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GEOTHERMAL RESOURCES OF PAKISTAN AND METHODS FOR EARLY STAGE EXPLORATION

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ABSTRACT

Methods for early stage geothermal exploration are reviewed and their advantages and disadvantages with regard to known conditions in Pakistan are discussed. Methods discussed include geologic mapping, geothermometry and general geochemical characteristics, thermal methods, resistivity methods and structural methods such as magnetics and gravity.

The main areas of geothermal activity are discussed and presented, including the Himalayan collision zone, the Indus basin margin zone and the Chaghi area in Baluchistan. Suggestions are made on exploration procedures in near future, including a systematic approach in collection of a detailed inventory of all surface manifestations in the country and geochemical sampling and analysis of fluids. Special suggestions are made for the some of the areas. Finally, the importance of selecting a feasible target area for exploitation of the geothermal resources, in order to prove the benefits of geothermal energy to the local population and decision makers are stressed.

1. INTRODUCTION

The government of Pakistan is presently studying ways to meet the increasing energy demands in the country by indigenous energy resources. Energy is produced by various means in Pakistan, including hydroelectric dams, coal, nuclear and gas fired power stations. One additional alternative is geothermal energy, which is the subject of the present study, but its contribution today is negligible. Geothermal areas have been identified in three areas of Pakistan, the Himalayan collision zone, the Chaghi volcanic arc, and the Indus basin margin (Figure 1). In the future these geothermal resources may be able to provide supplementary energy in selected areas.

Literature on the geothermal fields of Pakistan is limited and exploration generally in the very early stages (e.g. Shuja,1986; Geological Survey of Pakistan/JICA, 1988). This paper provides a short review of the geothermal exploration methods considered to be the most relevant in the early stages of exploration. The geothermal areas of Pakistan are described and recommendations made for a programme of geothermal exploration.

FIGURE 1: Map of Pakistan, showing areas of geothermal activity and some important geological and tectonic features

2. GEOTHERMAL EXPLORATION METHODS

A typical geothermal exploration programme proceeds through early stages where large areas or fields are studied with relatively inexpensive methods to more mature stages when the efforts are focussed on a few promising fields using increasingly more expensive methods. Initially stage a research programme needs to be established based on methods that are thought to be most suitable for the expected type of geothermal systems. The nature of low-temperature fields and high-temperature fields is usually quite different, as the former is usually based on heat transfer through general heat flow, while the latter has heat sources of intrusive origin. Similarly, low-temperature fields in sedimentary surroundings are different from those in crystalline rocks. A geothermal exploration programme must be based on the cost effectiveness of the methods with an emphasis on exploration routines that have proven to be successful in geothermal exploration under similar conditions.

Generally, the methods most relevant to early stage exploration, prior to drilling the first deep well, are geological mapping, geochemical study of the geothermal fluids and surveying by various geophysical methods, such as thermal surveys or resistivity sounding. Recording of data is very important and a good database of former surveys can often be very useful in planning new surveys.

2.1 Geological mapping

Upflow of geothermal water is often associated with structural weaknesses in rocks. Location of hot springs is often at faults or dykes that break up the rock series, such as volcanic lava series or sedimentary formations. Knowledge of these structures and the host rock for the geothermal flow is of the utmost importance for understanding the geothermal system. Hence, the first stage in exploring a new geothermal project should be detailed geothermal and geological mapping in order to make a reliable map of geothermal manifestations, record temperatures and flow rate of springs, map the geological stratigraphy along with regional dip and strike, and all structures visible on the surface, such as faults, fissures, joints and dykes. It is also important to estimate the hydrological characteristics of the strata.

The simplest case is where hot water flows to the surface along an exposed joint, fracture or dyke. However, rarely are circumstances that obvious (Figure 2).

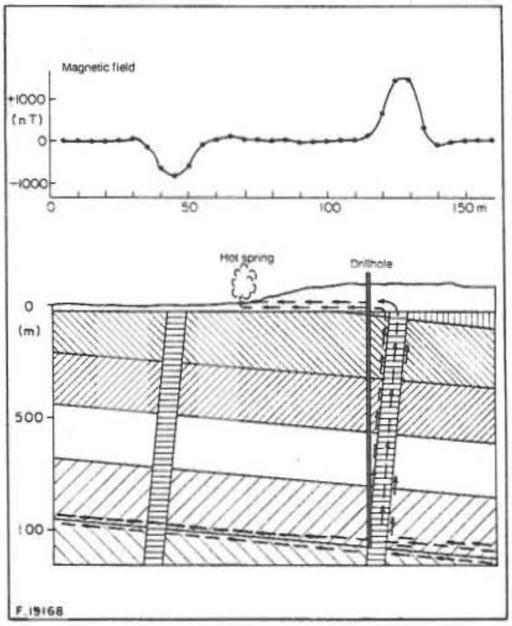


FIGURE 2: A near-vertical aquifer (basaltic dyke) leading hot water to the surface, and the magnetic anomaly associated with it; the water appears on the surface some distance away from the upflow area due to horizontal flow in the sediment cover

2.2 Geochemistry

Geochemistry has important applications in exploration for geothermal resources. In the early stages it is mainly used to provide estimates of the reservoir temperature and the general chemical characteristics of the geothermal water. This aids in the selection of geothermal areas for more detailed surface explorations and exploratory drilling. In the production phase it is an important monitoring method for controlling changes in geothermal reservoirs.

2.2.1 Geothermometers

The chemical content of various elements in geothermal water can be used to predict subsurface temperatures in geothermal systems. Various geothermometers have been proposed for this purpose, based on different relationships and reactions between the fluid and the host rock.

Qualitative geothermometers are based on the distribution and relative concentrations of various elements in the water which can provide an approximate estimate of properties in the geothermal reservoir. For example, high contents of HCO_3, Hg and H_2S or sulphate in near-surface waters are indicators of high temperatures at depth. Similarly, high Cl/F ratio and Cl/SO_4 ratio may indicate the existence of a high-temperature system. The presence of H_2 gas in a geothermal system is a good indicator of high temperatures and high concentration of Li points to high temperatures at relatively shallow depth. Information like this can be important and help in understanding the nature of a geothermal system, even though it cannot be quantified.

Quantitative geothermometers are based on known relationships due to water-rock interaction. They can be both theoretical or empirical. These include both chemical and isotopic geothermometers. Isotope geothermometers are usually used for high-temperature waters, whereas chemical geothermometers can be used in both high- and low-temperature geothermal systems. They are based on the assumption that equilibrium between specific minerals and the thermal fluid is attained at depth. Many chemical geothermometers have been developed during the past decades, the most commonly used ones being the silica geothermometers (e.g. Fournier and Potter, 1982; Arnórsson et. al., 1983) and Na-K / Na-K-Ca geothermometers (Fournier and Trusedell, 1973; Arnórsson et al., 1983). These geothermometers often give different reservoir temperatures for the same fluid. This may be due to lack of equilibrium between minerals and thermal fluids or mixing of cold water during the upflow. It may also suggest that the thermometers are not suitable for the area studied due to specific geological conditions. Different rates of response may show temperatures from different depths and/or ages.

The most commonly used geothermometer is the silica geothermometer. The quartz geothermometer is used for prediction of high temperatures (>180°C), while the chalcedony geothermometer is used for low reservoir temperatures. The solubility of silica is affected by the pH values of the fluid, thus, the pH has to be accounted for when it is greater than 9.5. In order to deal with high pH and hard waters that do not yield reliable temperatures when using the silica geothermometer, the Na-K and the Na-K-Ca geothermometers were proposed and have been used successfully in such systems.

The following equation describes the quartz geothermometer proposed by Fournier and Potter (1982):

$$t(°C) = -42.198 + 0.2881\,[SiO_2] + 3.6686 \times 10^{-4}\,[SiO_2]^2 + 3.1665 \times 10^{-7}\,[SiO_2]^3 + 77.034 \log [SiO_2]$$

In Table 1 some of the most common silica geothermometers are presented. They cover a temperature range of 20-250°C.

TABLE 1: Equations governing some selected geothermometers (Fournier, 1989)
(S is the concentration of dissolved silica, concentrations are in mg/kg)

Geothermometer	**Equation**	**Temperature range (°C)**
1. Quartz - no steam loss	$t(°C) = \frac{1309}{5.19 - \log S} - 273.15$	$20 < T < 250$
2. Quartz - maximum steam loss	$t(°C) = \frac{1522}{5.75 - \log S} - 273.15$	$20 < T < 250$
3. Chalcedony	$t(°C) = \frac{1032}{4.69 - \log S} - 273.15$	$20 < T < 250$
4. α - Cristobalite	$t(°C) = \frac{1000}{4.78 - \log S} - 273.15$	$20 < T < 250$
5. β - Cristobalite	$t(°C) = \frac{781}{4.51 - \log S} - 273.15$	$20 < T < 250$
6.Amorphous silica	$t(°C) = \frac{731}{4.52 - \log S} - 273.15$	$20 < T < 250$

2.2.2 General chemical properties

Generally, geothermal water contains a variety of elements with different solubility resulting from the water-rock interaction when the water flows through the rocks at the ambient temperature. These elements are mostly hydrogen sulphide, silica, sodium chlorides, bromide, sodium carbonates and other alkaline minerals. The origin of the water is also of importance, especially if it has been mixed with seawater. The chemical content of the water controls, to a large extent, its properties with regard to utilization and therefore it is very important to have a good database of it at an early stage.

Low-temperature geothermal waters in crystalline rocks are usually dilute, i.e. have low values of total dissolved solids (< 500 mg/l), and no harmful trace elements. Such waters can often be used directly, e.g. for heating of houses or swimming pools and even for direct agricultural use or drinking. However, if the chemical content is high, such as with low-temperature fields in sedimentary rocks, high-temperature fields and brine fields in general, indirect usage may be necessary in order to utilize the energy and avoid scaling or corrosion in pipes and systems. Often, heat-exchangers of various types can be used so that hot geothermal water heats up dilute cold water which is then used for the heating systems or agricultural purposes. Sometimes mixing chemicals can solve these problems. Of special importance is keeping the systems closed, so the water does not absorb oxygen, as this increases the corrosive properties of the hot water.

For electrical production, geothermal steam can usually be used directly, though in some cases mixing chemicals may be necessary to avoid scaling or corrosion.

2.3 Thermal surveys

The purpose of thermal methods is to discover and delineate potential geothermal fields and roughly to assess the resources. Of geophysical methods these are the most direct as they deal with the thermal properties of the geothermal system. Included are measurements of temperature in soil at about 0.5 m depth, temperature gradient and heat flow surveys based on shallow boreholes, 20-200 m deep, and airborne thermal infra-red surveys.

As discussed earlier, the location of geothermal springs is often associated with near-vertical structures that cut through the horizontal strata. This applies especially to low-temperature fields. If the surface is covered with soil the relationship between the spring and such structures may not be obvious. In these cases, soil temperature measurements can give important structural information. The temperature is measured in a grid with 10 m interval at about 0.5 m depth. A narrow approx. 40 cm deep hole is made by a steel rod. A rod with a thermistor is then pushed down to 50 cm. The temperature is registered with an accuracy of +/- 0.1°C. The results are presented on temperature contour maps (Figure 3). The temperature contours may show linear tendencies that indicate linear structures. Because of the annual variations in temperature it is important to carry out the survey in as short a time as possible and to do it when temperature changes are slow. Besides temperature changes in the soil due to the climatic variation, anomalies can occur due to changes in physical properties of the soil. Therefore, it is of importance to map obvious changes in the soil, such as variation in

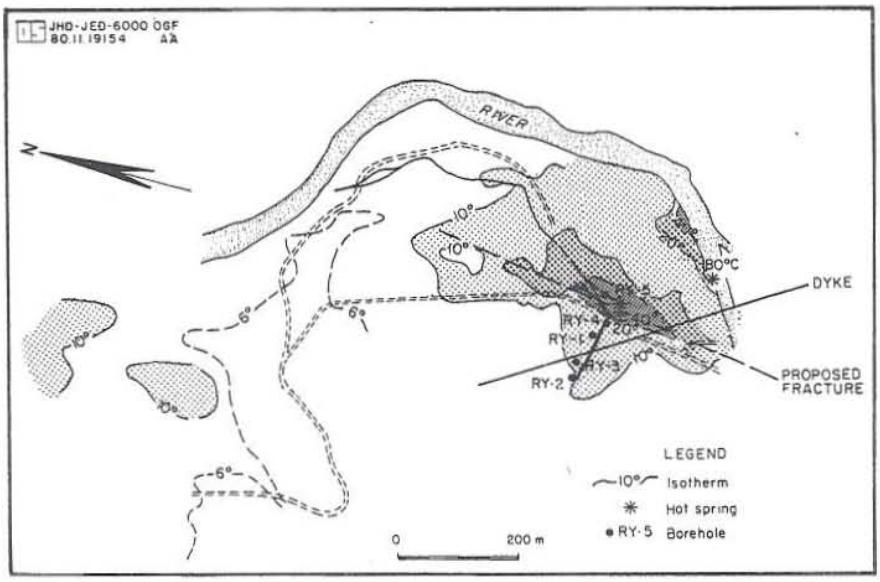


FIGURE 3: Contour map of temperature (°C) measured at 0.5 m depth at Reykir in Fnjóskadalur, N-Iceland; note the trend of the fracture that was proposed on the basis of the survey (Flóvenz, 1985)

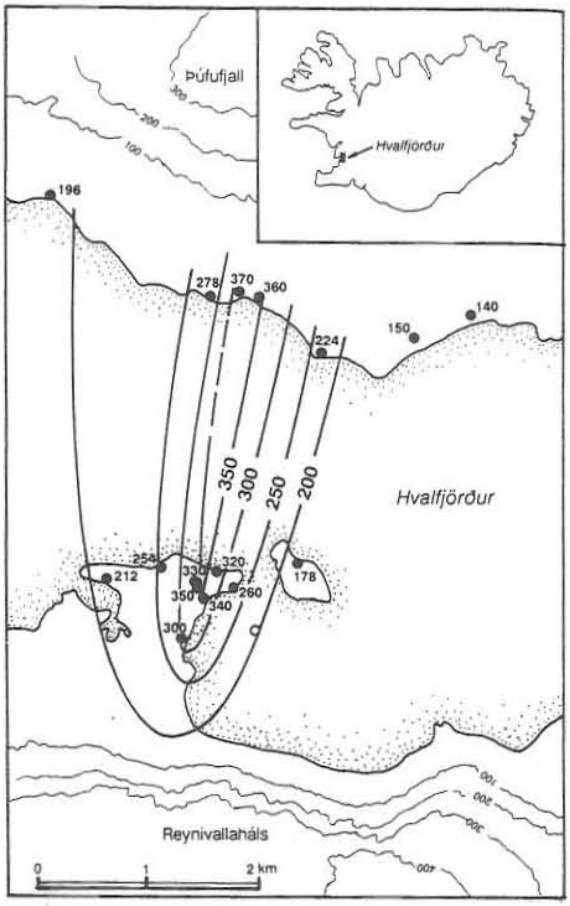


FIGURE 4: Temperature gradient anomaly in Hvalfjördur, W-Iceland based on 60 m deep gradient wells, where no surface manifestations of geothermal activity are found; drilling resulted in the discovery of an 80°C hot geothermal reservoir related to a N-S trending fracture zone (Flóvenz and Saemundsson, 1993)

water content, to investigate possible correlations with temperature anomalies.

One of the most common and most useful methods are measurements of thermal gradient in shallow bore holes. The depth of the boreholes can vary between 20 and 200 m but 40-60 m depth is often sufficient. It is cheapest to drill these holes with air-hammer drills. They can be drilled in one day even less and are therefore relatively low in cost. The main objective of a temperature gradient well is to obtain information on the subsurface temperatures. Linear increase of temperatures allows extrapolation to deeper levels. Usually the wells need several weeks to reach thermal equilibrium. Measurements in temperature gradient wells are made with a resistivity thermometer at every 2-5 m along the well with an accuracy of about 0.01 - 0.1°C, depending on the magnitude of anomalies present. An anomalously high thermal gradient is usually indicative of geothermal systems underneath.

In Iceland thermal gradient wells have been used for reconnaissance surveys and in estimating the areal extent of geothermal systems. Also the method has been very successful in locating narrow near-vertical fracture-dominated systems, where thermal anomalies have been found associated with active faults. Figure 4 shows delineation of permeable linear and near-vertical geothermal systems associated with faults. Thermal surveys may provide information about temperature, fractures and porosity in the geothermal systems and provide key information for successful location of production wells. Sometimes this has been accomplished by computer modelling. The following conditions and information are needed for computer modelling:

- Temperature measurements in non-flowing wells in thermal equilibrium with its surroundings;
- Knowledge of regional temperature gradients;
- The structure can be regarded as two dimensional;
- Mean annual temperature at the site;
- Some constraints on the temperature in the aquifers, either measured directly or estimated from chemical or isotopic geothermometers;
- Recharge and discharge of the geothermal system must have been stable for long enough time so the temperature distribution can be regarded as steady state.

Figure 5 shows an example of a thermal survey where a computer model was used. The calculated temperatures are compared to the measured ones. Improvement of the model is iterative by comparing calculated and measured data. On the basis of this model it was concluded that deepening of borehole 4 would result in the intersection of the fracture which feeds the hot springs. This was done and at a depth of 267 m a major aquifer was cut. Several tens of l/s of approximately 100°C hot water can be obtained from the well.

Airborne thermal (IR) surveys, employing infra-red scanners detecting radiation energy, have been used to map the occurrences and surface manifestations of geothermal areas. The method has the advantage that large areas can be surveyed rapidly and it provides an instantaneous picture for comparison with pictures at a later date. The disadvantages are low sensitivity, no depth penetration, sensitivity to disturbances by solar radiation and influence of the vegetation.

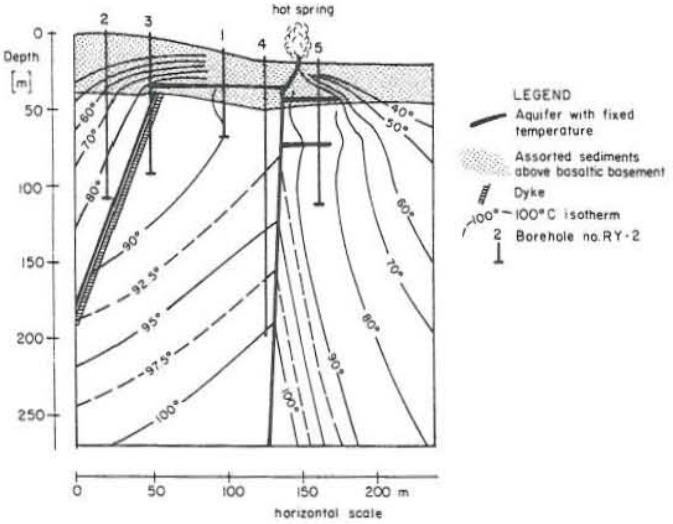


FIGURE 5: A simplified thermal model of the uppermost 250 m of the geothermal system at Reykir in Fnjóskadalur, N-Iceland, based on computer modelling of the thermal data (Flóvenz, 1985)

Finally it can be mentioned that photography of snow melt has been used to indicate and assess surface areas of slightly elevated temperatures. Areal photographs of the areas are taken soon after light snowfall, which make the thermally anomalous areas visible with the snow melting faster over these areas than in non-thermal areas.

2.4 Resistivity methods

One of the most important geophysical methods used for delineating geothermal fields is resistivity surveying. This includes many different methods which are all based on the same principle and the fact that parameters like temperature, permeability, porosity, salinity and alteration of the rocks are directly related to the resistivity of water-saturated rocks. They can be used both to delineate geothermal fields and estimate their potential and to locate near-vertical aquifers.

The principal relation of electrical resistivity can be expressed by Ohm's law as given by

$$E = j\,\rho$$

where

- E = Electrical field strength (V/m);
- ρ = Specific resistivity (Ωm), the reciprocal of resistivity is conductivity ($1/\rho = \sigma$);
- j = Current density (A/m^2).

Alternatively, resistivity can be defined as the ratio of the potential difference (ΔV) to the current (I) as follows:

$$\rho = \Delta V / I$$

The common principle of all resistivity sounding methods is to induce an electrical current in the earth and monitor signals at the surface generated by the current distribution. From this data the resistivity distribution at the measuring site can be calculated. This can be correlated with other geothermal parameters and other measuring sites and interpreted in terms of the geothermal potential of the site.

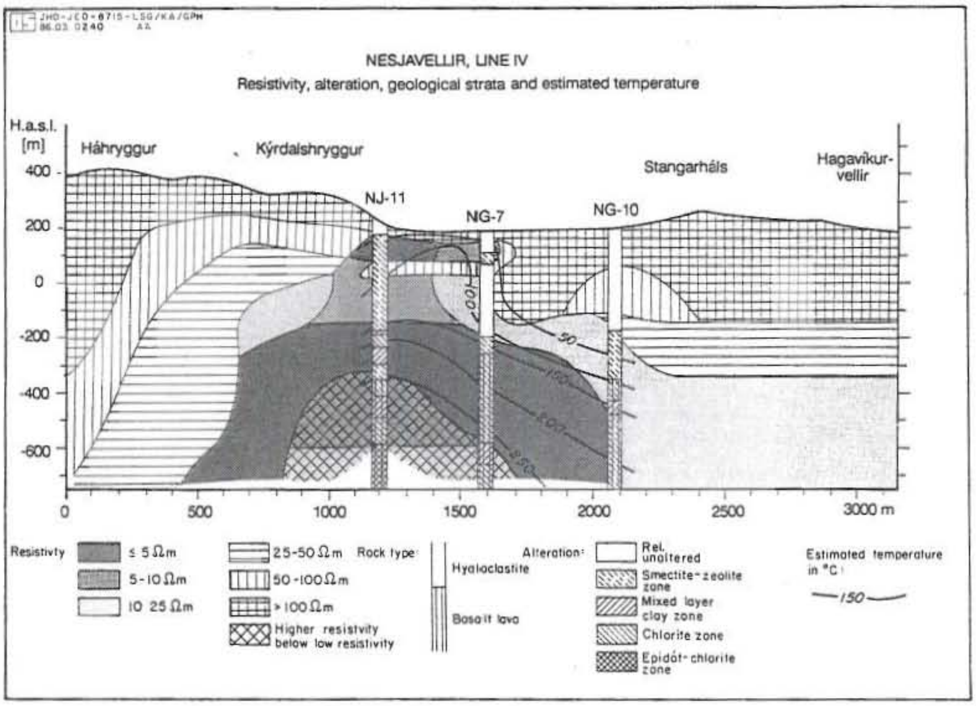


FIGURE 6: Resistivity cross-section from the Hengill high-temperature field, SW-Iceland, showing resistivity, compared with temperature distribution, lithology and alteration mineralogy in wells (Árnason and Flóvenz, 1992)

The most common methods are on one hand DC-methods such as Schlumberger sounding, Dipole sounding or profiling and head-on profiling, and on the other hand electromagnetic methods, such as MT, AMT and controlled source EM. Figure 6 shows a resistivity cross-section from a high-temperature field.

2.5 Structural methods

Magnetic surveying is a very useful aid to geothermal exploration often combined with other structural methods such as gravity and seismic methods in mapping geological structures. The method can both be used on the ground with handheld equipment and from aeroplanes. Over extensive regions with a thick sedimentary cover, structural features may be revealed if magnetic horizons such as ferruginous sandstone and shale, tuffs and lava flows are present within the sedimentary sequence. In the absence of magnetic sediments, magnetic surveys can provide information on the nature and form of the crystalline basements.

In geothermal exploration mapping geological structures associated with geothermal anomalies is of importance. The most important application are location and depth estimate of concealed intrusives, tracing dykes and faults buried under soil cover (Figure 2) and the location of hydrothermally altered areas. On the ground, measurements are made at regular intervals along parallel profiles, or in a grid with spacing depending on wavelength of expected anomalies. In low-temperature areas in Iceland, where dykes and fractures often need to be traced, it is common to do a magnetic survey with 20 m distance between the profile line and 5 m between the measuring points on each line with the magnetic sensor at 2.5-4 m height (Figure 7). In aeromagnetic surveys of high-temperature areas, the flight height above ground is some 100 m with about 100 m between lines.

Gravity surveys in geothermal exploration are used to detect geological formation with different densities. The method can be used to map various structures such as basement depth variation in

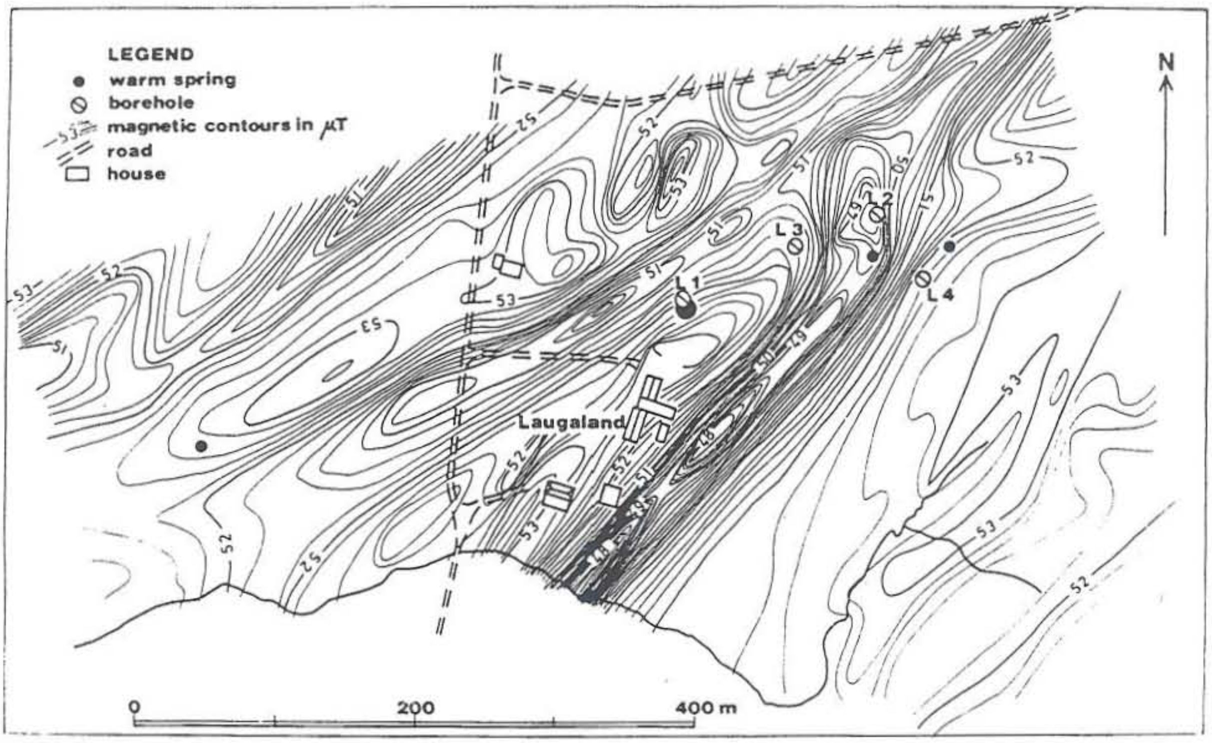
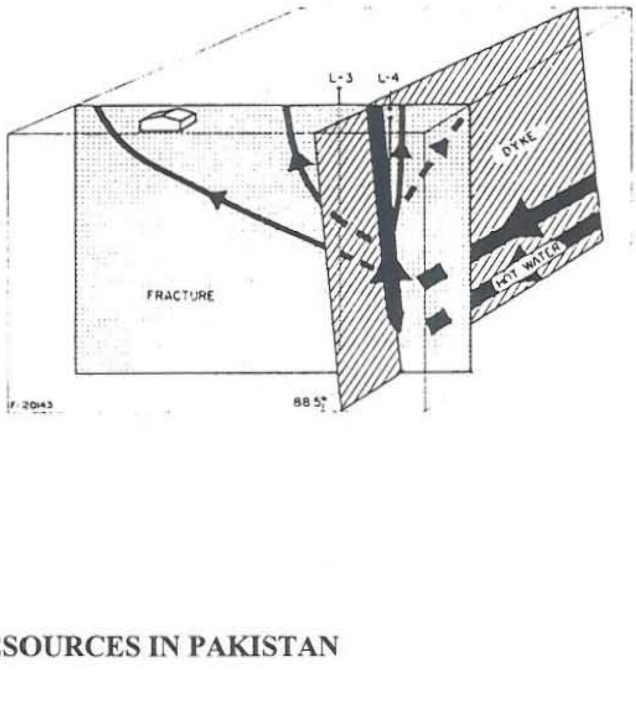


FIGURE 7: A magnetic contour map from the Laugaland geothermal field, S-Iceland and a simplified model of the geothermal system (Flóvenz and Georgsson, 1982)



sedimentary areas, intrusive rocks, alteration, porosity variations and fault and dyke systems. On a larger scale it can give important information on active or extinct volcanic systems associated with geothermal activity.

Seismic methods are the most commonly used geophysical methods in the world, due to their importance in oil and gas exploration. In geothermal exploration they are of much lesser significance, partly because this is a structural method and partly due to high costs.

3. EXPLORING FOR GEOTHERMAL RESOURCES IN PAKISTAN

3.1 Geological setting in Pakistan

Pakistan (Figure 1) is at the intersection of three continental plates, the Indian and Eurasian in the north and the Arabian plate to the south, and their interaction has shaped the country. The Indian plate has subducted beneath the Eurasian plate in the north. Same applies to the Arabian plate, after the collision with the Eurasian plate in the south. Main mantle thrusting and the main Karakoram thrust in the north are the major structural features and at the collision of these major continental plates the Himalayas, the highest mountain system in the world, has grown up. This structural and tectonic setup is the origin of the many geothermal systems in the collision zone.

Some of the active faults, such as the Chamman fault, the Gazzaband pass and Ornach-Nal faults, occur at or near the continental margins and are therefore of considerable significance in deciphering the geodynamic framework of Pakistan . The active faults are of four main types, transform faults, wrench faults, thrust faults and basement geofractures (Kazmi, 1980). These faults comprise the western boundary of the Indo-Pakistan subcontinent indicating strong left lateral movement.

The Indus sedimentary basin is at the margins of the Indo-Pakistani plate and stretches from North-Central Pakistan, south of the Himalayan mountain ranges, towards South Pakistan, including the salt range and syntaxial belt. It is near to the frontal thrust and it is a deep sedimentary basin dominated by the river Indus. Surface faults and joints are common, but in the east extensive alluvial cover has buried the structural evidence of faulting. Thermal activity is also found seen in various areas. It may be related to bending of the lithosphere, active basement faults transverse to the folds and the thrust belt.

In Baluchistan in the west, Tertiary and even Quaternary volcanics are found. The Chaghi volcanic arc is one of the characteristic features of a convergent plate boundary and is associated with the Makran subduction zone. The volcanics include diorite, grano-diorite and granite and are andesitic in nature.

3.2 Geothermal areas of Pakistan

On the basis of surface manifestations structural and geological evidence of geothermal fields in Pakistan can be divided into three important areas. These are the Himalayan collision zone, the Indus basin margin zone and the Chaghi volcanic arc.

Generally, geothermal waters in Pakistan are of meteoric origin, originating from precipitation in high mountains. In low-temperature systems, excluding sedimentary basins, the water percolates deep into the bedrock where it is heated by general heat flow, or cooling intrusives. It flows by hydrostatic pressure to lower elevations, along permeable structures such as faults, fractures, joints or high-permeability layers, in generally low-permeability strata. At lower elevations it appears at the surface through weaknesses in the crust. Most hot springs in North Pakistan or the Himalayan areas are probably of this type. On the other hand, geothermal systems in sedimentary grabens usually derive their origin from the difference in thermal conduction, i.e. the "isolating effect" due to low thermal conductivity of sediments. The geothermal activity in the Indus basin, such as in Kharachi, Dadu, and Azad Kashmir Kotli areas is due to sedimentary basins. High-temperature and intermediate-temperature geothermal systems are usually associated with active or recent volcanic centres where cooling intrusions are the heat source. The geothermal activity in Baluchistan in West-Pakistan seems to be associated with the volcanic arc which was active in Quaternary time and hence high temperatures may be encountered.

3.2.1 Himalayan collision zone

The Himalayan collision zone consists of the northern areas of Pakistan, Azad, Kashmir, Chiteral and Basham (Figure 1). Geologically, the area is a part of the northwestern continuation of the Himalayan mountain range, forming the Karakoram mountain range. Topographically, the area varies in elevation from about 1500 up to 8000 m above sea level. These highest mountain ranges of the world are mostly covered with glaciers and the Indus river originates from there. Tectonically, there are two major fault systems, the main mantle thrust (MMT) and the main Karakoram thrust (MKT). The geothermal systems are related to these majors faults.

Granite, granodiorite , amphibolites, meta sediments and other sedimentary rocks ranging in age from Precambrian to Quaternary are present. There is no evidence of younger volcanic activity in the area. According to Shuja (1986), the Murtazabad (Figure 8), Buldas and Chu-tran geothermal areas are related to MKT. There, hot water with temperatures above 90°C is found on the surface. On the basis of quantitative geothermometers, Shuja (1986) also estimated the temperature of the geothermal systems in Murtazabad and Buldas to be in the range 172-212°C (Table 2). Table 2 shows the temperature and some results of geothermometers for hot springs in the northern areas of Pakistan.

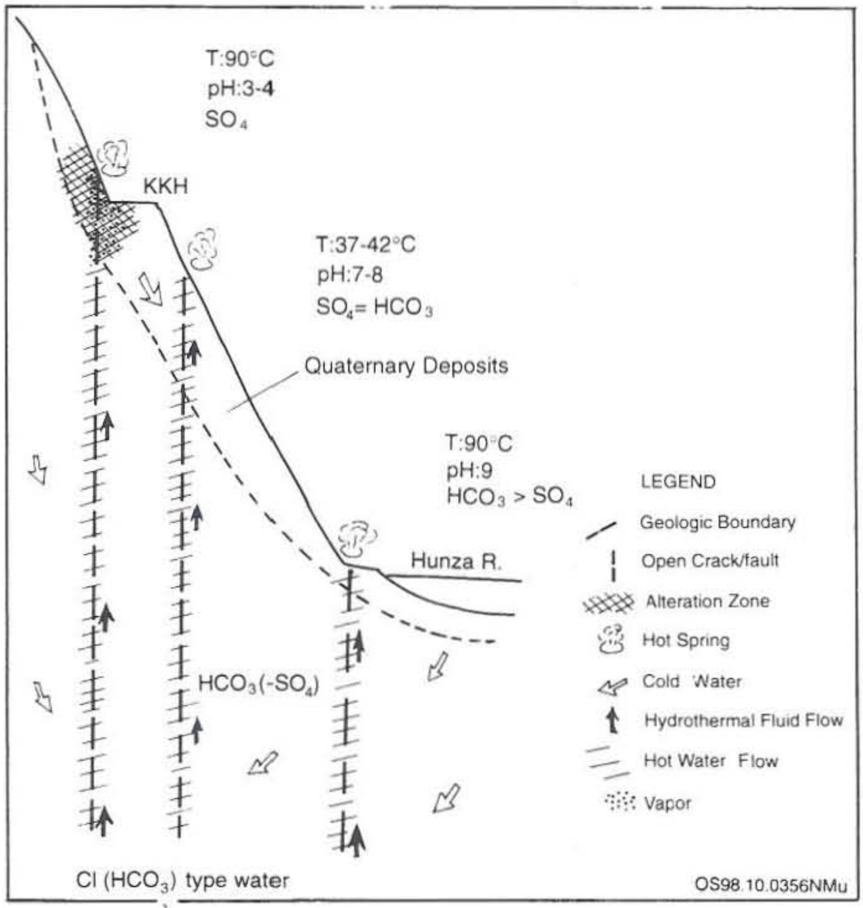


FIGURE 8: Conceptual model of the Murtazabad geothermal system, N-Pakistan (modified from Geological Survey of Pakistan / JICA, 1988)

There is a possibility that some of these springs are related to granitic rocks and acidic plutonic intrusions which would be very significant for the generation of thermal springs. Another possibility is that young intrusions of granite and granodiorite, which do not reach the surface, are still in the process of cooling. Existence of thermal springs in this region by friction of mechanical action may also be possible. In my view the source of heat (for the thermal springs) is related to orogenic movement.

TABLE 2: Temperature and geothermometer estimates based on samples from hot springs in the northern area of Pakistan (Shuja, 1986)

No.	Location	SiO_2 (°C)		Na-K	Na-K-Ca (°C)		Na-K-Ca	T-surface
		Adiabatic	Conductive	(°C)	$\beta = 1/3$	$\beta = 3/4$	(Mg- corr.)	(°C)
1	Chilas	83.0	79.4	215.5	171.7	75.2	66.6	20
2	Jaglot	85.4	82.1	56.9	56.9	127.7	84.8	65
3	Jaglot	88.7	85.9	85.0	148.6	160.1	43.2	50
4	Murtzabad	93.8	91.7	212.7	220.4	235.3	133.0	75
5	Murtzabad	110.0	110.5	240.6	226.8	221.3	8.9	80
6	Murtzabad	110.0	110.5	240.6	226.8	221.3	8.9	80
7	Murtzabad	119.6	121.7	312.7	235.2	175.4	7.2	26
8	Murtzabad	122.1	125.1	209.3	219.3	236.9	76.0	91
9	Hakuchar	115.4	116.7	252.3	191.3	97.9	53.4	50
10	Hakuchar	116.6	118.2	251.2	0.0	0.0	95.3	49
11	Buladas	113.4	114.2	159.1	116.6	116.6	23.7	39
12	Buldas	119.0	121.0	153.8	104.5	104.5	75.6	40

3.2.2 Indus basin margin zone

The existence of a large number of thermal springs concentrated along the Indus basin zone indicates the existence of widespread geothermal systems. The clusters of thermal springs in the Dadu district, and Mangho Pir and Karsaz area at Karachi represent interesting areas for geothermal exploration (Figure 9). Correlation between the hot springs and tectonics is not easy in the flat basin, prior to geological and geophysical investigations. The large number of thermal springs along the Indus basin marginal zone and its marginal extension at Karachi are good prospects for further study.

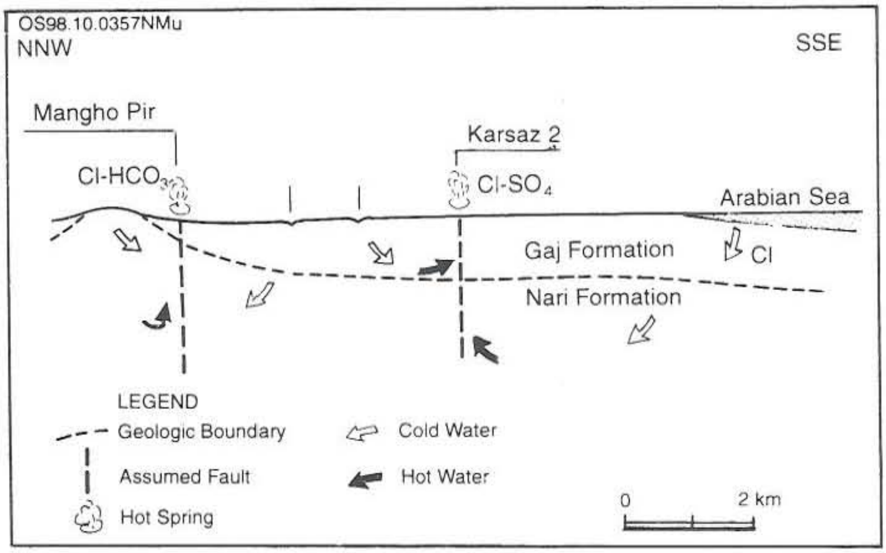


FIGURE 9: Conceptual model of a geothermal system at Mangho Pir and Karsaz 2 areas, Karachi, showing the probable transfer of heat from the subsurface (modif. from Geological Survey of Pakistan / JICA, 1988)

3.2.3 Chaghi area

Compared to the Himalayan collision zone and the Indus basin margin zone, there are only a few thermal springs in the quaternary volcanic arc in the Chaghi area. These springs are associated with the Sinjrani volcanics of the Koh-i-Sultan group having the character of quaternary volcanics (Figure 10). Their intrusive and extrusive structures are very promising for the generation of thermal springs. However,

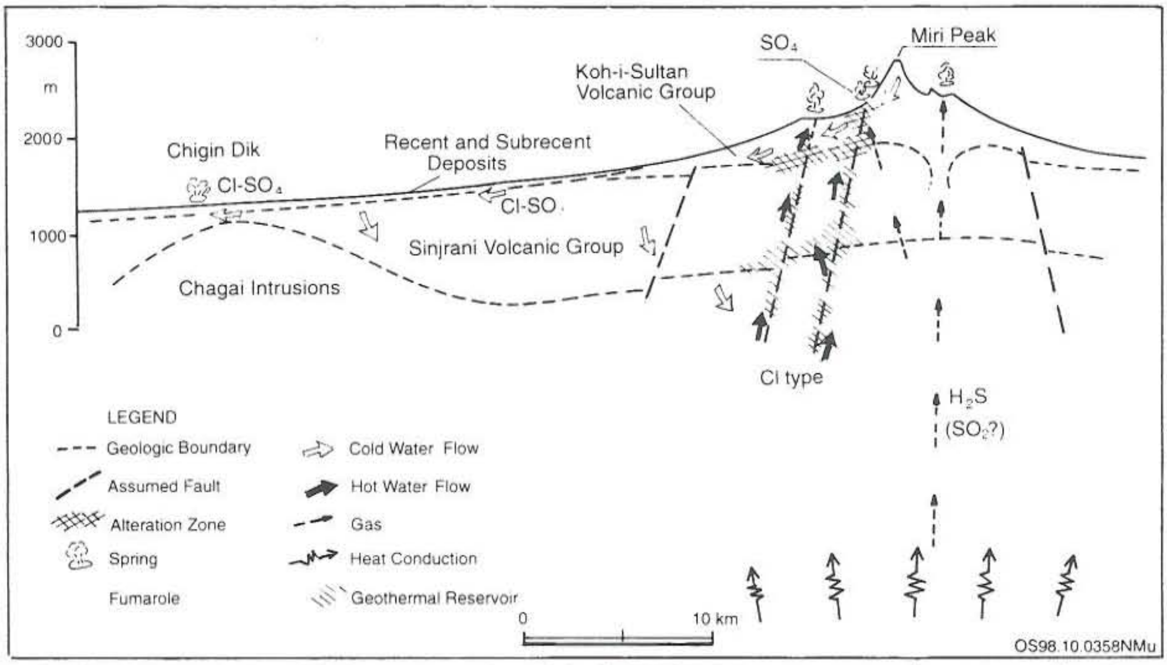


FIGURE 10: A simplified conceptual model of the Chaghi quaternary volcano zone showing the hydrothermal activity near Miri Peak and Chigin Dik areas in Baluchistan (modified from Geological Survey of Pakistan / JICA, 1988)

hydrological conditions are not favourable due to low precipitation rate in the area. On the basis of geological structures close to the Sinjrani volcanic group, secondary permeability is expected to be high due to the presence of numerous small structures like fractures and cavities in the area. According to Shuja (1986), the thermal springs in the southern part of Koh-i-Sultan volcanic group have some amount of hydrogen sulphide, which indicates the possibility of high thermal activity in the area under study. Therefore, the heat source is considered to be associated with young volcanism. Furthermore, one of the geothermal springs in Chigin Dik is associated with a fault as shown in Figure 10. Travertine deposits from thermal springs which remained active during the Mid Quaternary age in the southern margins of the Sinjrani volcanic group are also present.

3.2 Recommendations for a geothermal exploration programme

The following recommendations can be put forward for the exploration of geothermal development at an early stage in Pakistan.

3.2.1 General exploration

A first step is to make a detailed inventory of all surface manifestations in the country, i.e. thermal springs and fumeroles. At the same time, geological mapping and knowledge needs to be better correlated with the areas of geothermal activity, in order to form a thorough basis on which detailed local geological mapping in the geothermal areas can be based. A lot of this information exists today for example at the Geological Survey of Pakistan, but a more systematic approach is looked for.

Systematic geochemical sampling and analysis of fluids from geothermal areas should be carried out on a regional scale in the near future to obtain a better knowledge of subsurface temperatures and the flow pattern of hydrological systems. On the basis of these, the most promising fields with regard to potential and utilization can be selected for further studies.

3.2.2 Himalayan collision zone

The area is characterized by major tectonic settings, where volcanic rocks, and hydrological and structural features are promising for further geothermal exploration. With high surface temperatures and to some extent a favourable chemistry for direct utilization, promising fields close to villages which need hot water for heating, washing or bathing, need to be selected for detailed studies. Even electrical production with binary turbines cannot be ruled out. With reference to local situations, this might include the following:

Geochemical sampling and analysis of the water and a detailed geological mapping near and at the area of hot springs should have priority.

Where soil and thin sediments cover the area and correlation between near-vertical structures and the upflow of geothermal water is not obvious, soil temperature measurements might be a feasible choice. The method is economical and easy to carry out. Similarly, ground magnetic measurements might be a good alternative, especially where terrain is difficult and more expensive measurements are difficult to carry out, due to narrow valleys and high altitude.

On a larger scale, drilling of shallow (50-100 m deep) gradient wells might also be considered a good alternative. Despite its costs, it is usually a very cost-effective method. Especially, if temperatures prove higher than the ca 120°C geothermometer temperatures indicated in Table 2 for the region. Other methods might also be useful in this case, such as resistivity sounding, and as a follow-up a resource assessment for the respective fields.

Just as important is to select as early as possible a feasible target area, with markets nearby for the geothermal energy. For future development, the success and strength of geothermal energy needs to be established among the local people and that can best be done by pilot plants or projects where the benefits can clearly be seen. These do not need to be big. Heating of school houses or swimming pools with geothermal water could be enough. Also, possible use of geothermal water at 30-60°C should not be ruled out. Greenhouse farming, especially with regard to reducing nocturnal chill, and fish farming can be a viable alternative where some markets for products are nearby.

3.2.3 Indus basin margin zone

The area belongs to the sedimentary basin and along the whole margin zone, thermal springs present a positive indication of geothermal energy. Besides geochemistry, deep reaching methods are to be preferred, such as resistivity sounding and gravity. However, high salinity of the sedimentary rocks may, in some places, pose a difficulty for the usefulness of the resistivity method. Gradient wells could be used with advantage to map local near-vertical structures.

Due to the subtropical climate in the southern part of the area, such as near Kharachi and Dadu district, and with a resource of relatively low temperatures, a study of utilization prospects needs to be done before any expensive exploration programmes. The first alternatives to come to mind are greenhouses (reducing effect from cold nights) and fish farming where stable growing and breeding temperatures could be kept with geothermal water.

3.2.4 Chaghi area

Chaghi area is believed to be a high-temperature field due to travertine and the presence of H_2S in surface waters. So in order to get results, detailed geological mapping of surface structures is needed and profiles should be prepared for interpretation with geophysical data.

Resistivity sounding and magnetic methods are suggested for the determination of geothermal subsurface hydrological anomalies and to provide a basis for the assessment of the reservoir. Similarly, deep gradient wells (200-300 m) might be recommended to test the potiential of the field.

Chaghi is a remote area and far from major cities or power plants. It is very difficult to install large power transmission lines over such a long distance for so little market. The Chaghi area might be suitable for an instillation of a binary power plant to satisfy local needs.

4. SUMMARY

The advantage of geothermal power in a country like Pakistan, where coal and oil resources are limited, is obvious. The geothermal resources can provide a clean source of energy, especially in selected areas of the northern collision zone of Pakistan and in the Chaghi area in Baluchistan. Direct utilization for bathing and heating and possibly electrical production may satisfy local needs in villages and small towns. The review of the methodology and resources presented here can be summarized as follows:

1. Review is given of useful surface exploration methods for geothermal resources, including geological mapping, geochemistry and different geophysical methods.

2. Systematic approach of geothermal exploration is recommended including a detailed inventory of all surface manifestations in the country, and geochemical sampling and analysis of the fluids.

3. Target areas for further exploration need to be selected in order to find feasible production areas for further exploration and exploitation.

4. Geochemical analysis of a few hot springs based on data from the northern areas indicates that temperatures well above 100°C can be found at some localities in the Himalayan collision zone. Some of these areas may prove important local sources of energy, both for bathing and heating of nearby villages or towns.

5. The geothermal activity related to the Indus sedimentary basin may be used for heating greenhouses (reducing effect from cold nights) and possibly also to provide stable conditions for fish farming.

6. The Chaghi geothermal area in Baluchistan is related to Quaternary volcanism. If the existence of a high-temperature geothermal system is proven, the resource may be important to provide the inhabitants of this remote area with locally produced electricity.

7. Finally, the importance of selecting a suitable target area is stressed, where utilization can be started and the benefits of geothermal energy can be proven, both for decision makers and local population.

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