Kandhot and Sargodha structural highs (Kemal and others, 1992). Late Jurassic rifting also initiated separation of Australia and Antarctica from India. During Early Cretaceous time the Indian plate drifted northward and on the western shelf, marine shales, limestones, and near shore sandstones of the Lower Cretaceous Sembar and Goru Formations were deposited over a regional erosional surface on the Sulaiman Limestone Group. In the Kohat-Potwar area, this erosional surface is present at the top of the Samana Suk Limestone Formation and is overlain by Lower Cretaceous Chichali Formation sandstones and shales (Shah, 1977; Iqbal and Shah, 1980). Conditions were once again more quiescent by the mid-Senonian, as reflected by the development of a widespread carbonate platform across much of western Pakistan. Along the eastern portion of the Indian plate, Rajmohal Trap volcanics and the Bolpur and Ghatal Formations were deposited. Although the carbonates are recognized primarily on the eastern and western shelves today, it is likely that they were deposited over much of the northern Indian shelf. This shelf environment persisted through Late Cretaceous time when regressive sandstones such as the Lumshiwal and Pab Formations in the west and Tura Formations in the east were deposited. At this stage too, the micro continental fragments on the north side of Tethys were coalescing to form the southern edge of the Eurasian Plate, and Tethys was closing, but there was as yet no effect of this in Pakistan.

During the Late Cretaceous, India continued drifting northward and split away from Madagascar. Northward plate movement continued during the latest Cretaceous, and a transform fault became active along the ninety-east ridge with extensional faulting or reactivated as the western part of the Indian plate sheared southward relative to the main plate (Kemal and others, 1992). India also passed over the Reunion hot spot, resulting in the eruption of the Deccan Trap. These events resulted once again in uplift of the continental interior of the Indian Plate, and the replacement of the carbonate platform by a more clastic-dominated regime. From Late Cretaceous through middle Paleocene time, trap deposits and basal sands continued to accumulate on the Assam-Arakan, Indus, Bombay, and Bengal shelves (**Figure 9.1**).

Oblique convergence of the Indo-Pakistan plate with the Afghan and other micro plates resulted in wrench faulting and development or reactivation of regional arches such as the Jacobabad and Sargodha Highs in the Indus Basin (Kemal and others 1992). At this time too, there was interaction between the northwestern edge of the Indian Plate and the Afghan and Kakar-Khorasan micro continental blocks, resulting in sinistral transpression between them.

The Indian plate continued to move northward at an accelerated rate of 15-20 cm/yr. When the eastern edge of the plate passed over the Kerguelen hot spot, a chain of islands began to form near E 90° longitude. Northward-directed subduction has also continued beneath the Hindu Kush from the Mesozoic, when the region formed part of the southern margin of Asia, until

today. The Kohistan arc was accreted at ca. 100 Ma, followed by the Indian plate at 54–50 Ma. After the India-Asia collision, a regional crustal-melting event occurred at ca. 25–21 Ma to the east of the Hindu Kush in the Karakoram Range, producing the Baltoro pluton. In the eastern Hindu Kush Range, most of the granitoids appear to be subduction-related plutons that predate the India-Asia collision. However, the Gharam Chasma pluton is a two-mica ($\pm$ garnet $\pm$ tourmaline) leucogranite that has intruded into staurolite-grade schists and (sillimanite $\pm$ K-feldspar)–grade migmatites. U-Pb ages on monazite, xenotime, and uraninite from undeformed samples of the Gharam Chasma pluton and a leucogranite dike that crosscuts the migmatites indicate that crustal melting occurred at ca. 24 Ma, synchronous with the Baltoro melting event. This age also provides an upper limit on the age of the regional staurolite-grade metamorphism in the eastern Hindu Kush (Hildebrand et al., 2001).



a. Paleogeographic Map of the Latest Cretaceous (Approximately 69 Ma)



b. Perspective is from lat 20°S., long 68°E

Figure 8.1: Northward Drift of Indian Plate since Cretaceous (Modified from Scotese and Others, 1988; Scotese, 1997)

Continued northward movement and counter-clockwise rotation of the Indian plate slowly closed the Tethyan Sea along the northern and northwestern plate boundaries. The Sulaiman-Kirthar fold belt began to develop as a result of the oblique collision and rotation, with the Sulaiman lobe developing in a thin-skinned roof-duplex geometry (Jadoon et al., 1994). Regional uplift and rising mountain ranges on the Eurasian plates to the north and west created a new sediment source, and the prevailing sediment transport direction of south to north was reversed. From Eocene through middle Miocene time, carbonate platform buildup occurred intermittently on the shelves around much of the Indian plate. A trench formed along the subduction zone as the Indian plate began to slip beneath the Eurasian plate. The Eurasian plate shed large volumes of sediments into the trench as subduction continued. This terrestrial sediment influx from the

rapidly rising Himalayan, Sulaiman-Kirthar, Sino-Burman and Indo-Burman Ranges significantly exceeded carbonate buildup rates on late Miocene platforms (Roy Choudhury and Deshpande, 1982) and smothered carbonate reef formation along the shelf areas. The former shelf areas along the collision zones were either subducted or became emergent fluvial-deltaic environments. The shelf in the greater Indus Basin area tilted downward toward the west and northwest. In the Kohat-Potwar geologic province, shallow southwest-northeast-trending anticlines and overturned folds developed on multiple detachment surfaces. The detachment surfaces as deep as Eocambrian salts developed as a result of continued plate convergence and associated crustal shortening of as much as 55 km occurred (Kemal et al., 1992; Jaswal et al., 1997).

The proto Indus, Narmada, Ganges, Brahmaputra, Meghna, Chindwin, and Irrawaddy Rivers developed extensive deltas as the Himalayas and other ranges continued to shed sediments at a high rate. Today, uplift of the mountain ranges, crustal shortening, and subduction of the Indian plate continues and the growth rate of the Indus, Ganges-Brahmaputra (Megna), and Irrawaddy deltas remains high.

The Main Mantle Thrust (MMT) represents the tectonic boundary between metamorphic shield and platform rock of the Indian plate hinterland, and dominantly mafic and ultramafic rock of the Kohistan-Ladakh arc complex in Pakistan. In some areas, this boundary is a sharp planar fault with development of mylonite; in other areas, it is a brittle-ductile imbricate zone; in still other areas, it contains large, discontinuous, slices of internally sheared and deformed ophiolitic mélange. The character of the MMT along its entire trace is discussed and it is concluded that there is no single continuous fault which marks the contact between the Indian plate and the Kohistan-Ladakh arc. On this basis a revised definition for the MMT is proposed that is consistent with both the original definition and with the usage of the term in literature. We suggest that the MMT fault contact be defined as the series of faults of different age and tectonic history that collectively define the northern margin of the Indian plate in Pakistan. On this basis, faults that define the MMT vary in age from Quaternary to possibly as old as Late Cretaceous. Discontinuous lenses of ophiolitic mélange that overlie the MMT fault contact and which intervene between the Indian plate and the Kohistan-Ladakh arc, are considered to be part of an MMT zone that is equivalent with the Indus Suture Zone. (DiPietro, et al. 2000). Tectonic map of Pakistan (**Figure 8.2**) exhibits the tectonostratigraphic subdivision and structural configuration resulting from northward drifting of Indian Plate and its collision with the Eurasian Plate.

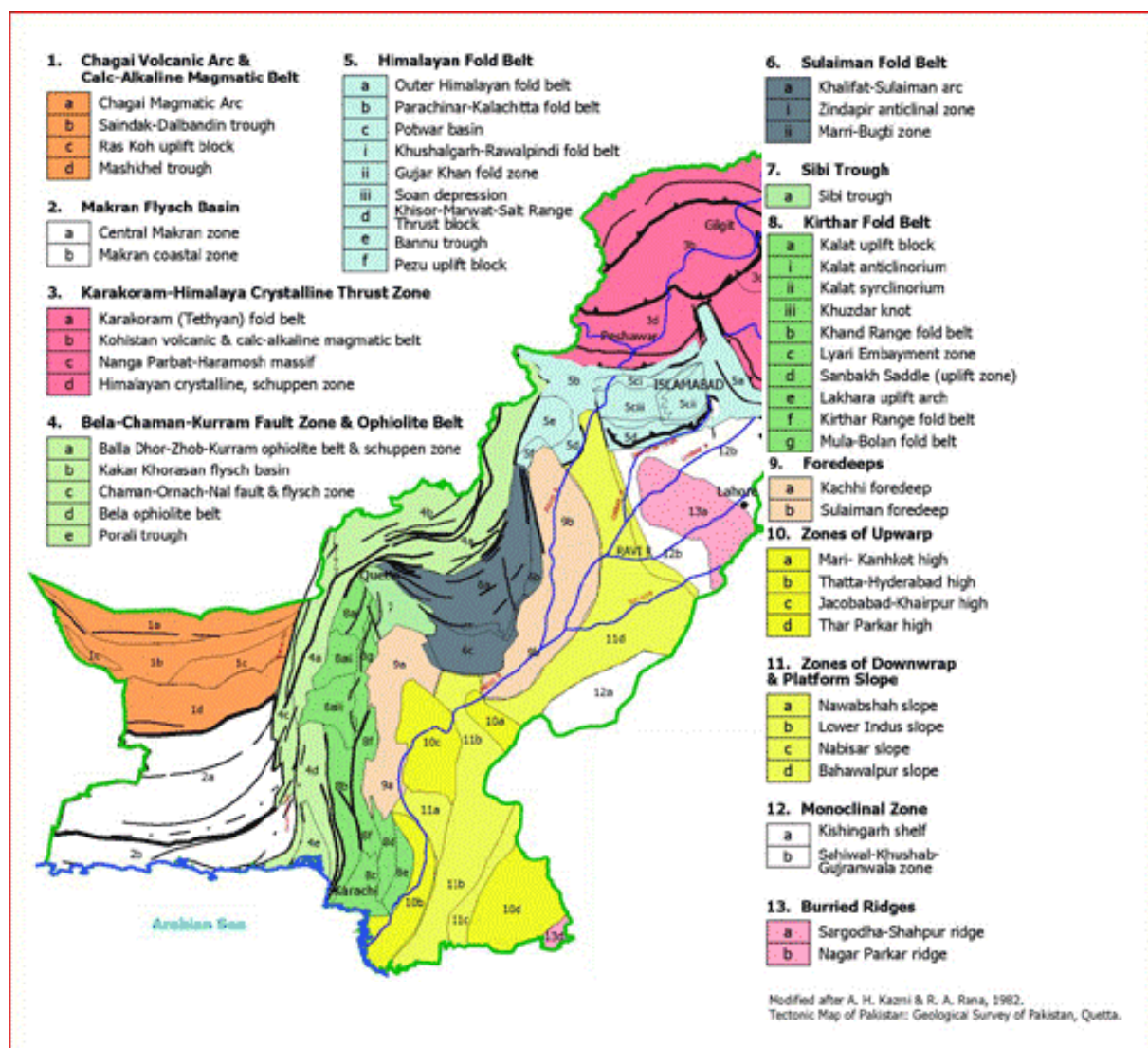


Figure 8.2: Tectonic Map of Pakistan

8.2 Stratigraphy (After Wandrey, Law, and Shah, 2000)

8.2.1 Precambrian and Paleozoic Stratigraphy

Precambrian and Paleozoic rocks are exposed in the Upper Indus Basin/Kohat-Potwar area. In the Middle and Lower Indus Basins, Precambrian and Paleozoic rocks have been encountered during drilling and observed in outcrop only at the easternmost edge of the basin. Precambrian granite basement rocks are overlain by the Precambrian-Cambrian, closed-basin, sedimentary rocks of the Jhelum Group. In the Kohat-Potwar area the Jhelum Group includes the Salt Range Formation shales and evaporites and the Middle and Lower Indus Basins are floored by the Indian Shield, Nagar Parkar Granite, and the younger interbedded slates, quartzites, andesites, and rhyolites of the Kirana Group (Iqbal and Shah, 1980; Shah, 1977).

Following a basin wide hiatus lasting from Cambrian to Permian, the Permian Nilawahan Group was deposited at least in the Kohat-Potwar area. The Nilawahan Group consists of the Tobra

Formation glacial tillites, siltstones, and shales; the Dandot Formation glacial coarse sandstones and shales; the Warchha Formation coarse grained argillaceous sandstones and minor shales and the sandstones and shales of the Sardhai Formation (Shah, 1977; Iqbal and Shah, 1980; and Kemal, 1992). Overlying the Nilawahan Group are the shelf carbonates of the Middle to Upper Permian Amb and Wargal Formation of Permian Amb and Wargal Formation of the Zaluch Group and the marls and coarsening-upward sandstones of the Chhidru Formation. The Tobra and Wargal Formations have produced oil and gas on the Potwar Plateau.

8.2.2 Mesozoic Stratigraphy

Mesozoic rocks in the Indus Basin are generally preserved in the Salt Range and southeast Potwar Basin; however, part or all of the Mesozoic stratigraphic section is missing from the Kohat Plateau and northwestern Potwar deformed zone (Jaswal et al., 1997). Westward depositional thinning and erosion account for the missing rocks. The Triassic Musa Kehl Group Mianwali and Tredian Formations continental, sandstones, shales, and carbonates were deposited unconformably on the Permian rocks. Overlying the Tredian are shelf carbonates of the Triassic Kingriali Formation. The Triassic formations were formerly referred to collectively as the Wulgai Formation. The overlying Jurassic rock sequence includes the Shirinab or Datta and Shinawari Formations that were deposited as near shore variegated siliciclastics containing some non-marine sandstone intervals (Khan et al., 1986). The Datta has produced oil and gas. Overlying these near shore rocks are as much as 900m of platform carbonates of the Samana Suk Formation. The Lower Cretaceous section consists of Chichali basinal shales and massive cross bedded sandstones of the Lumshiwal Formation (maximum basin flooding surface). The Upper Goru, Ranikot, Pab, and Moghal Kot siliciclastics, representing Late Cretaceous low stand events, are present southeast of the Salt Range but are not reported within the Potwar Basin.

The Cambrian-early Mesozoic hiatus in the Middle and Lower Indus Basin was probably followed by deposition of shallow-marine shales and limestones of the Triassic Wulgai Formation that are exposed in the Axial belt (Iqbal and Shah, 1980; Shah, 1977). Jurassic shallow-marine limestones and shales of the Shirinab, Chiltan, and Mazar Dirk Formations extend over the Lower Indus Basin, Sulaiman-Kirthar geologic province and Axial belt (**Figure 8.3**). The top of the Jurassic is marked by a basin wide unconformity.

Lower Cretaceous rocks are represented by as much as 250m of black shale and siltstone and argillaceous limestone of the Sembar Formation and as much as 500m of limestone, interbedded shale, and sandstone of the lower Goru Formation. The shelf to shallow-marine environment persisted through most of Late Cretaceous time, represented by carbonates of the Parh, shales, sandstones, and limestones of the Moghal Kot, and limestones and shales of the Fort Munro/Pab Formations. The regressive Pab Sandstone represents a change to a near shore environment. Unconformably overlying the Pab are the shallow marine limestones and shales of the Upper Cretaceous Moro Formation (Iqbal and Shah, 1980; Shah, 1977). iii) Cenozoic Stratigraphy

In the Lower Indus Basin and the Sulaiman-Kirthar geologic province, fluvial sandstones and estuarine shales and limestones make up the Paleocene Ranikot Group. Shallow marine to estuarine limestones and calcareous shales of the Eocene Laki Formation and contemporaneous shales and sandstones of the Ghazij Formation are conformably overlain by interbedded limestones and shales of the Eocene Kirthar Formation. The Kirthar was deposited in the Lower Indus Basin, Sulaiman-Kirthar geologic province, and Kohat Plateau (Iqbal and Shah, 1980; Shah, 1977). Nearshore sandstones and shales of the Oligocene Nari Formation and shales of the lower Miocene Gaj Formation make up the Momani Group. The Miocene to Pliocene clays, sandstones, and conglomerates of the Siwalik Group mark a change to nonmarine deposition.

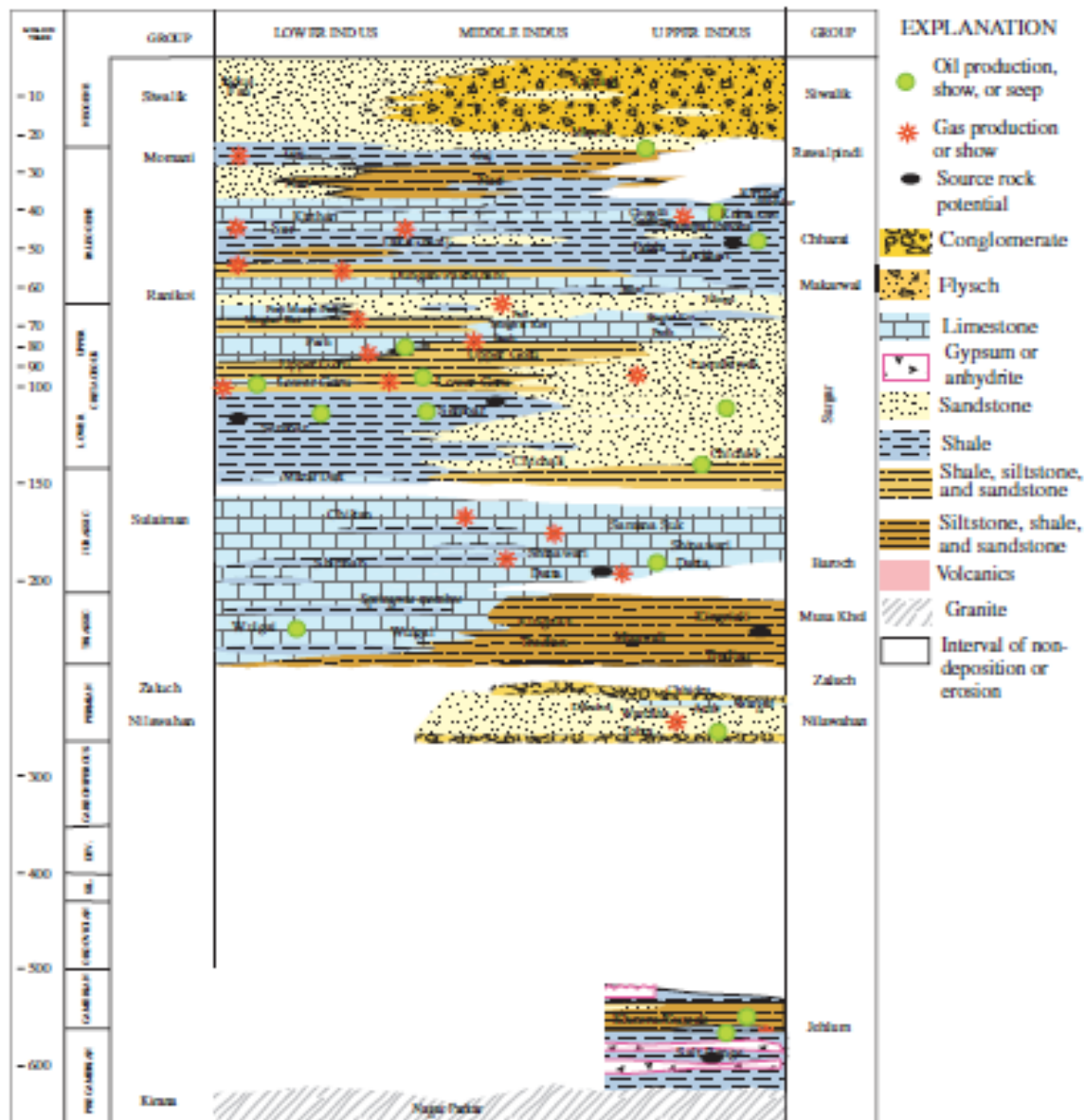


Figure 8.3: Generalized Stratigraphy of the Upper Indus Basin Area (Modified from OGDC, 1996; Quadri and Quadri, 1996; Kemal, 1992; Raza, 1992; Iqbal and Shah, 1980; and Shah, 1977)

8.2.3 Cenozoic Stratigraphy

In the Lower Indus Basin and the Sulaiman-Kirthar geologic province, fluvial sandstones and estuarine shales and limestones make up the Paleocene Ranikot Group. Shallow marine to estuarine limestones and calcareous shales of the Eocene Laki Formation and contemporaneous shales and sandstones of the Ghazij Formation are conformably overlain by interbedded limestones and shales of the Eocene Kirthar Formation. The Kirthar was deposited in the Lower Indus Basin, Sulaiman-Kirthar geologic province, and Kohat Plateau (Iqbal and Shah, 1980; Shah, 1977). Nearshore sandstones and shales of the Oligocene Nari Formation and shales of the lower Miocene Gaj Formation make up the Momani Group. The Miocene to Pliocene clays, sandstones, and conglomerates of the Siwalik Group mark a change to nonmarine deposition.

Hangu Formation siliclastics were deposited first, on an erosional surface marking the top of the Cretaceous Lumshiwal. There is a transitional contact between the Hangu and the overlying Lockhart Formation carbonate shelf system. The contact between the Lockhart and the overlying Patala Formation is also transitional (Shah, 1977, Iqbal and Shah, 1980, and Kemal 1992). The overlying Eocene Namal and Panoba Formations are shallow-marine to lagoonal shales and interbedded limestones with a transitional contact between the Patala and the Namal. Overlying the Namal and Panoba are marine limestones and shales of the Eocene Sakesar or Margala Hill Formations. Although Iqbal and Shah (1980) indicated that the probably contemporaneous lower Eocene Bahadur Khel Salt is present only in the Kohat Plateau area. The Chharat Group includes marine shales and interbedded limestones in the early Eocene Chorgali Formation, shale in the upper Eocene Kohat Formation shale, and shales and carbonates in the Oligocene Kirthar Formation. Oligocene rocks are missing or not recognized in most of the Upper Indus Basin. Unconformably overlying Eocene rocks are fluvial sandstones, siltstones, and clays of the Miocene to Pliocene Murree Formation, Kamli Formation, and Rawalpindi Group. The Murree Formation contains the youngest reported oil production in the Kohat-Potwar geologic province. Fluvial sandstones and conglomerates in the Pliocene and Pleistocene Siwalik Group are the youngest rocks in the Kohat-Potwar area.

Figure 8.4 is a simplified geological map of Pakistan displaying salient geological features which are a blend of its geological history and tectonics exhibiting the style and evolution of foreland structures.

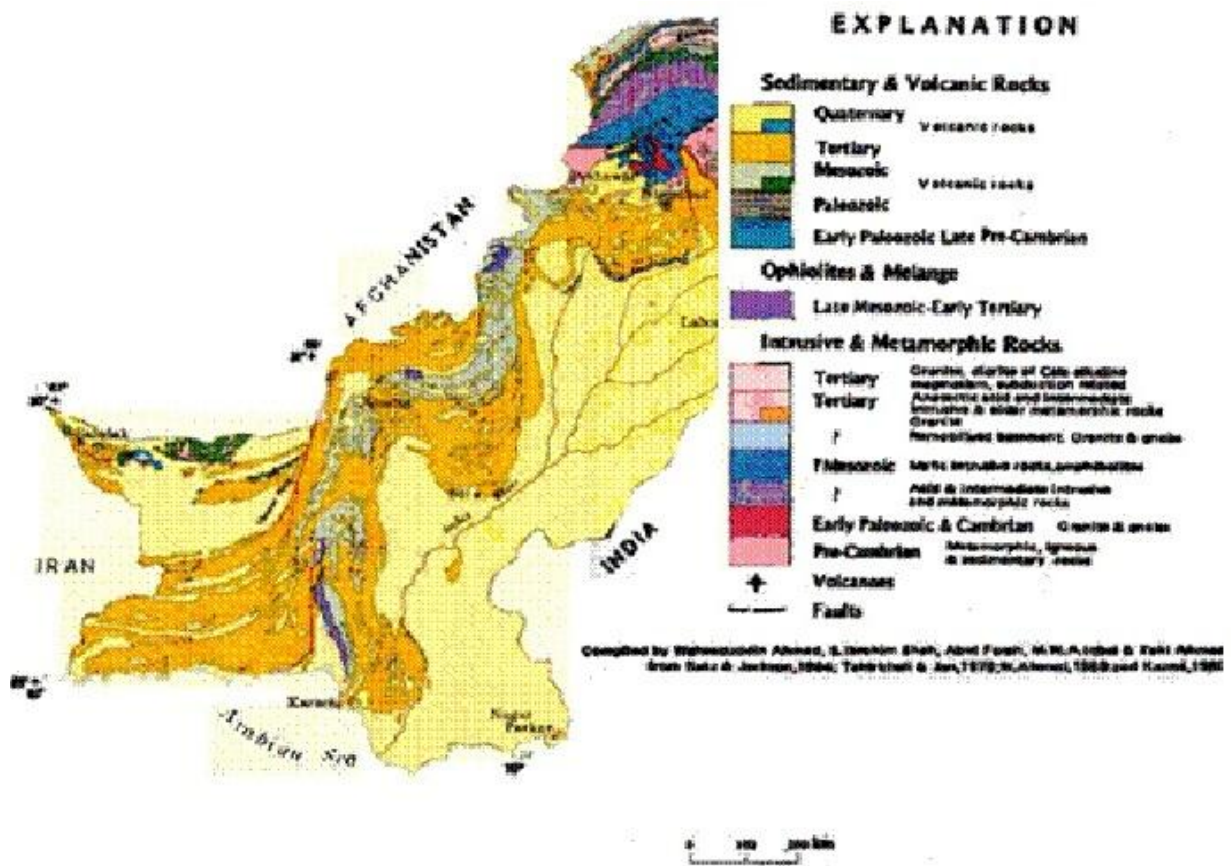


Figure 8.4: Geological Map of Pakistan

8.3 Surface Indications of Geothermal Source

At present 24 hot springs localities are known to occur in Pakistan. As may be seen from **Figure 8.5** and **Figure 8.6** that the occurrence of hot springs is wide spread from the thrust zones in the northern most part of the country to as much south as coastal area near Karachi. It is proposed that thermal prospectivity be classified according to the following tectonic zones and radioactive area.

1. Himalaya- Karakorum-Hindu Kush zone.
2. Chagai Volcanic Arc Zone
3. Geopressured and Deep Basinal Zone and
4. Radioactive Zone

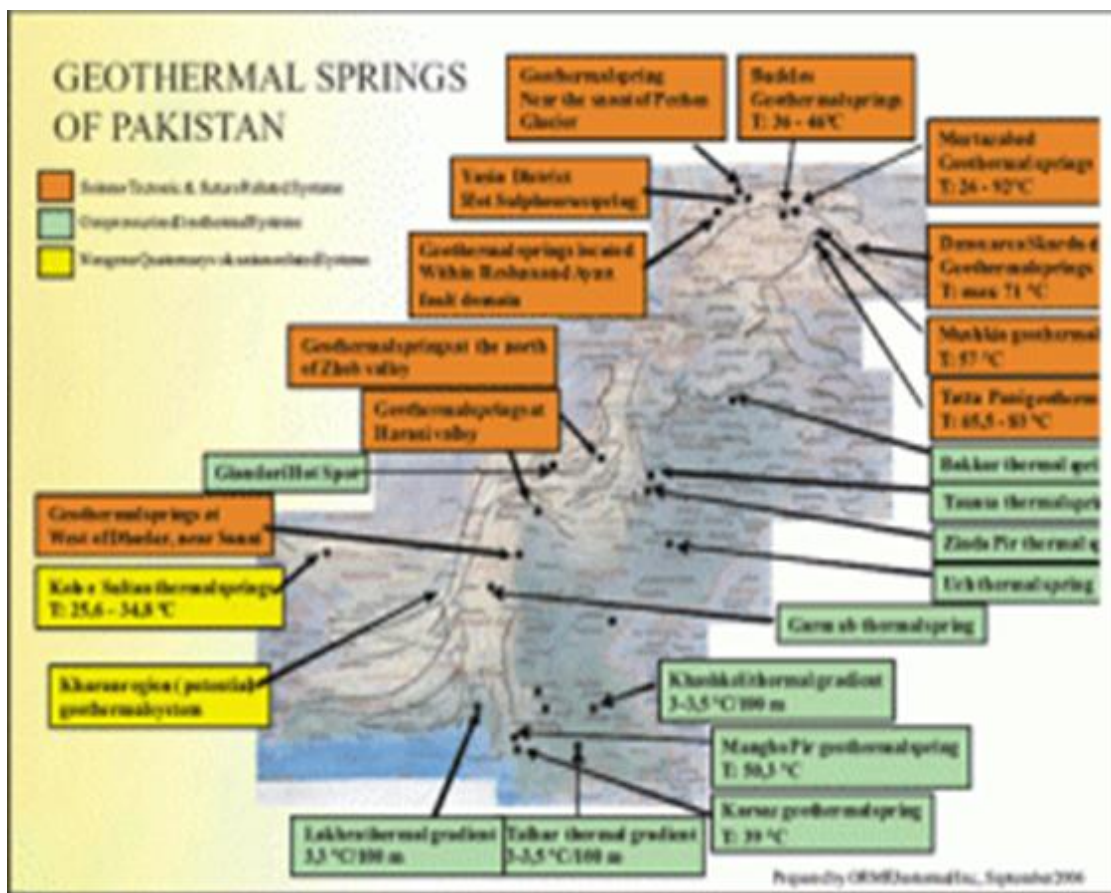


Figure 8.5: Locations of Known Geothermal Springs in Pakistan (After AEDB)

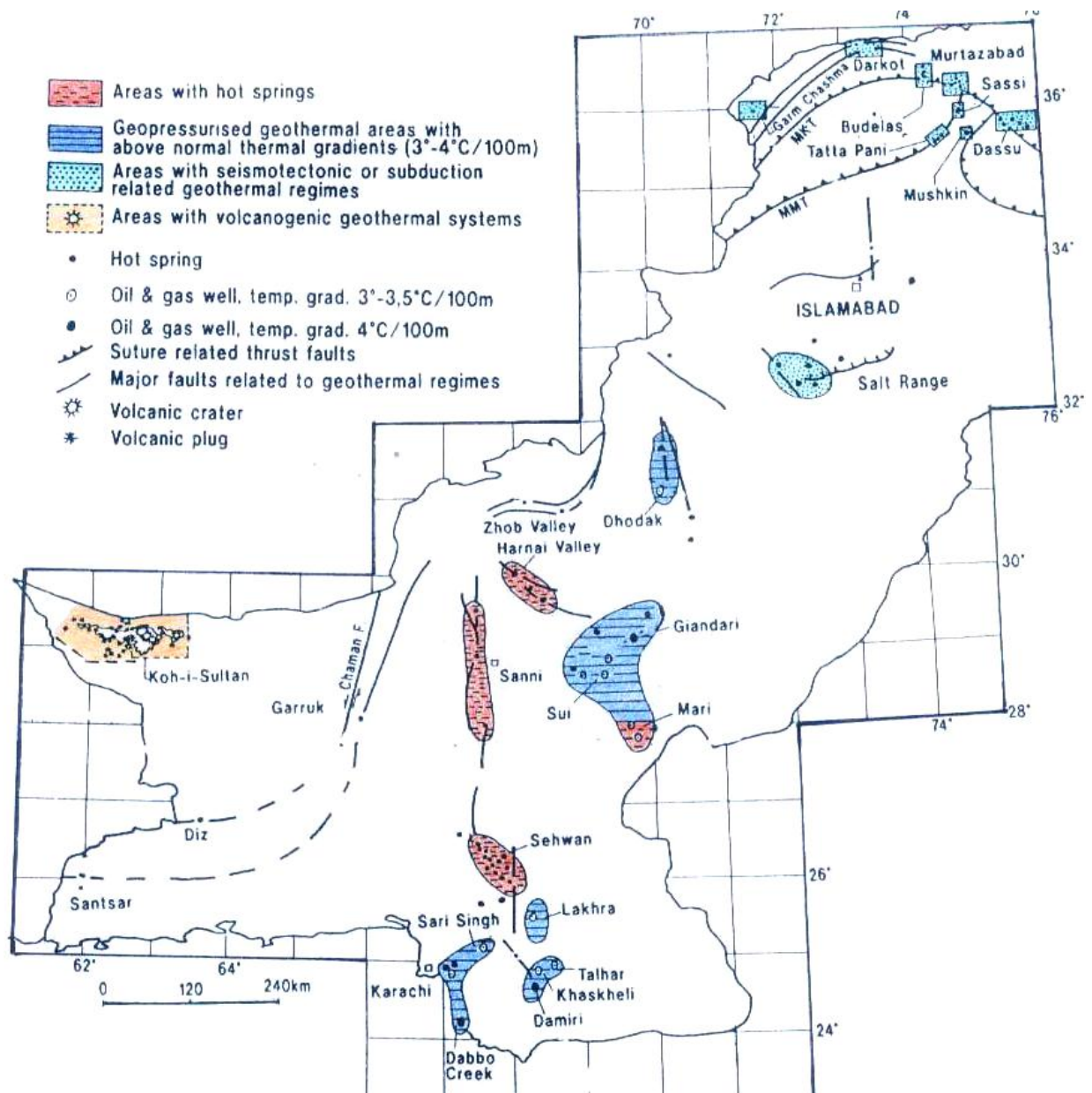


Figure 8.6: The Occurrences of Geothermal Resources in Pakistan

Source: Geological Survey of Pakistan

8.4 Geothermal Potential of Himalaya-Karakorum-Hindu Kush Zone

The rock units of the area range in age from Pre-Cambrian to recent. They represent sequences of the Indian Plate margin, Kohistan Island arc, Tirich Mir boundary zone and Hindu Kush region. The Indian Plate sequences comprise Cambrian stromatolitic dolomites transgressed on remobilised gneisses, around 500 Ma old granitoids exhibiting the widespread magmatic event, Phanerozoic shelf sequence of Gondwana of Middle-Paleozoic age, Metabasaltic dikes and granite gneiss of Early-Permian magmatic ages intruding into older Indian gneiss, and carbonatites (Kazmi & Jan 1997). Sedimentary records indicate that the onset of extension tectonics is Early Carboniferous (Pogue et al. 1992, Pogue et al. 1999). Marine shelf

sedimentation was re-established in the Late Triassic. The Mesozoic sedimentary history is that of carbonates deposited during thermal subsidence of a continental margin on the southern side of Neo-Tethys. All these rocks were deformed and metamorphosed between 75 and 40 Ma (Treloar et al. 1989, Chamberlain et al. 1991).

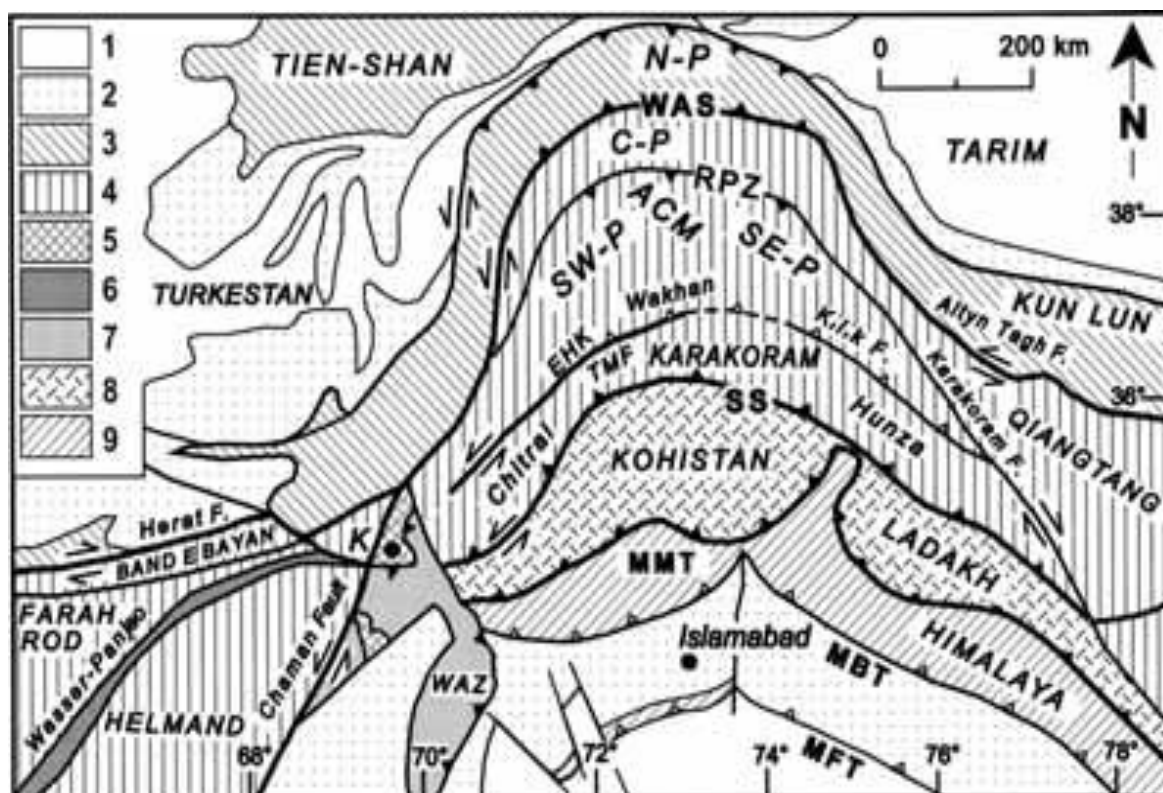


Figure 8.7: Tectonic sketch map of Northern Pakistan and surrounding regions. Modified from Zanchiet al., 2000 and Boulin, 1988. MFT: Main Frontal Thrust, MBT: Main Boundary Thrust, MMT: Main Mantle Thrust; SS: Shyok Suture; TMF: Tirich Mir Fault Zone, EHK East Hindu Kush, ACM Alitchur mountains, RPZ: Rushan-Pshart Zone; WAS: Wanch-Akbaital Suture, N-P: North Pamir, C-P: Central Pamir, SE-P: SE Pamir, SW-P: SW Pamir, WAZ: Waziristan, K: Kabul. 1: Quaternary, 2: Tertiary foredeeps, 3: Paleozoic belts, 4: Terranes of Gondwanan affinity, 5: Kabul Block, 6: Wasser-Panjao Suture, 7: Waziristan ophiolitic complex, 8: Kohistan-Ladakh arc terranes, 9: Himalayas. Heavy lines represent main sutures. (After Gaetani et al., 2004).

The Kohistan terrane in NE Pakistan is regarded as a fossil island arc obducted between the collided Indian and Asian plates (Bard et al. 1980, Tahirkheli et al., 1979).

The Karakoram sequences are represented by southern and intermediate metamorphosed belt, Karakoram batholiths and northern Karakoram sedimentary sequences.

The Tirich Mir Zone forming a narrow belt of amphibolites, met gabbros, peridotites, gneisses, and quartzites (Zanchi et al., 1997, 2000) and in Hindu Kush block the oldest rocks include possibly Cambrian deformed granitoids, the Qal'a-e Ust Gneiss in tectonic contact with the Paleo-Mesozoic meta sedimentary successions. Most of the belt consists of the Paleozoic

Wakhan Slates and the very thick and monotonous succession delivered in Chitral and in the Kan Khun Gol only bryozoans and brachiopods of Paleozoic affinity (Gaetani and Leven 1993), although Triassic conodonts may occur at the top of the unit in Afghanistan (Kafarsky and Abdullah 1976; Buchroithner 1980). Brief description of some of the geothermal springs is given hereunder.

8.4.1 Murtazabad Hot Spring

The Murtazabad hot springs are located in the toposheet No. 42 L/11. These springs emanate from the steep cliff which is made up of fluvial deposits, largely comprising gravel sand and silt. Chemical data was also interpreted with the help of qualitative geothermo metres. Water samples were collected from the point where the water naturally oozes out from the surface. There on-site measurements were made using digital electronic instruments. The flow rate was determined by using a calibrated container and a chronometer, where spring water could be collected. For sampling, heat resistant bottles were rinsed with sample water before they were completely filled.

Alteration zones cover an approximate dimension of 50m by 20m. The alteration zones commonly comprise white some sublimated sulphur with traces of mud pots.

The country rock is talus. Some cracks with direction N45°W are observed in this zone. Steam at 90 °C is issuing from the cracks. Its pH is between 3 and 4 by pH and test paper.

The Murtazabad area represents one of the major geothermal fields in Pakistan, with seven hot springs lying along the Main Karakoram Thrust. Discharge of the springs is 50-1200 Litre per minute with the surface temperature from 40 to 94°C. Environmental isotopes and chemical concentrations have been used to investigate the origin and subsurface history of thermal water. Four sets of water samples were collected and analyzed for various isotopes including ^{18}O , ^2H and ^3H of water; ^{34}S and ^{18}O of dissolved sulphates and chemical contents. Isotopic and chemical data show that the origin of thermal water is meteoric water. On the delta-diagram, $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data plotting below the local meteoric water line with a slope around 12.3 show that the original thermal water receives recharge from precipitation at higher altitude (3000m) and undergoes $\delta^{18}\text{O}$ shift of about 1 per thousand due to exchange with rocks. Different correlations between isotopes, temperature and Cl indicate that the observed isotopic compositions have evolved due to mixing of different proportions of shallow water at different spring paths during movement of thermal water towards the surface. It is also inferred from the tritium data along with $\delta^{18}\text{O}$ and $\delta^2\text{H}$ that the circulation time is long and is estimated to be more than 50 years.

8.4.2 Budelas Hot Springs

Budelas hot springs fall in toposheet No. 42L/7. These geothermal manifestations are located NW of Chalt on the bank of the Budelas river. An unmetalled branches off towards NW from the Gilgit Hunza near Sikanderabad locality. The nearest thermal spring is B-8, about 12 km from the main road. The spring issues from talus. Other manifestations i.e. B-9 and B-10 are located

7 km and 10 km further north on the right and left banks of the river. The springs are located between the Main Karakoram Thrust and the Karakoram granodiorite. The physical features of these manifestations are shown in **Table 8.1**.

8.4.3 Tatta Pani Hot Springs

The Karakoram highway is the major link heading up the mountains and yonder into China's Xinjiang and Tibet. It is also the source of many hot springs. The Tatta pani hot springs, named after a small village Tatta (alternatively Tatta, meaning 'warm') in the Rakhiot Valley, are located in the right bank of the Indus river near Raikot (Rakhiot) bridge. The springs and seepages are numerous and stretch along a 2-3 km wide zone located approximately SW of the Gilgit town. The springs emanate from unconsolidated to semi consolidated fluvial deposits. Amphibolites which are fractured by the Main Mantle Thrust constitute the hard rocks exposed along these thermal manifestations. These springs are located at the altitude of 1200 m. Brief characteristics are shown in **Table 8.1**.

8.4.4 Moshkin Valley Hot Springs

This geothermal manifestation is located on the top sheet no. I/11 on an unmetalled road off the Karakoram highway on the left bank of the Astore River at an altitude of 2135 m. The valley is very narrow with steep sides, and the exposed rocks around the spring are Nanga Parbat gneisses.

8.4.5 Darkot Hot Spring

Yasen valley is famous for the existence of various kinds of springs, which attract people from different parts of the Northern Areas. The Hot spring at Darkot, which flows at the height of about 10,000 feet near glacier of Darkot, is used for medicinal bath. Another spring of the same nature is situated at Thoi (Dooshter). The third spring Qaqabul is situated at Nazber (Asqurthan). It has slightly astringent taste. Most of the people believe and experienced that this is a certain cure of stomach diseases.

There is yet another kind of spring, which has a taste very much like 7 up, lying at the distance of one and half hour walk from Barkolti at Chelpay. This spring lowers the body temperature during high-grade fever and also proves to be an effective treatment for hot natured people, reduced high blood pressure and highly effective in peptic ulcer. In the Yasin valley two more hot springs at Pechuz and nearby area <http://www.iknowgreatplaces.com/community>.

8.4.6 Choutron Hot Spring

It is located in Basho valley also known as Chutung. 'The name literally means "hot water"; "Chu" means water and "tran" means hot in the Balti language. The Choutron hot spring occurs at the faulted contact of Triassic dolomite and underlying stratified gneiss (Record Geological Survey of India, Volume 14-14). Choutron is about 2 1/2 hours from Shigar or a little over 3 hours from Skardu. It is being used as a medicinal hot springs. Over the decades, the spa has become popular with the local people, who are even coming from beyond Hunza (15 hours by road) to

soak in the 40°C plus hot water. Nestled at the base of the northeast side of the Haramosh Range, Chutron is partially shaded and thereby relatively cool (**Figure 8.8**).

There is a government rest house with an outhouse which has supply of hot spring water. Apparently, there is another hot spring 3 hours further away, which is also used for medicinal purposes.



Figure 8.8: Views of Chutron Hot Spring

8.4.7 The Other Hot Spring in Baltistan

Other valleys in the north of Baltistan contain their own hot springs such as Bisil (Arandu valley, Baltistan). Bisil has a hot spring, with the small pool emitting strong smells of sulfur. (www.bergdias.de/pakistan/pakistan4).

There are hot springs in Dowo Kraming (Khaplu), quite close to the border with China. Dassu Hot spring and Sassi Hot Spring the details are not known.

8.4.8 Garam Chashma

Garam Chashma (Hot Spring; Figure 8.9) is located at an elevation of 1859 meters (6,100 feet). It is 45 km North West of Chitral and takes 3 hours to reach by jeep. Visitors have to take a spectacular drive up the Latbo/Latkho River through deep and narrow gorges to reach this place. This unspoiled enchanting valley of orchards, verdant fields and snow clad peaks is renowned for its boiling sulphur springs which are famous for healing effect on skin diseases, gout, rheumatism and chronic headache. The hot water comes from the hills. Near the residential area, a small steaming stream branch off to enter rooms for soaking and swimming pool before it joins the main course again ([www.taravel guide.pk/gramchasma](http://www.taravelguide.pk/gramchasma)).



Figure 8.9: View of Garam Chasma Pool

8.4.9 Reservoir Temperature

Temperatures measured by silica and Na-K-Ca are shown in **Table 8.1**. The estimated temperature of Budelas is excluded because of the effect of mixing of fresh water with the geothermal water. The temperature inferred by the silica geothermometer is generally lower than the temperature measured by the Na-K-Ca geothermometer. This is considered to be due to the influence of mixing of non-thermal water. The temperature estimated at Tatta pani ranges from 93-128°C, and at Mashkin it is about 169°C. On the other hand the silica geothermometer indicates temperatures from 51 to 97°C at Tatta pani, 86°C at Mashkin and 40°C at Sassi. It is noted that most of them are considered to be mixed with non-thermal waters.

8.4.10 Geothermal System and Main Mantle Thrust

The geothermal system at Tatta pani and Sassi lies along the Main Mantle Thrust. The hot springs come from the Quaternary talus deposits. The linear occurrences of the hot springs indicate that the MMT and the sub-fault system provided passage for hot water to seep from subsurface. However, the role played by the granitic rocks in the vicinity is uncertain. It has also been observed that the massive amphibolite sequence of the Kohistan Island arc is fractured by the MMT and micro fracture are likely to extend along the strike of fault. The strike of the MMT changes at Tatta pani from ENE to SSW. It is assumed that changes in strike direction may have also some affect in enhancing the permeability and transmitting the geothermal fluid (Bakhat, 2005). The hot springs water at Tatta pani is classified at the boundary of HCO₃ and SO₄ type and somewhat richer in Cl composition in comparison with the chemical composition of Murtazabad water. The chemical composition indicates possibility of high temperature regime in the deep reservoir source. Geochemical data for Mashkin and other hot springs is insufficient and more geological and geochemical studies are needed for complete understanding of the geothermal system.

Table 8.1: Physical and Chemical Characteristics of Hot Springs in Himalaya-Karakoram-Hindukush Areas (After Todaka et al., 1999)

Hot Spring Locality			Temperature (C)	Flow RateL/ min	pH	Electric cond. $\mu\text{S/cm}$	Feature of Hot Water	Geology	Remarks
HimalayaKarakoramHindukushAreas	Murtazabad	N1	42.3(Ambient temp. 35.0)	33	7.5	172	Colourlessod orless & tasteless	Terrace deposit Garnet schist	Bathing &cloths washing
		N2	30.0(Ambient temp. 33.5)	6.7	7.8	-	Colourless, H ₂ S smell & sour taste	Surface Soil Terracedeposit Garnet staurolite schist	Washing forPrayer
		N3	30.0(Ambient temp. 28.0)	500	9.21	2470	Colourless & H ₂ Ssmell	Surface soil Terrace deposit. Garnet staurolite schist	BoilingTemp 92 °C; CaCO ₃ depo sition
	Budelas	N8	46.0(Ambient temp. 32.0)	100	7.85	1540	Colourless H ₂ S smell, salty taste	Talus/Garnet mica schist (Baltit Group)	Bathing
		N9	36.0(Ambient temp. 17.0)	100	7.49	77.6	Colourless, H ₂ S sme	Talus/Garnet mica schist.(Baltit Group)	
		N1	Near boilingtemper ature (91°C)		7.64	1160	Colourless, H ₂ S smell	Talus/Garnet mica schist (Baltit Group)	
	Tatapani	N4	83.0(Ambient temp. 17.0)	> 621	8.83	1060	Colourless H ₂ S smell,salty taste	Terrace deposit orFractured Amphibolite	
		N5	65.5(Ambient temp. 36.5)	800	8.57	1540	Colourless, H ₂ S smellsalty teste	Terrace deposit orFractured Amphibolites	
		N6	78.0(Ambient temp.36.5)	Morethan 100	7.18	-	Colourless, H ₂ S smellsalty taste	Terrace deposit Fractured Amphibolites	
		N7	80.0	34	8	-	Colourless, H ₂ S smell. salty taste	Talus/FracturedA mphibolites	
	Mashkin		57(Ambient temp. 34.4)	1	7.87	1070	Colour less, H ₂ S smell	Surface soil/Gneiss (Nanga Parbat Gneisses)	Cloth washing
	Sassi		54.0(Ambient temp. 33.0)		7.87	1310	Colour less, Odorless	Talus/Gneiss (Kohistan Island Are sequerice)	CaCO ₃ Depo sition
	Chutran		43.9	200	7.74	5090	Colour less, Odorless	Talus/ Limestone (Eurasian Mass)	CaCO ₃ Depo sition

8.5 Geothermal Prospects of Chagai Volcanic Arc Zone

The area comprises a narrow belt which extends eastwards and truncates against the Chaman transform fault. Subduction of the Arabian plate under Eurasian plate resulted in formation of a trench south of Makran coast and emergence of a volcanic arc in Chagai area. The Koh-e-Sultan volcano and other volcanic cones in the Chagai area are part of the volcanic arc. The water from the thermal springs in Koh-e-Sultan area has been analysed and subsurface temperatures from 150°C to 170°C were reported (Schoppel, 1977).

The arc, together with an over 300km wide classic accretionary prism to its south (Platt et al., 1986), overrides the active Makran subduction zone (MSZ). The longstanding activity on the MSZ is manifested in intermittent magmatism in the Chagai Arc spanning about 70 Ma from the Late Cretaceous to the Pleistocene, which is unmatched in Neotethyan arcs preserved elsewhere in the Himalaya and Zagros Ranges (Alam, 2003). The Chagai arc exposes a >10,000 m stratigraphic succession from Late Cretaceous to Pliocene-Pleistocene, comprising volcanic, volcano-sedimentary and sedimentary rocks. A thick (~2,500 m) succession of massive basaltic-andesite lava flows (associated with lapilli tuff, volcanoclastic sediments and minor felsic lavas) dominates the Late Cretaceous Sinjarani Group (Ahmed et al., 1972; Siddiqui, 1996, 2004), the oldest unit exposed in the Chagai Arc. Volcanic rocks abundantly occur in younger stratigraphic units including the Paleocene Juzzak Formation, Eocene Saindak Formation, Oligocene Amlaf Formation, Miocene Buz Mash Koh Formation, and Pliocene-Pleistocene Koh-i-Sultan Formation (Alam, 2004). The Late Cretaceous-Paleocene volcanism is dominated by basalts and basaltic andesites. In comparison, Eocene and younger volcanism is dominantly andesitic to dacitic with minor basalts.

Detailed major, trace, and rare-earth geochemistry classifies the temporal volcanism in the Chagai Arc into three groups; 1) Late Cretaceous-Paleocene, 2) Eocene, and 3) Oligocene and younger (Heuberger et al., 2007). The following thermal springs occur in Chagai area.

8.5.1 Chicken Dik Spring

The Chicken dik spring is located 7.8 km southeast of Mashki Chah (Toposheet No. 35I/5). It is located at an altitude of 830m. The water is discharged from holes about 100m deep which Pakistan Industrial Development Co. has drilled for Iron ore in Mashki Chah. The water table was 2.3m at the sampling time. The surface rocks are recent deposits, however they may penetrate the Chagai intrusions or the rocks of Sinjarani volcanic group (Arthurton et al., 1979). The physical features of the springs are shown in **Table 8.2**.

8.5.2 Koh-e-Sultan Springs

The Koh-e-Sultan springs are located in the vicinity of the Miri crater (Toposheet No. 30 G/16). The hot springs seep from the river bed which consists of lava and agglomerate. The water temperature ranges from 25-32°C. The temperature is lower than the ambient temperature in the summer season. The spring waters in the alteration zone are strongly acidic. Their brief physical features are shown in **Table 8.2**.

8.5.3 Chemical Properties of Geothermal Water

Four water samples from thermal springs and one from the well in the vicinity of Koh-e-Sultan were collected and analysed in Karachi Laboratory of the Geological Survey of Pakistan. **Table 8.2** shows the results of analysis of the water samples. There is a high concentration of salts in the water. The electric conductivity is more than 10,000 s/cm and the TSM ranges from 13,700 to 67,540 mg/l. Gas is continuously dissolved into the very little amount of groundwater available in the area, resulting in a concentrated water.

It is assumed that the SO₄ type water flows horizontally into a shallow zone and is mixed with Cl type water from the deeper levels. By this way the water changes from SO₄ type to Cl,SO₄ type. As mentioned by Bakhat (2000) Anion Index can be calculated by the following equation.

$$\text{Anion Index (A.I.)} = \frac{0.5 \text{ SO}_4 + \text{Cl} \text{ SO}_4 + \text{SO}_4 + \text{HCO}_3}{\text{Cl}}$$

Higher values of A.I. indicate higher geothermal activity in a volcanic area. The reservoir temperature calculated by application of geothermometres may not reflect the true reservoir temperature. It is assumed that the process of mixing of ground water with the gases does not show the reservoir temperature at all.

**Table 8.2: Physical and Chemical Characteristics of Hot Springs in Chagai Volcanic Arc
(After Todaka et al., 1999)**

Hot spring Locality		Temperature (°C)	Flow Rate (L/min)	pH	Electirc Cond.(μ /cm)	Feature of Hot water	Geology	Remark
CHAGAI VOLCANIC ARC	Chicken Dik	29.9(Ambient temp: 40.9)		6.58	>10,000	Colour less,odorless salty taste	RecentDepo sit	CaCO ₃ Deposi tion
	KOH-E-SULTAN AREA	C2 29.5(Ambient temp. 34.7)	< 1	7.44	1060	Colourless, odorless salty taste	Basalagglom erate	Discharge from river bed
		C3 32.2 (Ambient temp. 38.6)	< 1	6.89	>10,000	Colourless,o dorless salty taste	Basalagglom erate	CO ₂ gas bubbling CaCO ₃ deposit ion Discharge from river
		C4 32.0 (Ambient temp. 36.9)	< 1	6-7		Colourless,o dorless salty taste	Basalagglom erate	CO ₂ gas bubbling CaCO ₃ deposit ion Discharge from river
		C5 26.9 (Ambient temp. 31.1)	< 1	2.77	>10,000	Colourless, H ₂ Ssmell	Alteredandes ite	Sulphur & Salt depositionDis charge from river bedC6
		C6 25.5 (Ambient temp. 31.9)		2		Colourless H ₂ Ssmall	Alteredandes ite	Sulphur & Salt depositionDis charge from river bed
		C7 27.5 (Ambient temp. 35.9)	10	7.13	>10,000	Pale brownodorle ss salty taste	Basalagglom erate	Water contains Fe discharge fromriver bed

8.6 Geothermal Prospects in Geopressured Areas

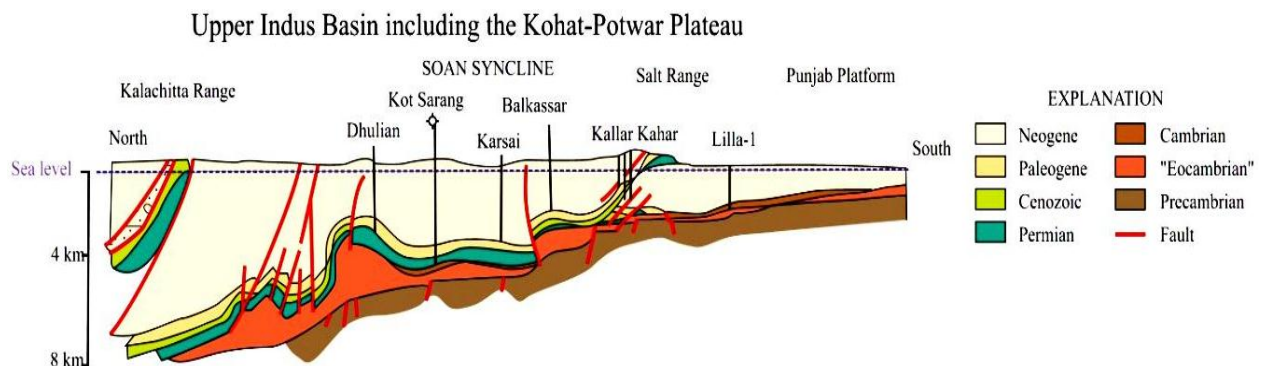
Geo-pressures are found in rock units in which flow of fluids has been effectively prevented by either the insitu formation of an impermeable barrier bed, or the appropriate placement of such a barrier through tectonic activities such as: folding, faulting, or diapiric action of shale or salts. A common source of pressure in a geo-pressured form are fluids which have been trapped within the formation and which, as compression proceeds, are forced to support the increasing overburden. Since the zone is effectively sealed with respect to expulsion of fluids, normal compaction does not continue with depth. As a result, geopressured formations are not depth dependent and have been encountered at depths up to 6100m (20,000 feet). Thus these geopressured units are of great interest in the petroleum industry.

These very high-pressured geothermal energy prospects are generally associated with the hydrocarbon-bearing strata. Geopressured thermal zones are deposits of water trapped and

buried under heavy overburden during process of sedimentation. In these zones the heat is trapped and insulated by encircling layers of sand, clay, and shale. The Geopressed zones are a dual source of heat and methane at the same time (Holt, 1977).

8.6.1 Upper Indus Basin Geothermal Prospects

Two distinct pressure regimes in Potwar foreland fold and thrust belt basin has been identified: one in Neogene rocks and another in pre-Neogene rocks. Pore pressures in Neogene rocks are as high as lithostatic and are interpreted to be due to tectonic compression and compaction disequilibrium associated with high rates of sedimentation. Pore pressure gradients in pre-Neogene rocks are generally less than those in Neogene rocks, commonly ranging from 0.5 to 0.7 psi/ft (11.3 to 15.8 kPa/m) and are most likely due to a combination of tectonic compression and fluid pressure. The top of abnormally high pressure is highly variable and doesn't appear to be related to any specific lithologic seal (**Figure 8.10**). The Neogene sequence in this area attains as much geothermal gradient as 2.5°C/100 m depth (Raza, 1981; Khan & Raza, 1986).



8.6.2 Salt Range Hot Springs

A number of hot springs and seepages are reported following the alignment of syntaxial bend and Salt Range thrust.

Rocks in the Salt range area range from Pre-Cambrian to recent. However the majority of the rocks are Tertiary. Temperatures of the thermal springs are from 25-32°C. The spring water is sulphurous and is known to have therapeutic value for skin disease.

8.6.3 Middle Indus Geothermal Prospects

In foredeep region of Middle Indus Basin, the Giandari well recorded the highest geothermal gradient of 4.1 °C/100 m. Around this hot spot further west ward gas fields of Mari, Kandhkot, Sui, Uch Pirkoh and Jandran occur showing geothermal gradients ranging from 3°C/ 100 m to 3.4 °C/100 m (Khan & Raza, 1986).

Huge accumulation of sediments in the foredeep region is mainly due to deposition of thick Neogene sequences alongwith thickening of underlying Mesozoic strata and westward tilting of the basement. (**Figure 8.11**). Since the Neogene strata were rapidly deposited pockets of abnormal formation pressures have been encountered in some of oil and gas exploratory wells. Geothermal gradient map of the area indicates that zone of high temperature regime follow the NS structural style in the periphery of Sulaimanf foredeep area.

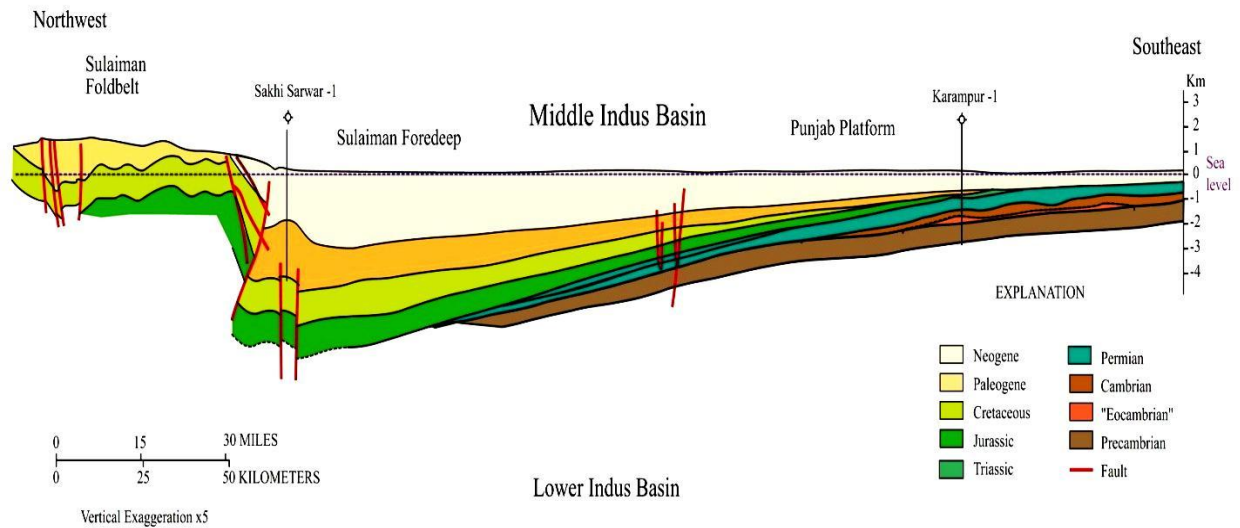


Figure 8.11: Cross Section of Middle Indus Basin Showing the Depth of Geopressured Neogene Sequence (After Wandrey et al, 2004)

8.6.4 Hot Spring Occurrences

In Middle Indus Basin thermal springs have been recorded at Uch, Garm Ab at the base of Mari Hills, Zinda Pir, Taunsa and Bakkur demonstrating vast area of geothermal energy (Oldham, 1882; Bakr, 1965). There are a number of other unrecorded geothermal springs in the area, which needs to be studied in some details. Compiled from web-based information a hot springs has been reported in Bugti area (**Figure 8.12**) and Kala Pani Hot spring Near fort Manro.



Figure 8.12: View of Hot Spring in Bugti Area

8.6.5 Geothermal Prospects of Lower Indus Basin

Further southward the Lower Indus Basin (**Figure 8.13**) shows relatively thin accumulation of Neogene sediments which is not the only difference with the adjoining Middle Indus Basin.

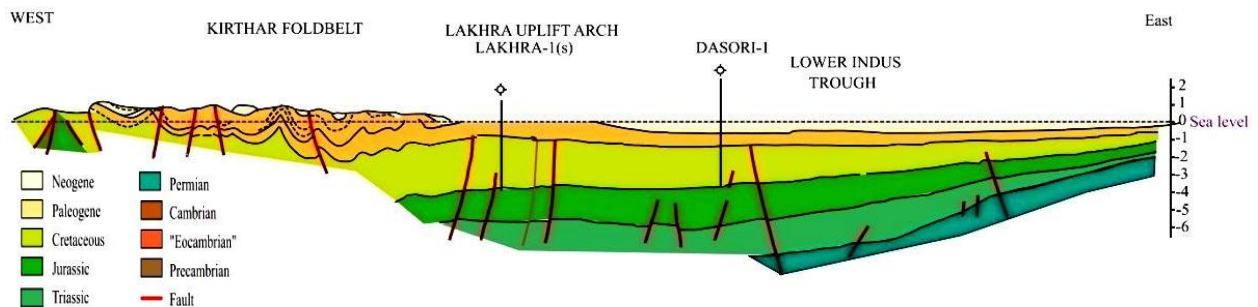


Figure 8.13: Cross Section of Lower Indus Basin Showing the Depth of Geopressured Neogene Sequence (After Wandrey et al, 2004)

The lower Indus Basin is characterized by occurrence of Deccan continental flood basalts at the boundary between Cretaceous and Tertiary periods. About 65 Ma to 1.64 Ma, huge lava flowed almost all over the eastern margin of Lower Indus Basin.

Based on a study involving the conductive steady state geotherms calculated by using observed high surface heat flow values and appropriate models, Gupta (1981) concluded a large degree of melting in the lower crust and upper mantle beneath the Cambay-Mehsana area. Considering this aspect and taking into account the existence of a normal crust about 37km thick below the Cambay-Tarapur and Ahmedabad-Mehsana blocks (as obtained from deep seismic soundings),

it has been inferred that the heat flow anomaly is due to transient thermal perturbations introduced from tectonic activity in the form of magmatic intrusions.

Geological frame work of Lower Indus Basin suggest a close similarity with the Cambay Basin, it is, therefore, inferred that heat flow may have cause high geothermal gradients in some of the exploratory wells drilled in Lower Indus Basin. The oil & gas wells drilled at Lakhra show thermal gradients above normal (3.3°C/100 m). Farther southward the oil & gas wells at Sari and Karachi revealed a geothermal gradient of about 3°C/100m.

The geological setting of the south-Kirthar geothermal zone is similar to that of the south-Sulaiman geothermal zone. The Kirthar zone also includes, a depression containing a pile of sediments 6-10km thick. The region is seismically active and epicenters of shallow earthquakes ranging in magnitude from 3 to 5 on Richter scale have been recorded.

The Lower Indus trough and the offshore geothermal zone are characterized by geothermal gradients above normal, which were encountered in borehole drilled for the oil & gas exploration. The well Damiri-1 had a geothermal gradient of 4°C/100m (Khan and Raza, 1986), whereas the wells at Talhar and Khaskheli have encountered geothermal gradients in the range of 3 °C to 3.5°C/100 m. The offshore well at Dabbo Creek revealed a geothermal gradient of 3.7 °C/100 m.

8.6.6 Hot Springs in Lower Indus Basin

In the Dadu area there is a large concentration of thermal springs where the average surface temperature is 40°C (Bakr, 1965).

In Karachi, two hot springs exist one at Mangho Pir and one at Karsaz. **Table 8.3** shows physical and chemical characteristics of these hot springs. There are hot and cold springs about a kilometer from the Manghopir shrine. Warm water is sulphurous and is said to contain some medicinal qualities.

Lakha Pir Hot Spring

This hot spring occurs in District Kachi at 27° 31' 0" North, 67° 31' 20". Blandford 1880 noted it at about 6 miles of its termination, the range is traversed by a small valley, in which a hot spring known as Lakha Pir with temperature of 44°C. The water issues in the bed of stream and is strongly impregnated with sulphurated hydrogen, like the spring of the same name at Laki, near Sehwan. At the spring no fault can be traced in the rocks which are Kirthar Limestone, and dip at from 20 to 40 eastward (Blanford, 1880).

Table 8.3: Physical and Chemical Characteristics of Karachi Hot Springs

Hot Spring Locality		Temperature (°C)	pH	Electric Cond. (μ/cm)	Feature of Hot Water	Remark
Karachi	Mangopir	50.3(Ambient temp.36.0)	7.45	2,380	Colourless; odorless	Surface soil CO ₂ gas bubbling
	Karsaz	39.0(Ambient temp. 5.4)	7.87	7,910	Colourless; H ₂ S small	CO ₂ gas bubbling

Source: Todaka et al., 1999

8.7 Conclusions

Tapping the geothermal energy appear attractive, as the hot springs are perennial and their surface temperature ranging from 37 to 90°C, but only attainable with strong technical base and commitment by the policy makers in the country. The earlier work summarized in the report provide preliminary knowledge concerning the geothermal occurrences in various parts of Pakistan. Further exploration is needed to undertake the surface-based studies that could constrain models for the deep thermal state of these occurrences. As stated above, even though the range of possible thermal conditions is large but uncertain, there is ample evidence of extensive hot reservoir from the ages of volcanic rocks in northern part of the country and Chagai volcanic arc as well as basaltic event of the Deccan Trap in southern part of the country. Because of the unique nature of the hydrology of these areas, in particular the deep water table and the large lateral hydraulic gradients, the depth, size, and temperature of this system remain indeterminate.

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CHAPTER – 9

GEOTHERMAL RESOURCES OF SRI LANKA

9.1 Tectonics of Sri Lanka

The tectonic history of Sri Lanka - India can be traced from the Precambrian to the present. On the basis of the geological record, the Highland Group of Sri Lanka represents Precambrian plate tectonic suture. Tectonic models of these Precambrian events may be presented by spreading, collision, subduction, shearing or in situ jostling.

The tectonic history of Sri Lanka and India relates to the evolution of the Indian Ocean since at least the Cretaceous. Although Sri Lanka is considered to be a part of the larger Indo - Australian plate, it may have had a local independent history as a block within the larger crustal unit of India (Desa et al., 2006). Their interpretation suggests that the separation of Sri Lanka from India was in part controlled by Precambrian structures and a history of translational, rotational and vertical adjustments to the Indian Ocean developmental plate tectonic stresses still operating.

Sri Lanka's position relative to India in the Gondwana-land reconstruction has never been well defined (Smith and Hallam, 1970; Crawford, 1974; Katz, 1978; Yoshida et al., 1992). Crawford (1974) repositioned Sri Lanka closer to India prior to breakup of Gondwana-land. The Precambrian formation of Sri Lanka was fitted against similar rocks of southeast India by closing up the Gulf of Mannar and Palk Strait and ignoring the intervening coastal Cretaceous and Tertiary deposits of southeast India and northwest Sri Lanka (Katz, 1978). The Southwest group of rocks of Sri Lanka continues into the Kerala belt of southwest India while the Highland series of Sri Lanka continues into the Eastern Ghats belt of the eastern coast of India. Katz (1978) suggested an approximately 200 km late Mesozoic drift of Sri Lanka away from India with possible anti-clockwise rotation during early breakup of eastern Gondwana-land.

Curry (1984) opined that the first rifting between India, Sri Lanka and Antarctica occurred through the Cauvery-Palk Strait-Gulf of Mannar zone but this rift did not progress into the seafloor spreading stage. Instead, the break occurred between Sri Lanka and Antarctica, as a result the Cauvery-Palk Strait-Gulf of Mannar Basin became a failed rift or aulacogen dating from the Late Jurassic/Early Cretaceous. He also proposed that Sri Lanka acted as a mid plate platelet moving slowly in a south-southeast direction relative to India.

Dissanayake and Chandrajith (1999) in their study on the Sri Lanka-Madagascar Gondwana linkage described the geology of Sri Lanka as mainly that of high grade metamorphic rocks in a Precambrian terrain. These rocks form three major litho tectonic units (**Figure 9.1**), namely, the Highland Complex, the Vijayan Complex, and the Wannai Complex. Among these, the Highland Complex is the largest unit and forms the backbone of the Precambrian rocks of Sri Lanka. Included in this unit are the supra crustal rocks of the former Highland Series (Group) and the Southwestern Group (Cooray 1962, 1984), together with a variety of igneous intrusions of

predominantly granitoid composition that now occur as banded gneisses. The rocks comprising the Highland Complex are mainly of granulite facies metamorphites, predominantly varieties of granulites including charnockites, quartz-feldspargarnet- sillimanite-graphite schists, quartzites, marbles, and calc-gneisses. On the basis of field and petrological evidences, Krõner et al. (1991) infer that a significant proportion of the rocks in the Highland Complex are of granitoid origin. Widespread Charnockite Formation has been observed within this unit (Hansen et al. 1987). These rocks are dated at about 550 Ma (Baur et al. 1991).

The Vijayan Complex, lying to the east of the central Highland Complex (**Figure 9.1**) consists of biotite-hornblende gneisses and scattered bands of met sediments and charnockitic gneisses. Among the other prominent geological features of the Vijayan Complex are the small plutons of granites and acid charnockites near the east coast (Jayawardena and Carswell 1976) and the north-west-trending suite of dolerite dikes at Kallodai. Milisenda et al. (1988) and Milisenda (1991) have described the gneissose granitoids of the Vijayan Complex as having compositions ranging from tonalite to leucogranite.

The Vijayan Complex is mostly of amphibolite-facies grade, and the fact that it has not been subjected to granulite facies metamorphism has been interpreted by Krõner et al. (1991) to mean that the charnockitic bodies within the Vijayan domain are klippen and/or unfolded or intersliced fragments of the Highland Complex. These are similar to the Kataragama klippe (**Figure 9.1**), of which the derivation from the latter complex has been established (Cooray 1978; Vitanage 1985).

The Wannu Complex consists of a suite of granitoid gneisses, charnockitic gneisses, and granites, along with a variety of amphibolite- to granulite facies rocks such as meta sediments of predominantly pelitic to semipelitic composition (Milisenda et al. 1991). Studies of detrital zircons from metapelites have shown that the Wannu Complex is younger than the Highland Complex, even though the boundary between these two litho tectonic units is still poorly defined.

Their study further suggests that Sri Lanka occupies a unique geologic position in Gondwana. Accordingly on the basis of recent age and isotopic data they concluded that the high-grade basement rocks of Sri Lanka are more closely associated with the southeastern part of Madagascar than with the Archean granulites of southern and eastern parts of India. They further noted that the occurrences of gem minerals and graphite in the centrally located Highland Complex of Sri Lanka can also be correlated with those of the Kerala Khondalite Belt (KKB) at the southern tip of India and of southeast Madagascar south of the Ranotsara Shear Zone. As such they were of the view that these geological and mineralogical features indicate the juxtaposition of Sri Lanka with Madagascar and also with the Lutzow-Holm Bay area in Antarctica. The very close juxtaposition of Sri Lanka with Madagascar suggested by them implies that there exists a distinct mineralized belt running from Antarctica through the Highland Complex of Sri Lanka into Madagascar, Mozambique, Tanzania, and farther north. This mineral belt is clearly of Pan-African origin and is now considered to be an important geosuture associated with the main Mozambique Belt. The position of Sri Lanka in Gondwana is of

particular significance because Sri Lanka acts as a bridge across the main East African and Antarctica crustal fragments.

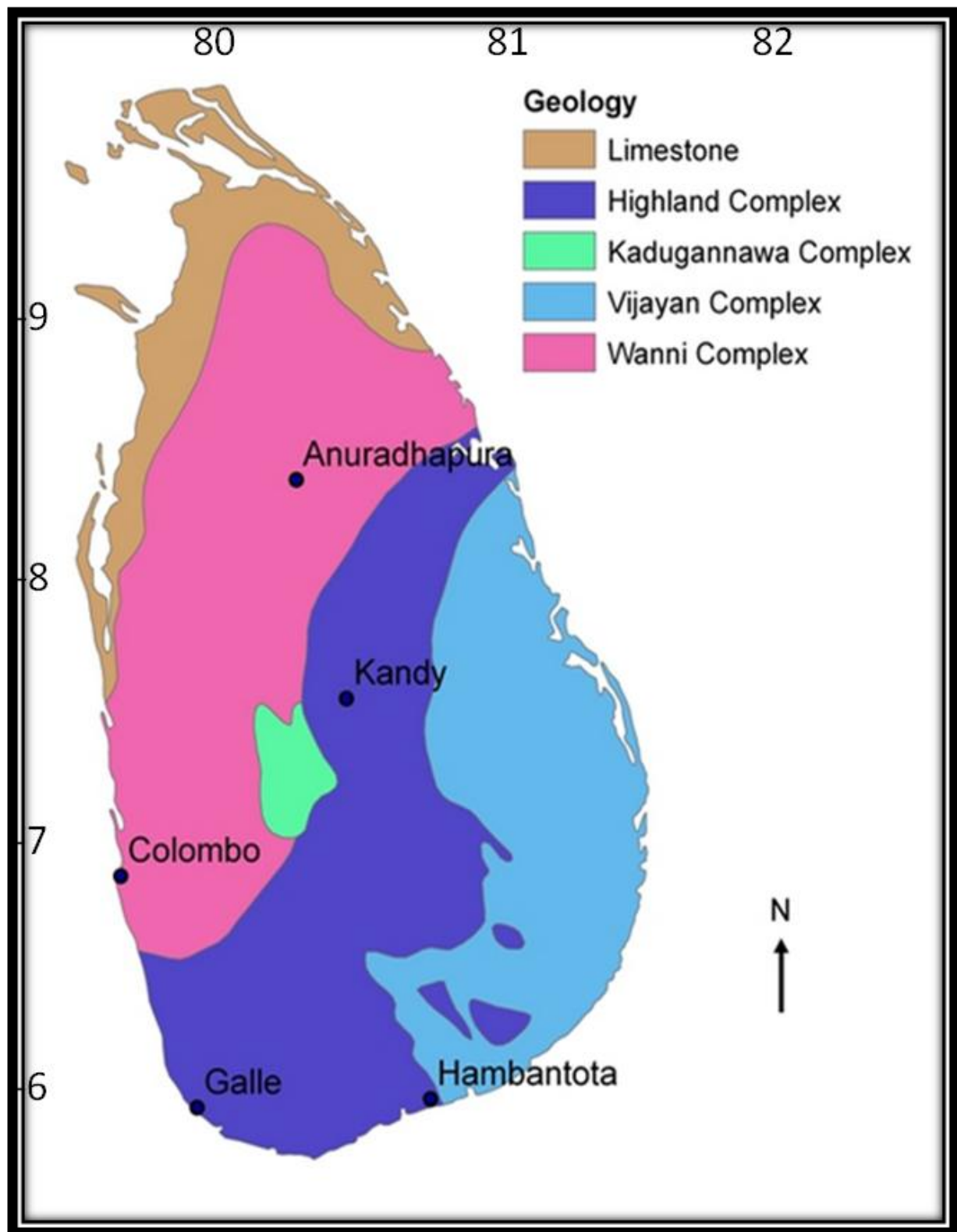


Figure 9.1: Geological Map of Sri Lanka

9.2 Stratigraphy

More than 90 percent of Sri Lanka's surface lies on Precambrian strata. The metamorphic rock surface was created by the transformation of ancient sediments under intense heat and pressure during mountain-building processes. Corray (1997) described the Precambrian units and sedimentary strata. The extract from his paper is given here under:

9.2.1 Crustal Units

Precambrian

The Precambrian is subdivided into three main parts and one subordinate lithotectonic unit. (1) High Land Complex occupying the central highland zone extending from SW to the NE of the island; (2) the Wani Complex occupying the lowlands to W of Highland complex; and (3) The Vijayan Complex to the E and S of it.

Highland Complex

The Highland Complex consists of supracrustal and igneous rocks characterised by common structural history and a granulitic facies of metamorphic grade and derived from ancient source rocks. The metasedimentary rocks are meta quartzite, forsterite marbles, scapolite-wollastonite granulite and gneisses, garnet sillimanite-graphite gneisses and quartz-feldspar granulites intercalated with these meta sediments and forming over 50% of HC are rocks of granitoid origin. These are quartzo-feldspathic banded gneisses and charnockitic gneisses. The banded nature of the gneisses is due to original compositional differences, dyke intrusion and metamorphic differentiation; tight isoclinal folding and thrusting has modified the original intrusive relations and stratigraphic sequences.

The main structural elements in HC are well developed gneissic foliation and a strong mineral and stretching lineations, both of which vary from E-W in the S to NNW-SSE in the center and to NNE-SSW in the N of the belt. At least four phases of ductile deformation with corresponding episodes of folding have been recognized in many parts of Precambrian basement. The main folding episode gave rise to prominent upright to overturned folds which predominate the present structure; they were preceded by mostly obliterated and isoclinal, sub horizontal to recumbent folds (Berger and Jayasinghe, 1976 and Kriegeman, 1991).

The depositional age of the supracrustal rocks is ca. 2000 Ma and the granitoids range from 1942 Ma to 650 Ma. Hence the HC represents a 2-3 Ga crust. Regional granulitic facies metamorphism took place at 665 to 550 Ma. Metamorphic conditions vary from ca. 3-5 kbar and 600-700°C in W to about 8-10 kbar and 800-900°C.

Wanni Complex

Wanni Complex (WC) consists of (1) scattered relics of a supracrustal series in (2) a suite of completely folded granodioritic gneisses, intruded by (3) a late microcline granite. The Tonigala Granite, and its surrounding granitic migmatites younger than 1100 Ma. A large extent of

charnockitic terrane is present in the N of WC, E of Vaviuniya. Preliminary data suggests the WC rocks to be about 1000 to 1100 Ma old and Nd model ages of 1.5 to 1.6 Ga.

The WC rocks are of lower metamorphic grade than those of HC, but there is no clear structural break between the two units. Various boundaries have been drawn between them on the basis of lithology or isotopic data, but there is as yet no conclusive evidence for either the nature or the position of WC_HC boundary.

Vijayan Complex

The Vijayan Complex (VC) consists of a variety of gneisses and granitoids ranging in composition from tonalite to leucogranite and containing xenoliths of metaquartzite and siliciclastic rocks. The original granitoids are strongly migmatized at many places and display well defined compositional layering. Zircon ages suggest that the metaquartzites have ages around 1100 Ma. Thus indicates that the enclosing granitoids are younger. Nd isotopic systematic and chemical criteria show the Vijayan orthogneisses to be derived magmatic precursors.

Much of the structural history of VC is comparable to that of the HC, but the two units are of completely different origin, brought together by thrusting. Within VC are tectonic klippen of HC rocks as at Kataragama and Maligawila.

Kadugannawa Complex

Infolded within HC is the Kadugannawa Complex. These rocks occupy distinct, well defined, elongated, upright doubly plunging synformal basins (arenas) around Kandy. They consist mainly of biotite-horn blend and biotite gneisses, together with concordant amphibolites, minor quartz-feldspathic and pelitic gneisses and metaquartzites. Early recumbent folds were over folded by asymmetric, reclined folds; large upright structures with variable axial planes gave rise to the present basin and dome pattern. There is still no agreement as to the origin of these rocks, though it is thought that all the rocks in the arenas once experienced granulite facies metamorphism.

The gneisses are tonalitic, trondhjemitic and granodioritic, with calc alkaline affinity, minor layered mafic and ultramafic rocks being more tholeiitic in nature. One interesting suggestion is that the latter represent a deformed and metamorphosed, large synchronous, layered intrusion.

The recent advances in knowledge of the geology of Sri Lanka (Mathavan, Prame, &Cooray, 1999) favour a strong geological correlation of the HC, and the VC of Sri Lanka, respectively, with the Lützow-Holm Complex, and the Yatmato-Belgica Complex in the East Antarctica. The geology of the WC suggests a possible correlation with Madagascar, and East Africa. The amalgamation of the three crustal units of Sri Lanka, is apparently related to the two distinct orogenic events that resulted in the assembly of the Gondwana supercontinent.

9.2.2 Sedimentary Rocks

The island contains relatively limited strata of sedimentation surrounding its ancient hills. Aside from recent deposits along river valleys, only two small fragments of Jurassic sediment occur in Puttalam District, while a more extensive belt of Miocene limestone is found along the northwest coast, overlain in many areas by post Miocene deposits. The details are hereunder:

Jurassic

Upper Gondwana beds occupy two small basins in the NW at Tabbowa and Andigama-Pallama, which are faulted into the Precambrian basement. The Tabbowa basin is internally faulted and tilted and the rocks are exposed at the surface. The major rock types at Tabbowa are arkose, feldspathic sandstone, siltstone and mudstone; they are thought to be a deltaic facies. Fossilized plant remains, several forms of which are identical to those found in Upper Gondwana deposits of India.

The Andigama beds, 30km S of Tabbowa, are mainly carbonaceous shales and calcareous sandstones, covered by recent deposits. Gravity data indicates that the thickness of sediments is 500m at Tabbowa and 900 to 1200m at Andigama (Hatherton, Pattiarachchi and Ranasinghe, 1975).

Exploration wells in the Palk Strait between Sri Lanka and India show a sedimentary succession of over 2500m of shales, limestone, claystone and siltstone, ranging from Lower Cretaceous to Upper Pliocene-Miocene. The basin has horst and graben structure and several unconformities are present in the succession.

Tertiary (Miocene)

The Jaffna Peninsula and surrounding islands in the extreme N and the NW coastal strip extending to Puttalam are underlain by the Jaffna Limestone of Miocene age. It is mostly partly crystalline, indistinctly bedded, creamy coloured rock, richly fossiliferous in parts (Wayland and Davies, 1923), and mostly flat bedded. Gravity data suggest (Hatherton, Pattiarachchi and Ranasinghe, 1975) that it forms an elongated NW-trending basin, 300m thick in the E but reaching 400m in the W, due either to down warping or faulting. A sandy facies is present in the NE, the result of periodic step-faulting. A small outcrop of Miocene rocks is present at Minhagalkande on the SE coast.

Post Miocene

The post Miocene rocks of the NW coastal belt have been subdivided into an Older and Younger Group. The Older Group consists of (1) a basal ferruginous gravel, 6m thick at places; (2) the Red Beds, 3-30m thick, forming prominent ridges and narrow, elongated plateaus parallel to coast; (3) terrace gravel, which form scattered deposits, 4-9 m above abandoned river courses.

The Younger Group consists of (1) lagoonal, lacustrine and estuarine clays and sand, alluvium; (2) beach and dunes sands and (3) beach rock.

The post Miocene coastal deposits occur also in the S and E coastal strips, especially N and S of Batticaloa. Lignite (30 to 35m thick) occurs extensively in the SW sector.

9.3 Surface Manifestations of Geothermal Resources

Considering that Sri Lanka is not an active volcanic region or situated within proximity to an active plate margin little attention was paid for extensive exploration of the source of hot dry rocks and geothermal reservoirs and their flow regimes. However surface manifestation of geothermal energy has been recorded at no less than 10 to 12 thermal springs.

In Sri Lanka these geothermal springs are distributed along a narrow eastern low land belt running from Hambantota to Trincomalee and occur within the boundary of two main geological units – the Highland and Vijayan complexes (Dissanayake & Jayasena: 1987). About 80% of hot springs belongs to the Vijayan complex and 20% to the Highland www.complex.amazinglanka.com has pointed out the following 12 hot springs in five districts of Sri Lanka.

Trincomalee District

1. Rankihiriya / Ulpotha / Gomarankadawala
2. Kanniya

Polonnaruwa District

1. Madawawa
2. Nelum Wewa / Gal Wewa
3. Mutugalwela/ Gurukuburain Maduru Oya national park

Polonnaruwa District

1. Madawawa
2. Nelum Wewa / Gal Wewa
3. Mutugalwela/ Gurukuburain Maduru Oya national park

Ampara District

1. Mahaoya
2. Wahawa
3. Kapurella
4. Kivulegama- Jayanthi Wewa (Emmbilinne?)

Hambanthota District

Madunagala / Mahapelessa /Sooriyawewa

The **Figure 9.2** exhibits locations of some of the important geothermal springs in Sri Lanka.

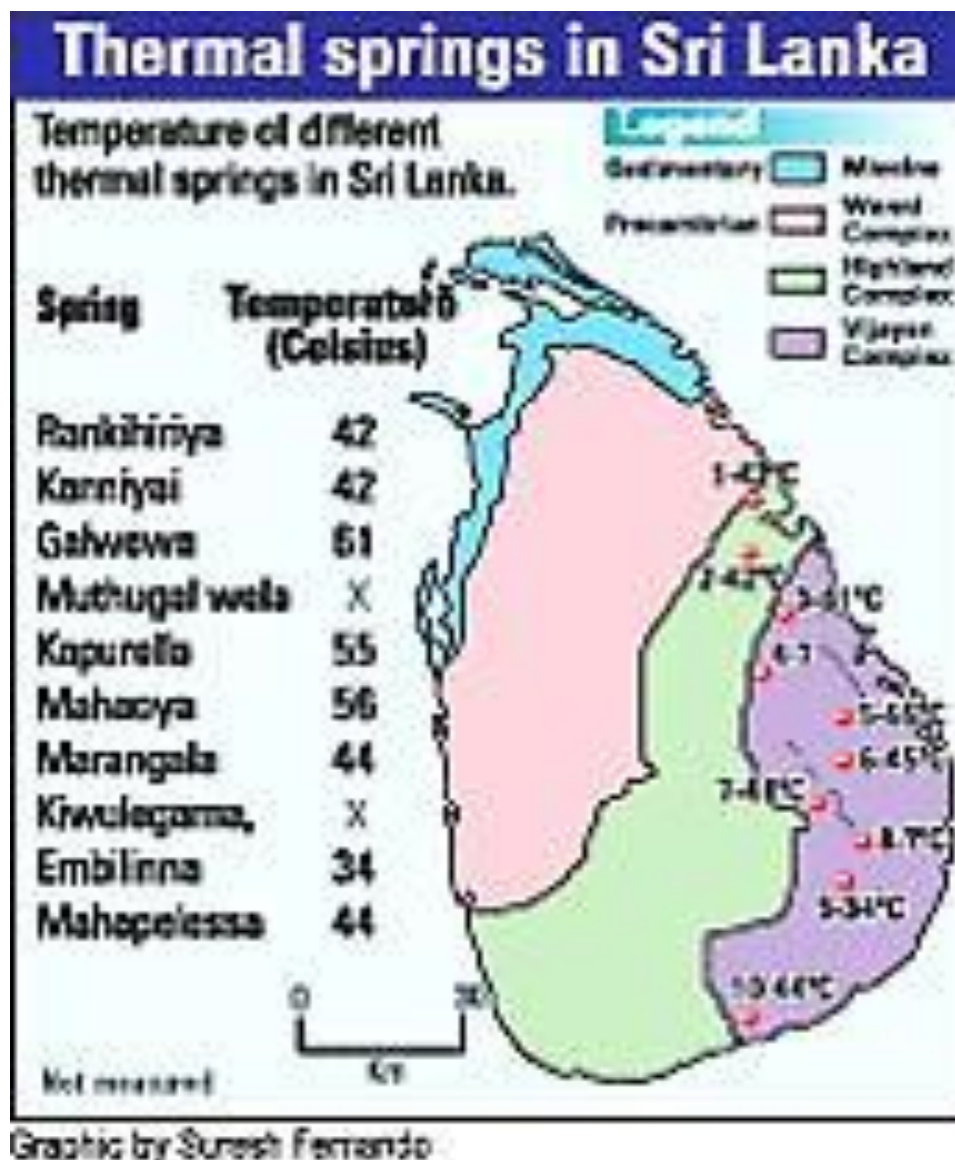


Figure 9.2: The Location of Important Geothermal Springs in Sri Lanka

Available details of these hot springs are given hereunder:

Wahawa Springs

The Wahawa hot spring is located at about 10 km SE of Padiyatalwa town ($7^{\circ} 21' N 81^{\circ} 18' E$), in southern part of the Ampara District, in the eastern province of Sri Lanka (**Figure 9.3**). Wahawa-Padiyatalawa is situated at 100 m above MSL. The Maha Oya River is the main surface water source which runs through a valley cutting through the dolerite dike formation for a distance of about 12.4km with a width of about 2 km across the Wahawa area (Senaratne and Chandima, 2011).

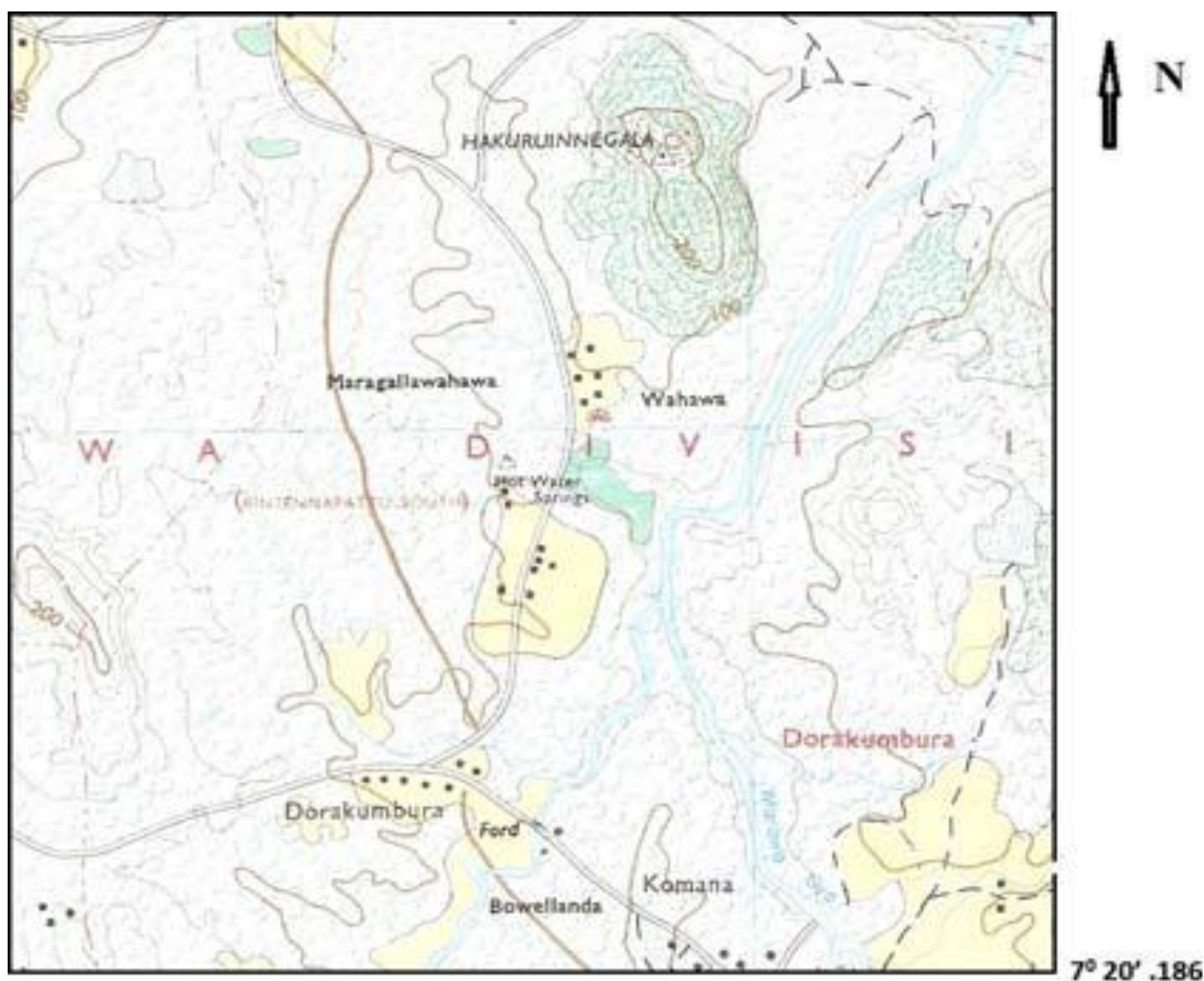


Figure 9.3: Location Map of the Wahawa Hot Spring

The Wahawa hot springs occur in the Vijayan Complex underlain by granites, granitic gneisses, quartzites and dolerite bodies (Dahanayake and Jayasena, 1983). Unmetamorphosed dolerite dikes occur cutting across the granitic gneisses of the Vijayan Complex (Cooray, 1978). Based on the K-Ar dating of dolerite dike present in the Wahawa area is of Triassic-Cretaceous age ranging from 152.6+ to 7.6 Ma (Yoshida et al 1988). The dolerite dike occurs westward of the thermal springs. The dike is 50m in width and more than 20km in length. Strike of the dike is N 600 W. Senaratne and Chandima (2011) studied 4 major hot springs out of approximately 18 to 20 closely spaced springs scattered in the village and the paddy fields. They are built in form of tanks but it seems that only a few that are being used. Among these wells are flowing artesian well which is used by the villages for bathing and washing.

Wahawa-1 hot spring has a temperature range of 50–52°C with a flow rate of 0.5 L/s (**Figure 9.3** and **Figure 9.4**). The spring appears in a paddy field along fractures in the granitic gneiss. Physically, the flowing water of the hot spring is clear with bubbles of sulfurous gas.

Wahawa hot spring-2 has measured temperatures between 55-60°C with a flow rate of 0.016 L/s, with an area of discharge of about 10x5 m, with sulfurous gas bubbling through mud. Altered minerals are white, black, and brown in color.

Wahawa hot spring-3 has a temperature of 51-55°C with a flow rate of 0.017 L/s. The water is muddy with no sulfur smell.

Wahawa hot spring- 4 was observed near a fracture in granitic gneiss. It has temperatures between 53 and 55°C with a flow rate of 0.015L/s. No alteration or sulfur smell was noted in spring no.4.



Figure 9.4: Views of the Wahawa Spring-1

Mahapelessa spring

This spring is located near Embilipitiya lying in the deep south of the Hambantota district. The hot spring shows out flow temperature ranging between 44 to 46°C. Medicinal bathing is popular at the Mahapelessa spring due to healing properties including the therapeutic power for skin conditions and rheumatic arthritis. (amazinglanka.com)

Kanniya Hot Spring

There are 7 hot springs now converted to bathing wells (**Figure 9.5**). The temperature of each is slightly different from each other. It is also believed the water from the wells have therapeutic healing powers and can cure many ailments.

This well goes back in the times of King Ravana who ruled the country over 5000 years ago. (www.amazinglanka.com).



Figure 9.5: Views of the Kanniya Hot Spring

Mahaoya Hot Springs

Mahaoya Hot Springs is located about 2km off Mahaoya town. This is said to be the hottest spring of all the hot springs on Sri Lanka. At this locality there are seven well maintained hot springs with different temperatures (**Figure 9.6**). The temperature of the hottest well is about 56 °C. Only two wells are of bathing temperature. The other wells emit continuous steam and its evaporation (www.amazinglanka.com).



Figure 9.6: Views of the Mahaoya Hot Springs

Polonnaruwa Hot Spring

This is newly known hot spring identified in Polonnaruwa near the Nelum Wewa and Gal Wewa reservoir close to the foothills of Dimbulaga mountain range in the Mahaweli B Zone. Out of the hot springs in Sri Lanka this is the most recent discovery. The existence of the spring was made public in 2009 (www.amazinglanka.com). A faculty member of the Peradeniya University who has studied the spring has measured the temperature of the water to be 61°C, which makes it the hottest spring in Sri Lanka. This spring is also unique in the sense that it is inside a wewa reservoir and submerged during the October 2009 rains. About six more springs surrounding

this area has also being discovered and considering the picturesque location, attempts are made to make it a tourist attraction (**Figure 9.7**).



Figure 9.7: View of Newly Discovered Geothermal Spring in Polonnaruwa

9.4 Hydrogeological Studies

A hydro geological study was conducted by Ranjana, U. K. Piyadasa and P.R.E.R. Ariyasena, (2011) on two types of hot springs at Kinniya springs in Trincomalee and Madunagala springs in Sooriyawawa which are located in the Highland and Vijayan geological complexes. The research objective was to identify hydro geological characteristics of the spring areas and identify physical and chemical characteristics of the hot springs. The results of their study are reproduced here.

The Kinniya springs and Madunagala springs belong to the semi arid zones. Further, the Kinniya springs are located in the eastern coastal belt and the Madunagala springs to southern lower flat plains. The annual rainfall for Kinniya is 1200-2000mm and the Madunagala area receives 950-1500mm. The study area receives rainfall from both the southeast and northeast monsoons. Geological structures of the studied thermal springs were completely different. Geologically, quaternary unconsolidated alluvial deposits extensively covered the thermal spring areas and several small outcrops are exposed sporadically in and nearby the thermal springs.

Water samples from thermal springs were collected in August and December 2009 and April 2010 to identify water quality parameters. Thermal water temperature was identified using the geothermometer and electrical conductivity and pH was measured using the portable Electrical Conductivity (EC) and pH meter. The temperature of spring water was measured directly in the field by a standard thermometer. To determine the chemical properties of thermal water, laboratory analyses were carried out subject to cation and anions.

The surface temperatures of the Kinniya spring water range from 30°C to 37°C, all of which can be classified as warm springs. The spring water is classified as weakly basic as indicated by the invariable pH from 6.7 to 7.3. Conductivity of the Kinniya hot springs at 25°C shows insignificant variation ranging from 288 to 428 µS/cm (**Table 9.1** and **Table 9.2**). In the surface temperatures of the Madunagala spring water range from 34°C to 46°C, all of which can be classified as warm thermal springs. The spring water is classified as weakly basic as indicated by the invariable pH from 6.8 to 7.9. The Conductivity of the hot springs at 25°C shows insignificant variation ranging from 6800 to 7890 µS/cm (**Table 9.1**). Further study reveals that due to increases of atmospheric precipitation decreases the thermal temperature decreases and a corresponding decrease atmospheric precipitation which defines increases the thermal water. Therefore, there is an existing intimate relation between atmospheric precipitation and thermal groundwater.

The chemical analysis results revealed that Kinniya spring water contains more HCO₃ and Madunagala spring water contained more Cl ions. Our geochemical analyses of Madunagala spring waters reveal that they belong to the Steam Heated water- type with quite high contents of SO₄ over recommended standards and the Kinniya springs belong to the mature water with high concentration of Cl (Chloride).

Table 9.1: Electrical Conductivity and pH Variation in the Kinniya Hot Spring

Well No:	December 2010		April 2011	
	Electrical Conductivity (µS/cm)	pH	Electrical Conductivity (µS/cm)	pH
01	294	7.2	371	6.7
02	288	7.1	340	6.8
03	296	7.0	343	6.6
04	305	7.2	369	6.8
05	298	7.3	369	6.9
06	308	7.3	428	6.8
07	306	7.3	362	6.9

Table 9.2: Electrical Conductivity and pH Variation in the Madunagala Hot Spring

Well No:	December 2010		April 2011	
	Electrical Conductivity ($\mu\text{S}/\text{cm}$)	pH	Electrical Conductivity ($\mu\text{S}/\text{cm}$)	pH
01	7100	7.7	7610	7.4
02	6900	7.9	7750	6.8
03	7200	7.9	7680	7.2
04	7100	7.9	7840	6.8
05	7300	7.9	7890	6.8
06	6800	7.8	7780	7.1

Geologically Kinniya area belongs to Highland series and it's containing some calcium carbonate sediments. Using the Ternary diagram, the type of water identified and its reveals that Kinniya thermal groundwater belongs to chloride type and Madunagala thermal water contains more SO_4 . The study identified the temperature regime of the thermal springs and the results reveal that the Madunagala thermal springs water temperature is higher than the Kinniya spring water.

9.5 Geothermal Potential

There is no dearth of geothermal springs in Sri Lanka which shows out flow temperature suitable for direct use as well as for generation of electricity. At Mahapelassa off Embilipitiya, Kanniya off Trincomalee and Mahaoya springs show their out flow temperature ranging between 34°C to 45°C . The hottest springs lie at Polonnaruwa (61°C), followed by Kapurella (56°C) and Mahaoya (55°C), Marangala-Wahawa close to Padiyatalawa ($42\text{--}45^\circ\text{C}$), Mahapelassa ($44\text{--}46^\circ\text{C}$) and Nelumwewa, which was known earlier as Madawewa and now under a lake, records 4°C in mud samples (Fonseka 1994, Premasiri, 2006).

An interesting observation reveals that most of geothermal springs in Sri Lanka are located near dolorite dykes in Highland and Viyayan complexes. Takigami et.al. (1999) has ascertained the ages of these dolorite dykes on the basis of $^{40}\text{Ar}\text{--}^{39}\text{Ar}$ as 160-170Ma. This shows the youngest intrusions in the area and providing sufficient heat energy.

Hydrogeological studies combined with Magneto Telluric (MT) investigations of the areas of the hottest geothermal springs would ascertain the size of the reservoir for basing a power plant

9.6 Conclusions

Even though, Sri Lanka is not located in an active volcanic ground unlike the vast majority of the countries that utilize geothermal energy, there are indications that a sufficient reservoir of geothermal energy exists at low enthalpy. The contact of Highland and Viyayan complex extends for over 300km and runs through some of the most underdeveloped regions of the country and occurrences of geothermal springs can be utilized for power generation or direct uses.

Sri Lanka has a major challenge ahead in its search for alternate fuels with the ever growing demand for power and energy sources and research into other forms of energy has long been overdue. Environmental concerns have always impeded the utilization of many fuels and geothermal energy has minimum negative environmental impacts.

The alternative power system can be used to solve electrical power problem in some areas in Sri Lanka. One of the low cost and popular energy systems in many countries over the world is geothermal sources. Many of the western and Asian countries use these resources to generate electricity, USA - 2.8GW, Mexico - 743MW, Italy - 742MW, Philippines - 1.8 GW, Indonesia 589 MW etc. They use different technologies, such as flash steam, dry steam and binary systems. Therefore after assessing the potential geothermal energy resources in Sri Lanka, a suitable electricity generating system can be designed. Therefore, it is necessary to assess the all geothermal potential in Sri Lanka with the view of generating electricity for the country. Here use of geophysical techniques along with drilling to estimate capacity of geothermal reservoirs can be planned. Finally, the suitable locations are needed to be economically assessed for establishment of geothermal electricity generating plants in Sri Lanka.

These hot water or thermal springs along a narrow belt running from Hambantota to Trincomalee occur within the boundary of two main geological units — Highland and Vijayan complexes. This boundary is considered as the priority region due to occurrence of youngest intrusions of dolerite dykes with K-Ar age of 150Ma. The presence of thermal springs in association with a dyke indicates that the thermal component may have been added from relatively young intrusion.

However, to develop the potential geothermal prospects for industrial exploitation, systematic geological, geochemical and geophysical techniques are required to locate and delineate shallow producing geothermal fields. Such work will pinpoint with accuracy the particular depths of hot-water reservoirs for drilling exploratory investigation boreholes.

Institute of Fundamental Studies (IFS), with the assistance of the Government Geological Survey and Mines Bureau had planned a joint survey utilizing a modern scientific technique known as Magneto Tellurics (MT) to map out the geothermal reservoirs from the Southern region of the tectonic belt at Mahapelessa in Hambantota and to be continue up to the North (www.priu.gov.lk/.../20100622sl_develop_geothermal_power.ht). Though the results of the survey are not known, yet it is the first step towards exploration and utilization of geo thermal energy in Sri Lanka.

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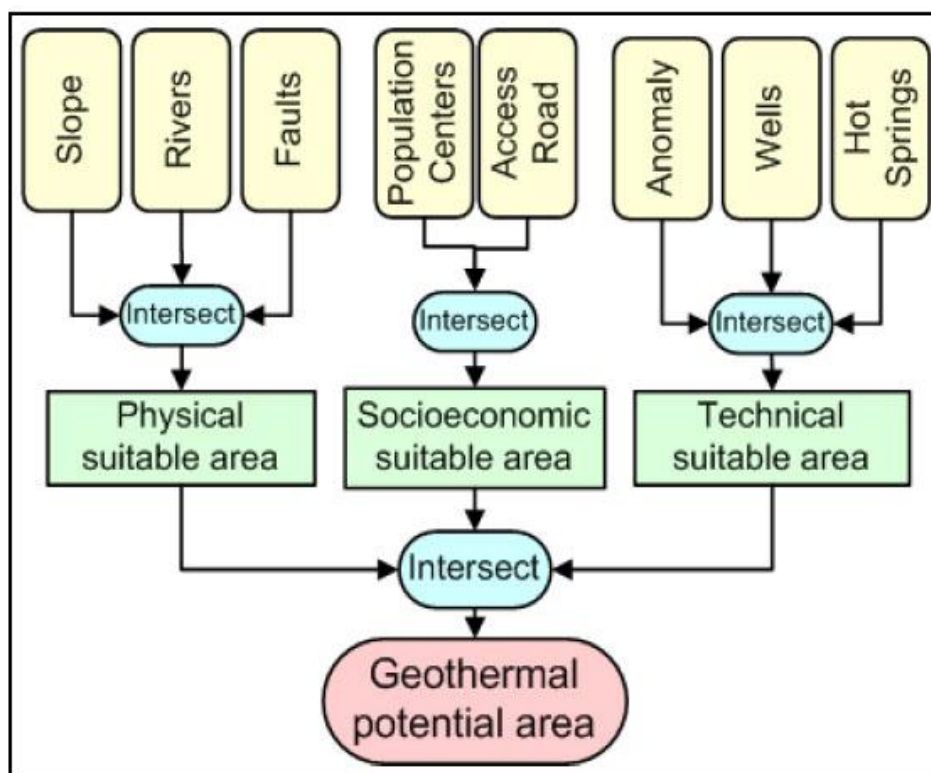
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CHAPTER – 10

CONCLUSIONS AND RECOMMENDATIONS

1. The energy-related challenges of the SAARC countries will become manifolds during the coming decades. The technical and policy actions must be taken to overcome these challenges. The geothermal energy industry and business can play important role in designing and implementing efficient solutions.
2. Data gathered during the present assessment indicates that there is high probability of a geothermal system existing in the Himalayan part as well as uplifted basement areas of the SAARC countries.
3. Tectonics and stratigraphic evolution of SAARC region is indicative of suitable conditions for widely distributed occurrence of low to high temperature geothermal resources and hot water springs in SAARC Member States. These potentials are suitable for direct-use and power generation.
4. Given the current low level of exploration, it is recommended that testing to demonstrate the presence of a geothermal system can best be completed by undertaking a coordinated exploration programme and drilling.
5. Generally locations of geothermal sites are near the plate boundary or in the vicinity of volcanic activity along with occurrences of hot water springs. However, it is not necessary that these have to lead to viable thermal reservoirs. There could be blind geothermal resources as well with no indications at the top surface.
6. To develop the potential geothermal prospects for industrial exploitation, systematic geological, geochemical and geophysical techniques are required to locate and delineate shallow producing geothermal reservoir fields. Such work will pinpoint with accuracy the particular depths of hot-water reservoirs for drilling exploratory investigation boreholes. A major exploration effort is needed to characterize geothermal reservoirs and prepare an inventory of potential geothermal areas for further development.
7. The following schematic diagram illustrates various aspects for identifying a geothermal power plant site.



8. The first step for determining the technical suitability and geothermal exploration is to identify potential geothermal sites for electric power generation or direct use. In this context all available data of hot water springs in context to regional geological environment are to be obtained. This provides basis to estimate cons and pros for geothermal utilization.

9. The size of the resource and preliminary potential is established by undertaking geothermal geological mapping/structural mapping, lineament analysis, chemical analyses and interpretation of fluids from the geothermal springs, surface geophysical methods including

10. Time Domain Electromagnetics (TEM) and Magnetotellurics MT resistivity surveys, study of geothermal gradients of the oil and gas wells if they exist in the area, micro-seismic study, drilling, reservoir evaluation, and environmental study.

11. Subsequently after establishing the geothermal resource further exploration and development work is to be carried out including appraisal/development drilling, well testing, fluid sampling and chemical analyses and final geological, geochemical and reservoir modeling is required to establish the size of the geothermal power plant.

12. Identified Potential Locations of Geothermal Resources

The data available for this study from all available sources is mainly limited to surface manifestation of geothermal energy mainly in the form of hot springs. Evaluation of these indications in the context of regional setting facilitated interpretation of the following potential locations have been identified for further exploration of geothermal resources in South Asia.

Afghanistan: The Hindu Kush geothermal springs seem suitable sites for further exploration for power generation and direct uses. Geothermal manifestations in these areas are mostly marked in the fracture systems of active faults within basins and linear faulted valleys or wide valleys of the southern structural component of Afghanistan.

Bangladesh: The Rangpur Saddle and Bogra Shelf areas have a thin veneer of sedimentary overburden above igneous/metamorphic basement with relatively higher temperature regime due to uplifted basement. Abandoned onshore wells with high geothermal gradients in Bangladesh may be tested for geothermal energy exploration.

Bhutan: Most of the thermal springs are sporadically located in Greater Himalayan regions near the exposure of leucogranites. Further research in the area is needed to determine potential geothermal locations.

India: It has a history of geothermal exploration and some of areas are in advance stage of setting up thermal power plants. Tattapani geothermal field where a project for tapping the electric generation for 5 MWe capacity is being planned; other promising geothermal sites are Puga, Chhumathang and Manikaran. Proposal of setting up geothermal power plants are under consideration at Khammam district of Andhra Pradesh and in Gujarat state.

Nepal: In the central region of Sribagar area thermal spring (surface temperature 73°C), and Sadhu Khola spring area (surface temperature 68°C) can be considered as candidate for generation of electricity due to possibility of a large geothermal reservoir.

Pakistan: The Murtazabad area in the Himalaya-Karakorum-Hindu Kush Zone represents one of the major geothermal occurrences, with seven hot springs discharging hot water flowing at the rate of 50 to 1200 liter per minute with the surface temperature from 40 to 94°C. The other potential area worth investigation is Koh-e-Sultan spring area in Balochistan Province. Although the surface temperature and discharge of these hot springs is low, it is interpreted that due to several phases of volcanic activity a substantial geothermal reservoir may exist.

Sri Lanka: A number of springs exhibit out flow temperatures ranging from 34°C to 61°C. The Wahawa hot springs are the most favorable location for consideration of further investigation. These springs show measured temperatures between 50 to 60°C with a flow rate of 0.016 liters/sec, with an area of discharge of about 10x5 m, with sulfurous gas bubbling through mud.

Maldives: There is no Information on geothermal occurrences in Maldives.

13. The geothermal renewable energy resources can be exploited on cost competitive basis for today's energy starved SAARC region. Geothermal energy resources are available by extracting natural hot water or underground rocks by appropriate technology, which is readily accessible. High-temperature geothermal resources suitable for power generation are generally located in volcanic or seismic activity areas at or near plate boundaries, where geothermal resources can make a worthwhile contribution by providing a reliable and renewable energy source for the region. Geothermal energy is not dependent on the weather unlike solar, wind or hydro power. Therefore, the development of potential geothermal energy resources of the Member States can meet significant part of their energy requirements.

14. In the electricity sector, the geographical distribution of suitable geothermal fields is more restricted and mainly confined to countries or regions on active plate boundaries or with active volcanoes. With an interconnected grid, it would be easy to provide the electricity to the entire country. In order to determine the feasibility of a project based on geothermal energy at a particular location there are number of factors to be considered via:

- i. Electricity and / or heat demand in the region
- ii. Proximity to transmission and distribution infrastructure
- iii. Volume and surface expression of a geothermal reservoir
- iv. Reservoir life and replacement wells
- v. Circulating fluid chemistry
- vi. Flash vs. binary technology
- vii. Cost / installed MWe and cost / MWh delivered to a local or regional market
- viii. Plant reliability and safety.

15. The commercial viability of geothermal power production is influenced by capital costs for land, drilling and physical plant; operating and maintenance costs; the amount of power generated and sold from the plant; and the market value of that power. However, because geothermal power plants incur high capital costs at the beginning of the project, they are typically at an economic disadvantage to conventional fossil fueled power plants. Fossil fuel plants have lower up-front capital costs, but incur fuel costs for the life of the plant.

16. A geothermal system is made up of four main elements: a heat source, a reservoir, a fluid, which is the carrier that transfers the heat, and a recharge area. The typical geothermal system used for electric power generation must yield approximately 10kg of steam to produce one unit (kWh) of electricity (Manzella, 1995). Production of large quantities of electricity, at rates of hundreds of megawatts, requires the production of great volumes of fluid. Thus, one aspect of a geothermal system is that it must contain great volumes of fluid at high temperatures or a reservoir that can be recharged with fluids that are heated by contact with the rock.

17. The utilization of geothermal energy is a viable option for SAARC Member States as presently they are heavily dependent on imported oil. The most important economic aspect of geothermal energy use is that it's homegrown. Utilization of indigenous resources reduces the dependency of the country on imported energy sources, which in turn will decrease the annual trade deficit that translates into more jobs and a fairly healthy economy. At the same time, a vital measure of national security is gained when the country control its own energy supplies.

18. Although fossil fuels are draining the foreign exchange reserves of these countries being very costly, their consumption is growing and will continue to grow in the foreseeable future by necessity, causing further stress to the overall economy and to the very fragile economic environment of most of SAARC countries. On the other hand, geothermal energy is a clean, renewable and sustainable energy source, available for exploitation on its own turf, either directly as a heat source or to generate electric power.

19. Geothermal power, in addition to easing SAARC region's energy problems, it will also offset global gas emissions. One of the major concerns of modern times is the ever-increasing emissions of greenhouse gases into the atmosphere and the threat of global warming. There is an international acceptance that a continuation of the present way of producing most of the energy needed - by burning fossil fuels - will bring about significant climate change, global warming, rises in sea level, floods, droughts, deforestation, and extreme weather conditions. The sad fact is that the poorest people in the world, who have done nothing to bring on the changes, will suffer the most. One of the key solutions to avoid these difficulties is to reduce the use of fossil fuels and increase the sustainable use of renewable energy sources. In many parts of the world, geothermal energy can play an important role in this respect.

20. As geothermal is one of the environmentally clean and friendly sustainable renewable energy sources, the member countries may also be able to get financing under the Clean Development Mechanism (CDM) promoted by the Kyoto Protocol, which encourages developed countries to invest in renewable energy projects in developing countries. The greenhouse gas credits created by geothermal power plants could be sold on global markets to bring extra cash revenues.

21. In the direct use sector, the potential for geothermal is very large, as space heating and water heating are a significant part of the energy budget in large parts of big cities of the SAARC countries. The literature review for the report indicate that there are widespread low-temperature geothermal occurrences in most of the areas of thermal springs, which can be widely used for space heating, balneology, fish farming and greenhouses during the cold winter months, and also for tap water in the summer.

22. Legislative amendments may be required in some of the Member States for direct use and for power generation. Geothermal direct use could have a very positive impact on the economy and living standard of masses by supporting existing industrial, agricultural and domestic requirements, promoting diversified agriculture, creating jobs, and reducing dependence on imported fossil fuels.

23. From the study it can be concluded that geothermal energy for power generation especially the direct use is a viable option for the South Asia. In this context a significant allocation of funds are needed to ensure economic feasibility and to explore a stable source of heat for a high temperature geothermal application.