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GEOCHEMICAL STUDIES OF SOME THERMAL SPRINGS IN NEPAL

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ABSTRACT

Most of the major geothermal springs of Nepal are located close to and north of the Main Central Thrust and south of the Main Boundary Fault. The geothermometer temperatures of eight springs at Darchula, Jumla, Jomsom, Tatopani-Mustang, Sadhu Khola, Rior, Mayangdi, Chilime and Bajhang-Tapoban are in the range of 85 to 115°C and these thermal springs are not found to be mixed with cold ground water. Most of the spring waters seem to be peripheral but those at Tatopani-Mustang and Sadhu Khola are mature with respect to major anion concentrations. A combination of the results of previous isotope studies and the present ones suggests that a large geothermal reservoir exists in the Sadhu Khola - Jomsom area in central Nepal. Many thermal springs in Nepal are yet unexplored for their potential use, except for bathing and laundering purposes. Detailed scientific studies should be conducted to gain more information about these and estimate the prospective reservoirs. The location of many of the springs in sparsely populated areas, mostly in the remote, steep Himalayan terrain, and the absence of adequate knowledge of the utilization of low-temperature thermal waters have been the major impediments to the promotion of this resource. In view of the comparatively good accessibility, relatively high population density, and the possibility of a large reservoir, the central region of Nepal should be given priority. Thermal waters can be used in Nepal for a wide range of economically productive purposes and for reducing environmental pollution.

1. INTRODUCTION

1.1 General description

Nepal is located between the two giant countries of Asia, China in the north and surrounded by India on the other three sides. The country (147,181 km^2) is in difficult terrain which can be broadly divided into the high mountains, or the Himalayas (44%), a central region of mountains and terraced hills (41%) and the remaining 15% the Terai, an extension of the Indo-Gangetic Plain.

The Himalayas are the world's youngest and highest mountain range. They were pushed up when the Indian subcontinent collided head-on with the Eurasian landmass about 75 million years ago. The mountains are still rising as India bulldozes northwards into Tibet squeezing rocks upwards. The average rate of convergence over the last 20 m.y. has been between 10 and 25 mm per year (Molnar, 1987). The movement of the tectonic plates makes the Himalayas among the world's most seismically-active regions. The

Himalayas contain the following structural units (from south to north): Sub-Himalayas, Lower Himalayas, Higher Himalayas, Tibetan Himalayas and Trans-Himalayas.

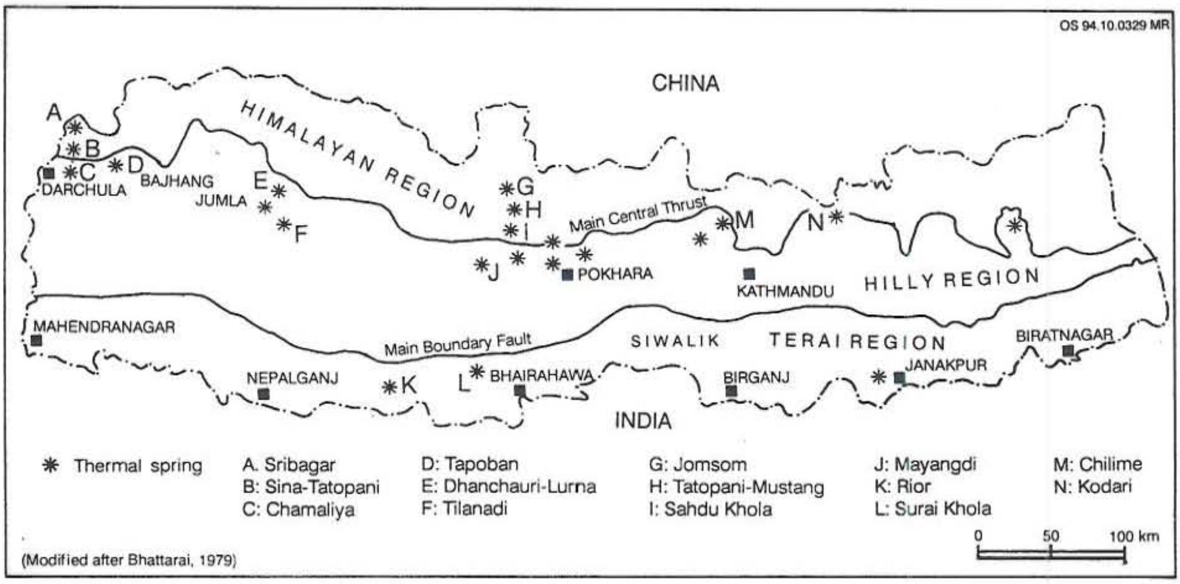

FIGURE 1: Location of thermal springs in Nepal

Twenty-three major geothermal springs have been identified in different parts of Nepal (Figure 1). Most of these are confined to three distinct tectonic and structural features that characterize the Himalayas in general. The first group is located beyond Higher Himalayas in a geological formation similar to the Tibetan region of China and to the north of the Main Central Thrust (MCT). The Main Central Thrust is situated between the units of the Lower and the Higher Himalayas. It dips northward and separates into two very different packages of rock. Below it are gneiss, schist, phyllite, quartzite, and marble of the Lesser Himalayan Formations. Above it a sequence of high-grade metamorphic rocks, the Higher Himalayan Crystalline Series, crops out at the front of the Higher Himalayas. The second group of thermal springs lies close to the Main Central Thrust. Along much of the southern edge of the Lower Himalayas, klippen of high-grade rock overlie, in sharp fault contact with the lower-grade rock of the Lesser Himalayas and marks the southern known limit of the Main Central Thrust, and is termed the Main Boundary Fault (England et al., 1992).

1.2 Descriptions of geothermal localities

The geological descriptions of some of the major thermal springs follow.

Darchula thermal springs. The thermal springs in the Darchula district are found in three places:

1) 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 (NW-SE direction) on which many springs are aligned.

2) In Sribagar, the hot springs rise from the recent river sediments and are located near the tectonic contact between the autochthonous metasedimentary zone of Baitadi-Bajhang and the crystalline sheet. The tectonic contact is marked by the highly crushed chlorite-sericite-quartz phyllites on the ridge, east of Sribagar.

3i) The Chamaliya spring issues from the recent terrace deposit and is confined to the metasedimentary autochthonous zone composed of various slates and carbonate rocks. A major NE-SW directed fault occurs along the Chamaliya river which passes through the axial part of an anticline. It displaces the contact of the underlying black slate and the overlying cherty dolomite (Bashyal, 1984).

Bajhang thermal springs. The thermal springs of the Bajhang district are located near the major thrust between the crystalline allochthonous and metasedimentary autochthonous zones. The purple shales 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.

Chilime thermal spring. This spring is not situated on the bank of a river and has only one discharge point. The surrounding bedrock consists of quartz, biotite sandstone, graphitic argillaceous schist and siliceous limestone.

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

Jumla thermal spring. Figure 2 shows a geological map of the Jumla area. The thermal springs in the Jumla district occur mainly in two places Tila Nadi and Dhanchauri (Bhattarai and Bashyal, 1983).

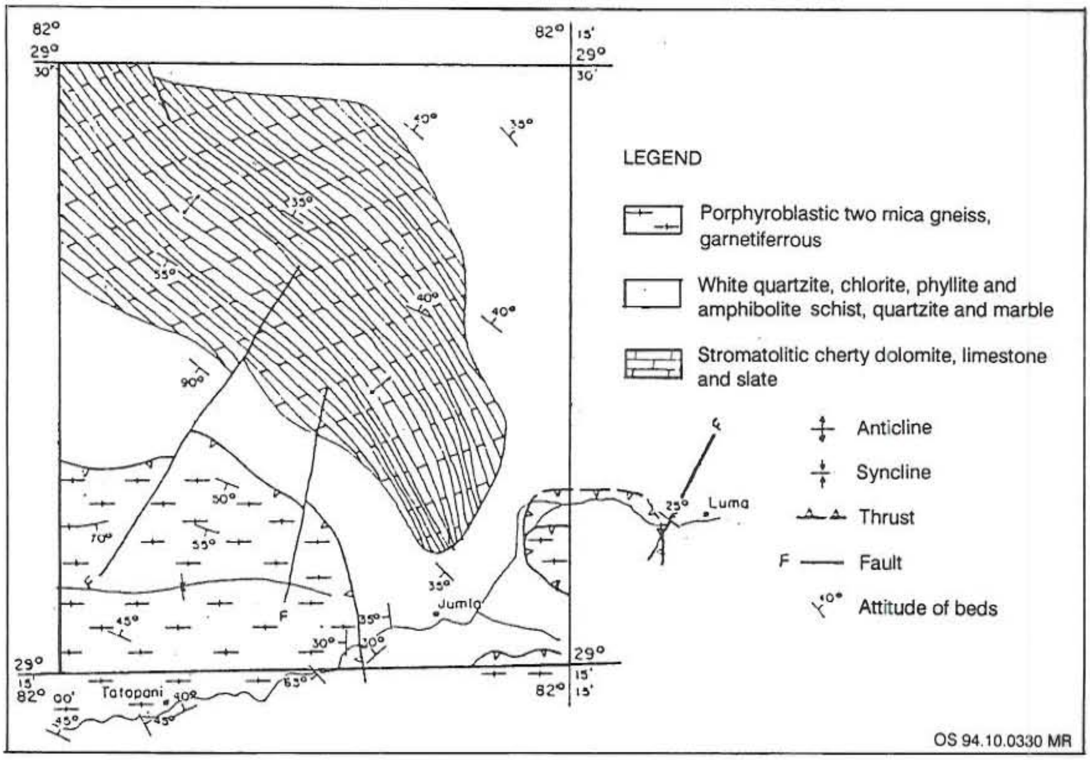

FIGURE 2: Geological map of Jumla (Bhattarai and Bashyal, 1983)

1) Tila Nadi. Figure 3 shows a vertical geological section along Tila Nadi of Jumla. There are seven closely located hot springs on the right bank of Tila Nadi, below the Tatopani village. 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. The joints strike N-S and they dip west or east steeply.
2) Dhanchauri. In this area, the spring issues from the light-grey platy dolomite and is characterized by a thick tuffaceous deposit consisting of carbonate and silica. Three major hot springs are located here.

Rior thermal spring. This spring is located in the Siwalik formation in the south, and the immediate vicinity is covered by soil.

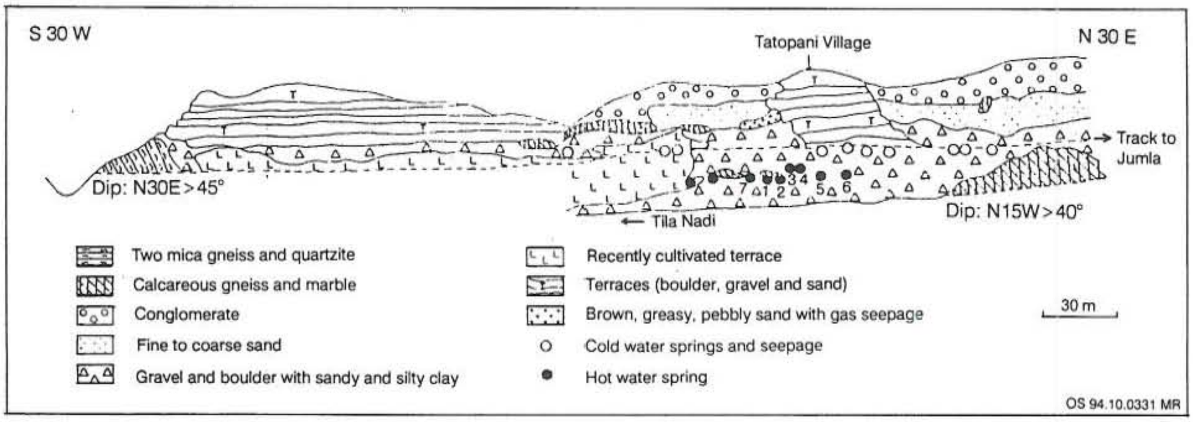

FIGURE 3: A vertical geological section along Tila Nadi (Bhattarai and Bashyal, 1983)

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

Kodari thermal springs. Hot water issues at several points in the Kodari area. The surrounding bedrock is of quartz biotite sandstone overlain by slightly graphitic argillaceous schist and underlain by siliceous limestone.

Jomsom thermal springs. The springs are grouped at the foot of a berm (a horizontal shelf that modifies or breaks the uniformity of an earth slope) about 100 m high on the bank of the Kaki Gandaki River, consisting of fine crystalline and pelitic Lias limestones. Figure 4 shows the geological map of the Thak Khola-Mustang area where the Jomsom springs are located. There are five springs in the locality.

2. GEOTHERMAL ENERGY IN NEPAL

2.1 General

Nepal is still in the infancy stage in the field of geothermal energy exploration. So far, surface temperature measurements and chemical analysis have been carried out on 14 thermal springs, albeit on a sporadic basis. The maximum surface temperature recorded is 73°C in Sribagar (Darchula district), followed by 71°C in Tatopani (Mustang district), and 69°C in Sadhu Khola (Rupandehi district). Temperatures above 40°C were recorded for four other springs. Sub-surface temperatures of eight springs calculated, employing the Na/K (Arnorsson et al., 1983a), quartz (Fournier and Potter, 1982) and chalcedony geothermometers (Fournier, 1977) were in the range 85-115°C.

Most of the spring waters are colourless and characterized by low flow rates. Some hydrogen sulphide odour can be noticed in the Jomsom, Bajhang, Rior and Darchula spring areas. The thermal springs of Mayangdi, Kodari, Rior and Surai Khola are alkaline in character. In all cases, the calcium and magnesium concentrations in the thermal water are smaller than in the local cold water.

2.2 The need for the development of geothermal energy in Nepal

Nepal's energy sector is dominated by few resources. The bulk of the country's energy requirements is met by traditional resources such as fuel wood, agricultural waste, and animal dung (Table 1). Commercial energy, mainly comprising petroleum products, coal, and electricity contribute about 5% of the total energy supply. The country's problems are twofold, an excessive reliance on non-renewable energy sources and the consumption of one form of renewable energy at an unsustainable rate while keeping others virtually unused. Despite intensive efforts made in the past to reforest and conserve this resource, the forest area is declining every year, inviting ecological stress, land degradation and a decline in agricultural production and productivity.

Biomass is the major fuel used for cooking and heating in rural households. Combustion of biomass such as fuel wood, dried animal dung and dried agricultural residues causes significant indoor air pollution with the emission of relatively high levels of respirable hydrocarbons, particulates of several types, as well as carbon monoxide. Poor ventilation especially in kitchens in rural areas has magnified the problem because the houses are tightly insulated against the cold.

Hydro-electric resources represent a large proportion of the total theoretical energy potential of Nepal. The country is estimated to possess 1,857.7 million GJ of raw energy out of which hydroelectricity alone is estimated to contribute 78.6% (Sharma et al., 1991).

Biogas holds out the prospect of becoming a significant and economical substitute for fuel wood, primarily in the Terai region where the relatively warm climate favours digester operation and pre-conditions needed for the promotion of this technology exist.

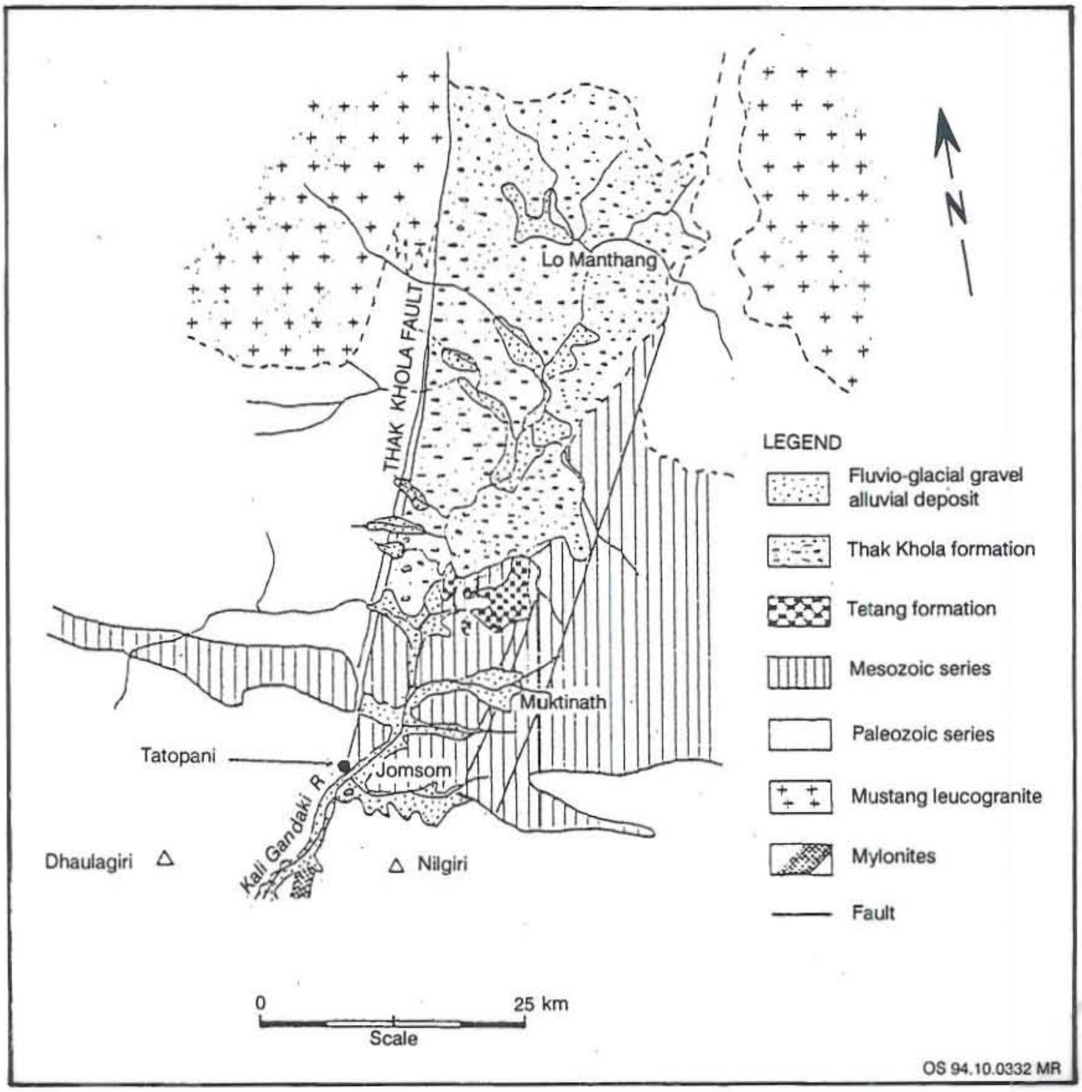

FIGURE 4: Geological map of the Thak Khola-Mustang area (Bhattarai and Bashyal, 1983)

TABLE 1: Energy consumption in Nepal in thousand tons of coal equivalent/year
(from the Water and Energy Commission, His Majesty's Government of Nepal)

Energy sources	1980/81	1985/86	1990/91	1992/93*
Traditional				
Fuel wood	4476.4	6248.0	6834.3	6890.0
Agri. waste	79.2	893.0	1067.1	1060.0
Animal dung	30.1	696.0	761.3	831.0
Commercial				
Petroleum	174.4	268.0	355.2	496.0
Coal	32.3	46.0	58.0	91.0
Hydroelectricity	20.2	39.0	72.0	96.0
Total	4812.5	8190.0	9148.3	9464.0

* Estimate

Direct solar energy accounts for a negligible proportion of the energy consumed, excluding sun-drying for which no estimates are available, and less than 1% of the long-term, theoretical indigenous energy potential on a raw GJ basis. At present, conversion of sunlight is a simple but high technology option. With further reduction in the cost of solar photo-voltaic devices and the development of storage systems, solar energy holds some promise for future application as a village-level power source.

Wind energy is not used to any practical extent in Nepal even though some institutions are working on the development of windmills and water turbines to be used in remote areas. Wind remains a site-specific consideration whether for mechanical or electrical applications. There are no known commercial resources of fossil fuels in Nepal. Seismic and other types of exploration are under way.

It is clear that the long-term path for the sustainable development of Nepal lies in exploiting the abundant hydropower for energy. The fundamental questions on the utilization of the energy resources for a new development are whether investment in this sector will, 1) lead to a wider participation of the population in sharing the benefits of the investment, 2) act as a stimulus to agricultural and agro-processing industries, 3) serve as an overall impetus to rural industrialization, and 4) minimize adverse environmental consequences. In the case of Nepal, the mega-project approach is time-consuming and expensive work that demands a heavy reliance on foreign loan assistance and aid. His Majesty's Government of Nepal has, in recent years, put much emphasis on the utilization of this resource on a mini/micro scale by attracting private entities. However, the effort has a long way to go in order to be realized.

In view of the above situation, the utilization of geothermal resources can be a very good option for many purposes. It complies with all the four sets of conditions outlined above. Geothermal energy is a renewable resource, and its operation costs and investment requirements are low compared to mini/micro hydro plants. Given attention, the available low temperature geothermal fields in Nepal can be extensively used for a wide range of economically productive purposes, for example, hatching of fish and fish farming, space heating, mushroom growing and greenhouse production, soil heating for double cropping etc. and balneological purposes in most of the colder areas in the north.

3. AVAILABLE DATA ON GEOTHERMAL SPRINGS IN NEPAL

So far, the sampling and chemical analysis of some thermal springs of Nepal have been carried out on a sporadic basis and data for flow rate, pH, major cations and anions, dissolved solids, silica, surface temperatures are available. Geothermometer temperatures, ionic balance and discharge enthalpy were calculated from the chemical data using the Program WATCH (Arnorsson et al., 1982; Bjarnason, 1994). Such information is given in Table 2 along with information on the locations. As can be seen from the table, the maximum surface temperature recorded was 73°C in Sribagar, followed by 71°C in Tatopani-Mustang, and 69°C in Sadhu Khola. Temperatures above 40°C were recorded for four other springs. Table 3 lists the results of the chemical analysis for some of the thermal springs.

TABLE 2: Information about geothermal localities and temperature

Locality	Symbol in Fig. 1	Location		Flow rate (l/s)	Surface temp. (°C)	Geothermometer temp. (°C)			Ionic balance (%)	Discharge enthalpy (kJ/kg)
		Latitude (E)	Longitude (N)			SiO_2	Chalcedony	Na/K		
Darchula:										
Sribagar	A	80.6°	29.9°	0.85	57-73	86.2				361
Sina-Tatopani	B	80.7°	29.9°	0.76	warm					
Chamaliya	C	80.6°	29.7°	0.25	warm	37.6				158
Bajhang-Tapoban	D	81.2°	29.6°	0.2	warm	55.1				126
Jumla:										
Dhanchauri-Luma	E	82.3°	29.3°	0.6	24	107		88.2		448
Tila Nadi	F	82.1°	29.2°		36-42	111			-34.26	464
Jomsom	G	83.7°	29.8°	0.2- 5	21	50.3			1.61	211
Tatopani-Mustang	H	83.7°	28.5°	1.8	71	115			-0.19	484
Sadhu Khola	I	84.2°	28.4°	1.39	69	110		115	4.52	460
Mayangdi	J	83.5°	28.4°	2	40	89.8			-21.03	376
Rior	K	82.7°	27.9°	1.5	33		54.2	52.3		227
Surai Khola	L	83.3°	27.8°		37		50.1	100	4.8	210
Chilime	M	85.3°	28.3°	8	55	92.1				386
Kodari	N	83.9°	27.9°	5	42					17

TABLE 3: Chemical analysis results for some thermal springs in Nepal (in mg/kg)

Location	Temp. (°C)	pH	Na	K	Mg	Ca	Cl	SO_4	HCO_3	CO_2	SiO_2	B	TDS
Jomsom[1]	21	8	60	5.6	54	113	95.9	249	302	218	14.3	2.4	889.3
Tatopani -Mustang[1]	71	7	365	90	30	102	555	217	387.5	280	67.6	13	1841
Jumla[2]													
Tila Nadi	36-42	>7	56	0	1.2	6	45	130	0	0	60	0	353
Dhanchauri-Luma	20-24	7	49	1.3	0.2	6.1	82	104	217	157	56	0	803
Mayangdi[3]	40	8	460	49	17	2	351	68	430	310	43	0.3	1340
Rior[3]	33	9	310	4	3	4	14	70	7.93	5.72	37.5	6	788
Surai Khola[3]	37	9	123	3.9	28	18	3.19	70	370	267	38.5	trace	510
Darchula[4]													
Sribagar	57-73	7	100	11	8.5	n.d.	34.2	18.5	n.d.	0	35	0	516
Chamliya	warm	7	n.d.	n.d.	n.d.	n.d.	39.6	10.7	n.d.	0	10	n.d.	1320
Tapoban-Bajhang[4]	warm	<7	n.d.	22	10	n.d.	50.1	25.9	n.d.	0	16	0	444
Sadhu Khola-Mustang[1]	69	7	300	12	0.6	10	286	197	78	56.3	60	0	954
Chilime-Rasuwa[1]	55	7	23	17	14	30	0	0	120	86.6	40	0	148
Kodari[3]	42	7	150	25	21	82	31.5	65	621	448	3.85	3	822

1. Bhattarai, 1986; 2. Bhattarai and Bashyal, 1983; 3. Bhattarai, 1980; 4. Bashysal, 1984.

The isotopic composition of waters from central Nepal is presented in Table 4 and the map of the area in Figure 5.

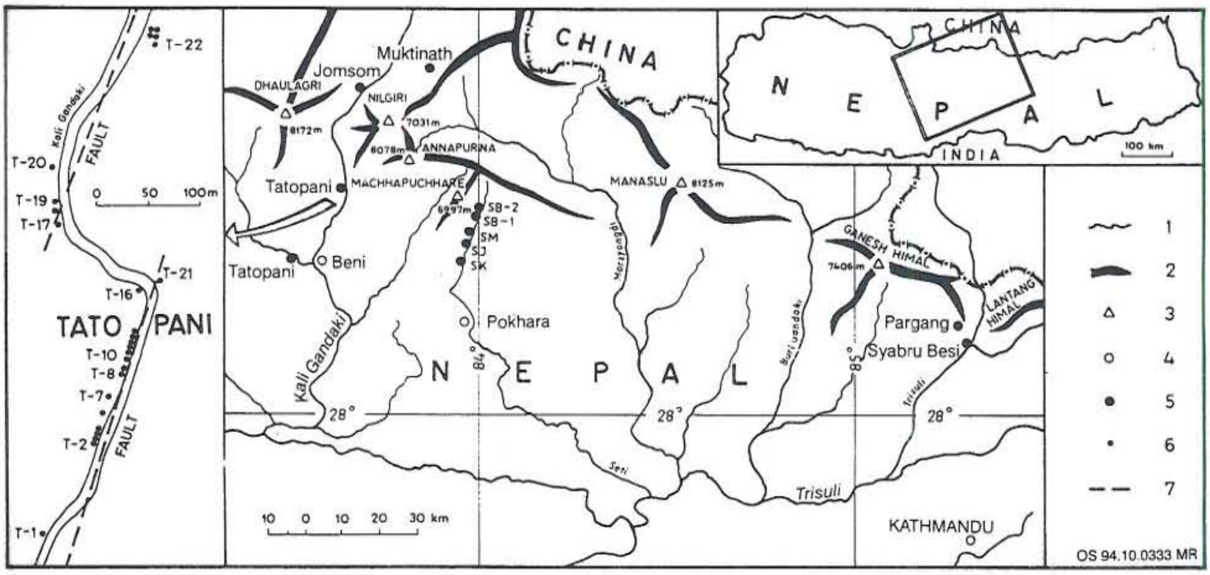

FIGURE 5: Location of hot springs investigated in the central parts of the Nepal Himalayas; 1) river, 2) massif, 3) peak, 4) locality or village, 5) springs region, 6) hot spring, and 7) wrench fault (Grabczak and Kotarba, 1985)

4. METHODOLOGY

In the present study, the subsurface temperatures are calculated from the chemical composition of the discharged fluid by using the programme WATCH, (Arnorsson et al., 1982; Bjarnason, 1994) employing the Na/K (Arnorsson et al., 1983a) and quartz (Fournier and Potter, 1982) geothermometers for the springs lying on the Main Central Thrust. The chalcedony geothermometer (Fournier, 1977) is used to derive temperatures in the areas lying on the Main Boundary Fault because this belt is in a recent formation and chalcedony rather than quartz is likely to be in equilibrium with ground water in such formations. The origin and type of water are studied with the aid of isotopic data and the Cl-SO_4-HCO_3 diagram.

4.1 Speciation programmes

The WATCH programme is dependent on the input of various chemical analysis data, for example, pH and the temperature at which it was measured, and the reference at which the composition is to be calculated. An initial estimate of the ionic strength of the water is obtained using only the concentrations of the major cations. This value is used to compute activity coefficients, at the temperature of the pH measurement, using the extended Debye-Huckel formula. The chemical equilibria and mass balance equations are solved simultaneously at this temperature to obtain a distribution of the species. From the new distribution of species, a proper ionic strength is computed. The ionic strength is used to recompute the activity coefficients and species concentrations at the temperature of the pH measurement. The calculation of pH, activity coefficients, ionic strength and the iteration of mass balance are all, in turn, done repeatedly by selecting various reference temperatures. Such reference temperatures can be chosen as the measured temperature of the spring or well, or as chalcedony, quartz, or Na-K geothermometer temperatures. The geothermometer temperatures are calculated from the concentrations of chemical species. This sort of operation gives a number of output values, for example, the component and species concentrations at the reference temperature, activity coefficients, ionic balance, geothermometers, redox potentials etc.

TABLE 4: Isotopic composition of waters from central Nepal (Grabczak and Kotarba, 1985)

Region - altitude (m a.s.l.)	**Spring no.**	**Temp. (°C)**	**Dischar. (l/s)**	**TDS (g/l)**	**$\delta^{18}O$ (‰)**	**δD (‰)**	**Tritium (T.U.)**
Tatopani-Ben-900	B-1	35.8	1	0.46	-8.6	-65	45± 2
	B-2	34.4	0.4	-	-8.6	-64	-8.60
	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	-	-10.0	-69	-
	T-7B	61	0.2	-	-10.0	-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-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
	J-1c	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	-10.90	-72	14±1.5
	SK-2	35.4	0.6	-	-11.0	-74	-
Jamile-1500	SJ-1	30.6	0.05	-	-11.3	-79	-
Machhapuhare base camp-800	SM-1a	64	2.2	1.02	-13.0	-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	-	-11.0	-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

Finally, the ion activity products, log Q, and solubility products, log K, are obtained and used to calculate the corresponding saturation index, log Q/K. A plot of this index value versus temperature gives an idea about the state of equilibrium of thermal water and the geothermal reservoir temperature.

4.2 Origin and type of water

The determination of the true isotopic composition of a sample is extremely difficult, whereas measurements of differences in composition are relatively easy. The usual way of measuring isotopic composition of samples in routine is therefore comparison of the samples with a reference standard sample R_{std} of known isotopic composition. The isotopic ratio is conveniently expressed as deviation per mil

$$d = (R_{sample} - R_{std})\, 10^3 / R_{std} \tag{1}$$

The standard adopted for $\delta^{18}O$ and δD in waters is SMOW (Standard Mean Ocean Water), whose isotopic composition represents a good average of the ocean water (Craig, 1961a). This standard was so chosen because the oceans represent initial and final points of any important hydrological circuit. In addition, the ocean has a fairly uniform isotopic composition. By definition SMOW has $\delta O^{18} = 0$ and $\delta D = 0$.

Local meteoric waters in different geothermal areas can have different isotopic compositions. In fact, the mean annual isotopic composition of precipitation is, by and large, related to the local mean annual temperature: the lower the temperature, the lower the content of heavy isotopes; in other words, $\delta^{18}O$ and δD are more negative in colder regions. An altitude effect, a latitude effect and a continental effect will in turn be observed. Due to preferential removal of the heavier isotopes from precipitating clouds moving towards higher latitudes, the δ-values decrease (become more negative) with increasing latitude. For the same reason, one would expect the δ-values to decrease towards higher altitudes and with distance from the coast (Arnason, 1976).

The relation between δD and $\delta^{18}O$ is a linear correlation

$$\delta D = 8\,\delta^{18}O + B \tag{2}$$

where the constant B is in most cases 10, which means that, independently of their absolute concentrations, in a δD-$\delta^{18}O$ plot, the isotopic compositions of waters recharging the geothermal systems will fall on a line called the meteoric water line (Craig, 1961b).

The deuterium concentration is constant for each system and equal to that of the local meteoric water of the area, but the oxygen-18 concentration may show a characteristic enrichment which is known as an "oxygen shift", meaning the shift of the isotopic composition towards an $^{18}O/^{16}O$ ratio higher than that of the local meteoric water (Truesdell and Hulston, 1980). This shift is a consequence of oxygen isotope exchange between the water and rocks constituting the geothermal reservoir and is most pronounced at high temperatures and low water-rock ratios, i.e. when a relatively large amount of water is in contact with the rock and this may mean poor permeability. The meteoric waters infiltrating at depth to form a geothermal reservoir are in isotopic disequilibrium with the rocks and exchange their oxygen with the surrounding rocks, much richer in heavy isotopes than the waters themselves, in order to approach the equilibrium corresponding to the temperature of the geothermal waters. The oxygen isotopic composition of the water is shifted toward that of the rocks because of the high temperatures at which the exchange takes place. Such modification in oxygen isotopes is most characteristic for deep high temperature geothermal waters usually with negligible tritium concentration.

Tritium, T, the radioactive isotope of hydrogen, with mass 3, is a commonly adopted isotope in geothermal investigations. It is formed in the atmosphere by the interaction of cosmic radiation-produced neutrons with nitrogen

$$^{14}N + n \Rightarrow {}^{3}T + {}^{12}C \qquad (3)$$

The tritium content in natural waters is expressed in T.U. (tritium unit); 1 T.U. corresponds to a concentration of 1 tritium atom per 10^{18} hydrogen atoms. The basis for tritium analysis is the tritium released during the H-bomb tests in the fifties increasing the tritium contents of surface and ocean waters.

4.3 Cl-SO_4-HCO_3 diagram

Most geochemical techniques may with confidence be applied only to specified types of fluids with limited ranges of compositions. For instance, most ionic solute geothermometers work only if used close to neutral waters containing chloride as the major anion. Any such interpretation of geothermal water samples, therefore, is best carried out on the basis of an initial classification, e.g. in terms of their major anions Cl, SO_4 and HCO_3. The position of data in such a triangular plot is obtained by first forming the sum S of the concentrations c_i (in mg/kg) of all the constituents involved, and then working out the percentage of each component in that sum.

In contrast to logarithmic plots, mixing lines in triangular diagrams always remain straight. The diagram allows the immediate "eyeball" statistical evaluation of groupings and trends. However, such three-component plots only tell part of the story and some apparent correlations may be purely accidental. Highly acid chloride-sulphate waters are likely to result from the absorption of magmatic gases in groundwater followed by close to isochemical dissolution of the rock contacted. They are assumed to derive from the deep and primary neutralization zone, the characteristics of volcanic origin. Spring waters associated with copious discharges of CO_2 reactivities at the periphery of hydrothermal systems are characteristic of low temperatures fields. Discharges from deep geothermal wells and associated neutral chloride springs are likely to represent well-equilibrated fluids from the major upflow zones (Giggenbach, 1991).

4.3 Geothermometers

One of the major applications of geochemistry in the exploration of geothermal resources is the prediction of subsurface temperatures using chemical geothermometers. Various methods have been developed by using, for example, Na-K ratio, K-Mg ratio, Na-Li ratio, Na-K-Ca-Mg, CH_4/C_2H_6 ratio, concentrations of SiO_2, CO_2, H_2S, H_2, CH_4 etc.

The chemical geothermometers can be broadly classified into qualitative and quantitative ones. The qualitative techniques use the distribution and relative concentrations of various "indicator" elements in the water. For example, B and NH_4 are high in geothermal waters rising from sediments or sedimentary rocks, such as in Italy. The high content of HCO_3, Hg, and H_2S (which oxidizes to sulphate and lowers the pH of water) in near-surface waters may be due to high temperature at depth (Tonani, 1970). High Cl/F and Cl/SO_4 ratios in geothermal fluids are indicative of high temperature systems and variations in CO_2/NH_3, CO_2/H_2 and CO_2/H_2S may indicate zones close to deep hot water (Mahon, 1970). Sigvaldason and Cuellar (1970) noted that the presence of H_2 gas in a thermal system is a good indication of high temperature. Fournier and Truesdell (1970) used the Cl/(HCO_3+CO_3) ratio to distinguish waters from different aquifers, the high ratios coming from hotter aquifers and anomalously high concentrations of nonvolatile trace elements may also be due to high subsurface temperatures. Brondi et al., (1973) suggested that the presence of high concentrations of Li is good evidence of high temperatures at relatively shallow depths. Friedman and Denton (1976) argued that variation in helium content may be used as an indicator of high subsurface temperature.

The quantitative techniques are based on the chemical analysis data for thermal waters from springs or wells and they mainly use solubility and exchange reactions, both temperature-dependent. Solubilities of minerals generally vary as functions of temperature and pressure. Solute geothermometry and mixing models can be used as tools to evaluate temperatures in the geothermal reservoir at depth below the cooling zone, and also for the areas where deep hot water is mixed with shallow cold water, using data on the chemical composition of waters from hot springs and shallow drill holes. However, if applied to unmixed waters, the mixing models tend to give too high temperatures.

The silica geothermometer originally suggested by Bodvarsson (1960) and developed by Fournier and Rowe (1966) is based on the solubility of quartz and is widely used to predict the subsurface temperatures in hot water systems. However, at lower temperatures other silica species such as chalcedony, cristobalite or amorphous silica may control the amount of dissolved silica in the water (Fournier and Truesdell, 1970; Arnorsson, 1975).

The Na-K geothermometer originally suggested by White (1965) and then developed by various workers is more reliable for high temperature areas. The Na-Li geothermometer (Kharaka et al., 1982) is very sensitive to slight changes in the Li content that result from exchange reactions involving other ions than Na. Hence it is recommended to use this geothermometer only in combination with other geothermometers.

Temperatures in geothermal reservoirs are generally not homogeneous, but variable, both horizontally and vertically. Chemical geothermometry, when applied to specific hot springs can, at best, be expected to reveal the temperatures of the aquifer feeding the respective springs. Temperatures encountered in deep drill holes may thus be higher than those indicated by chemical geothermometry of springs, particularly if the springs are fed by shallow aquifers (Arnorsson, 1991).

Various assumptions are made in predicting such subsurface temperatures. Hence, the accuracy of the results depends, to a large extent, on making site-specific assumptions. The basic assumptions are that, 1) a temperature-dependent equilibrium is attained in the geothermal reservoir between specific solute(s)/gas(es) and mineral(s); 2) no mixing takes place between different waters during ascent to the surface, or an evaluation of the results of such a mixing is possible.

4.3.1 Silica geothermometry

The rates of dissolution and precipitation of quartz and amorphous silica change as logarithmic functions of absolute temperature, with moderately fast rates at very high temperatures and extremely slow rates at low temperatures (Rimstidt and Barnes, 1980). Solutions become saturated with respect to a given silica mineral in a geothermal reservoir after prolonged water-rock interaction at a constant temperature, thereafter little dissolved silica polymerizes and precipitates during relatively fast upward movement to the earth's surface. In general, significant amounts of silica precipitate from a given quantity of an ascending solution only when the solubility of amorphous silica is exceeded. At temperatures less than about 300°C, and at depths generally attained by commercial drilling for geothermal resources, variations in pressure at hydrostatic conditions have little effect on the solubilities of quartz and amorphous silica (Fournier and Potter, 1982). The dissolved silica concentrations in hydrothermal solutions with near neutral pH can generally be used as one of the more reliable chemical geothermometers when applied to waters collected from wells where steam fraction is known.

In general, the quartz geothermometer is applied in high-temperature reservoirs, and the chalcedony geothermometer in low-temperature reservoirs. Chalcedony is a very fine-grained variety of quartz, composed of aggregates of very tiny crystals. The individual quartz grains are so small that they have relatively large surface energies compared to "normal" quartz, and this results in an increase in solubility.

With time quartz becomes predominant because the aggregates become pressed and form larger crystals and eventually there is very little chalcedony left. In countries where rocks may be considerably older, quartz equilibrium seems to be obtained at lower temperatures, down to 90-100°C and in some cases even over the whole temperature range.

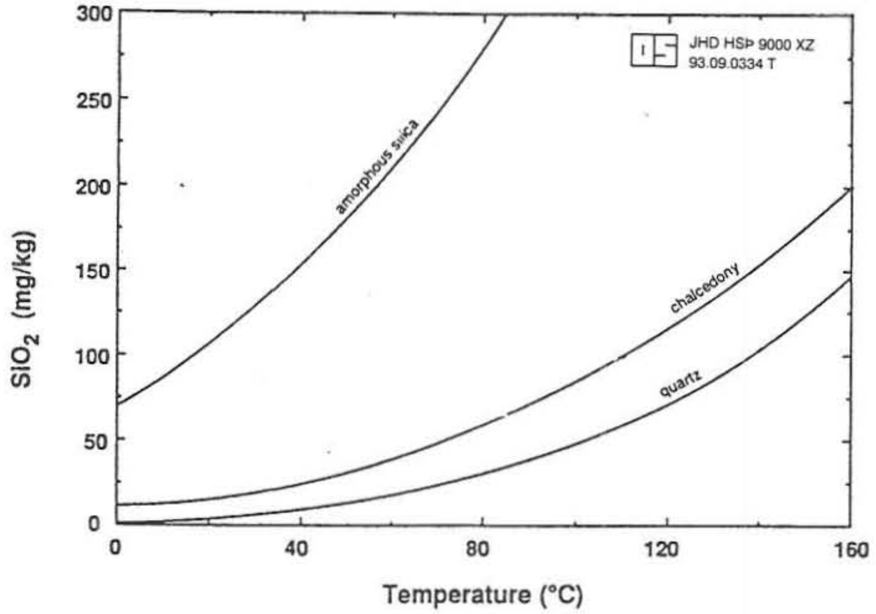

FIGURE 6: Solubility curves of silica minerals with temperature

Pressure and increased salinity have little effect on the solubilities of quartz and amorphous silica below about 300°C. These results are the basis for allowing the dissolved silica concentration in a hydrothermal solution to be used as a chemical geothermometer. The basic assumption made is that the solubilities of different silica minerals are different (Figure 6).

Below 340°C the solubility decreases rapidly with temperature, so that silica may polymerize and precipitate from the solution as a result of conductive and/or adiabatic cooling before it reaches the surface, causing low estimated reservoir temperatures. However, it is very difficult for silica to precipitate in low temperature reservoirs because the solubility of amorphous silica (i.e. silica species that deposit from geothermal waters), is much greater than those of quartz and chalcedony controlling silica concentrations in high- and low-temperature reservoirs, respectively.

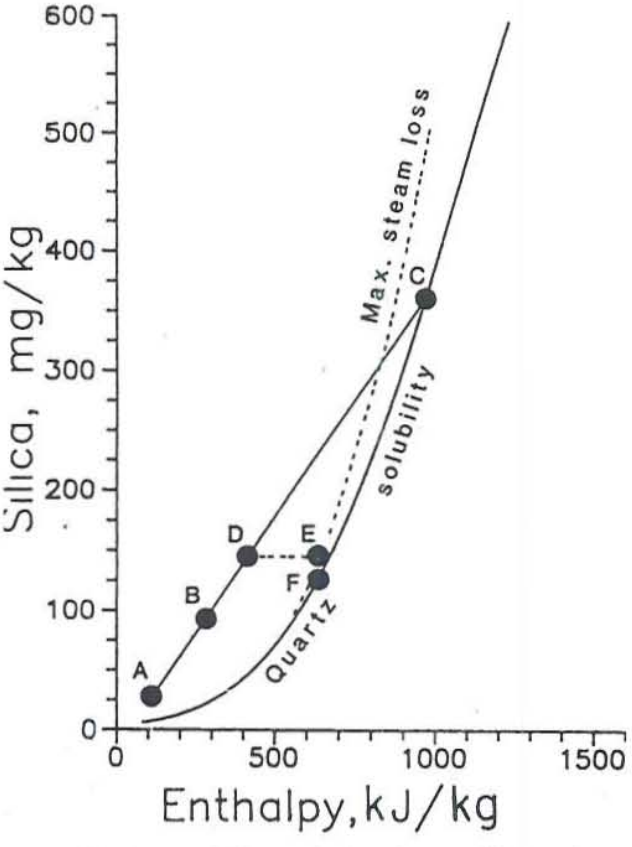

FIGURE 7: Silica-enthalpy diagram illustrating use in calculating silica mixing model temperatures (Fournier, 1977)

If we consider the silica-enthalpy diagram (Figure 7) and assume that any steam formed adiabatically (as the hot water component moved up), did not separate from the residual liquid water before mixing with the cold-water component. Then, the straight line drawn from a point representing the non-thermal component of the mixed water (point A) through the mixed spring water (point B) to the intersection with the quartz solubility curve gives the initial silica concentration and enthalpy of the hot-water component (point C). If steam was lost at atmospheric pressure prior to mixing (point D), a horizontal line drawn from point D to the intersection with the maximum steam loss curve gives the initial enthalpy of the hot water component (point E). The initial dissolved silica prior to boiling and steam separation is shown by point F which lies on the quartz solubility curve directly below point E (Fournier, 1977).

4.3.2 Na-K-Ca geothermometer

The Na-K-Ca geothermometer of Fournier and Truesdell (1973) was developed specially to deal with calcium-rich waters that give anomalously high calculated temperatures by the Na/K method. Changes in concentration resulting from boiling and from mixing with cold, dilute water will affect the Na-K-Ca geothermometer. The main consequence of boiling is loss of CO_2 which can cause $CaCO_3$ to precipitate. The loss of aqueous Ca^{2+} will generally result in Na-K-Ca calculated temperatures that are too high.

The effect of dilution on the Na-K-Ca geothermometer is generally negligible if the high-temperature geothermal water is much more saline than the diluting water. However, if a particular water is thought to be a mixture of hot and cold water with less than 20-30% hot water component, the effects of mixing on the Na-K-Ca geothermometer should be considered (Fournier, 1981).

4.3.3 Na-K-Mg geothermometer

Giggenbach (1988) suggested that a triangular diagram with Na/1000, K/100, and $\sqrt{Mg}$ at the apices can be used to classify waters as fully equilibrated with rock at given temperatures, partially equilibrated, and immature (dissolution of rock with little or no chemical equilibrium) as shown in Figure 8. The temperatures and composition at which "full equilibrium" is shown may change significantly, depending on which of the many Na/K geothermometers one assumes to be correct and the mineralogy (including structural states) of the phases that are in contact with the reservoir fluid. The position of the full equilibrium line also changes

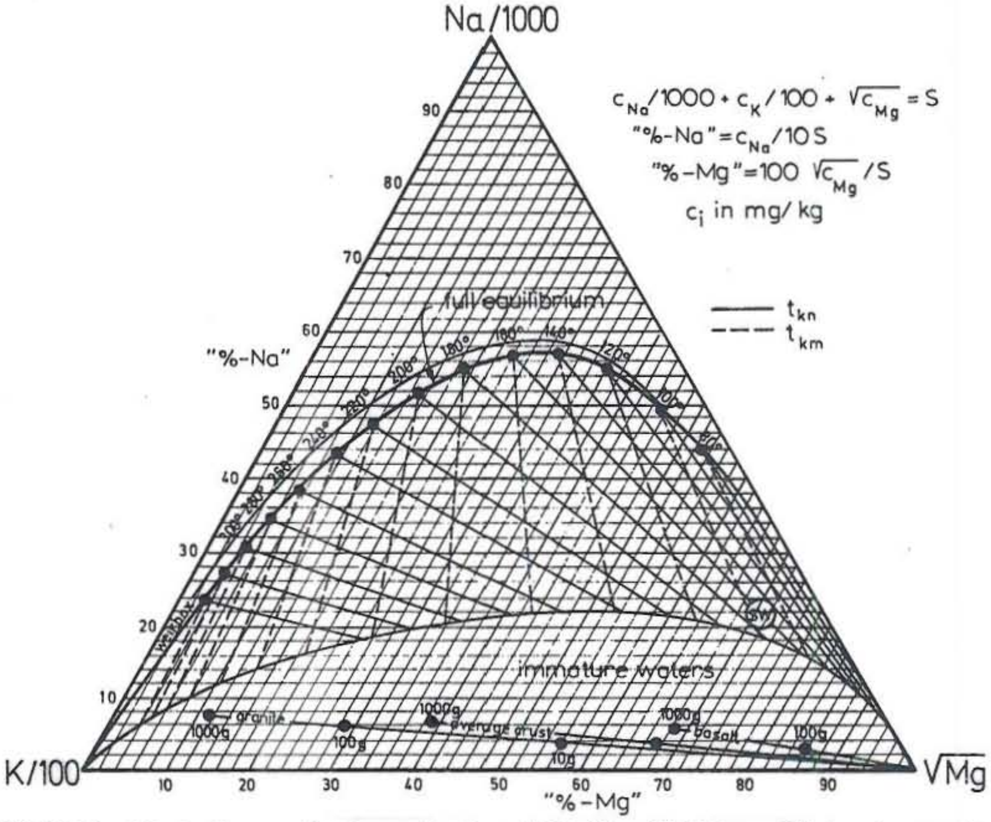

FIGURE 8: Blank diagram for the evaluation of Na-K and K-Mg equilibrium temperatures (Giggenbach, 1988)

as the assumed $K/\sqrt{Mg}$ geothermometer (Giggenbach, 1988) equation changes and is most uncertain at low temperatures (Fournier, 1991).

Magnesium concentrations in geothermal fluids tend to decrease as temperature increases. As geothermal fluid flows from a high-temperature to a low-temperature environment, it appears to pick up, relatively easily and quickly, significant amounts of Mg from the surrounding rock. This leads to a major ambiguity in the application of the Fournier and Potter (1979) Mg correction; that is, a truly low-temperature water may require an Mg correction to give a correct picture, but an Mg correction applied to a high-temperature water which has picked up Mg during up-flow will yield too low a reservoir temperature. One way to deal with these ambiguities is to sample and analyze many different springs and wells (if available). Then use a combination of silica and various cation geothermometers to evaluate possible mixing of different waters and possible retrograde reactions that may occur during up-flow, but this is a complex operation which may not be necessary because the diagram suggested does not suffer the same ambiguity.

4.3.4 The log(*Q/K*) diagram

Saturation index, *SI* is the degree of saturation of minerals in aqueous solutions. It can be determined by using the results of aqueous speciation calculations at different temperatures

$$SI = \log Q/K = \log Q - \log K \tag{4}$$

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

The *SI* value for each mineral gives an estimate of the equilibrium state. For example, values of *SI* more than, equal to and less than zero represent supersaturation, equilibrium and undersaturation respectively. The values for Q and K were calculated using the WATCH programme on the basis of the calculated chemical speciation in natural waters. For a mineral in equilibrium with the aqueous solution, the temperature corresponding to the intersection point of the mineral equilibrium curve and the $SI = 0$ line gives the theoretical equilibrium temperature. This characteristic of convergence of log(Q/K) curves for the mineral assemblage to zero at the temperature of equilibrium can be used to confirm the most probable temperature at which the mineral used as a chemical geothermometer reaches or approaches the equilibrium line, SI=0 (Reed and Spycher, 1984).

5. APPLICATION OF GEOCHEMICAL METHODS TO DATA FROM HOT SPRINGS

The present study is based on limited data obtained up to 1985 for some thermal springs in Nepal. Some of the data had to be ignored because of the large differences in ionic balance which are not suitable for the WATCH programme. The Na-K-Mg geothermometer temperature was determined using a blank ternary diagram provided by Giggenbach (1988). Likewise, a diagram for Cl-SO_4-HCO_3 provided by Giggenbach (1991) was employed to reveal the type of groundwater. The silica-enthalpy diagram was plotted to gain information on the initial enthalpy of the hot water component.

5.1 Mixing characteristics of thermal waters

The following characteristics of mixing are described by Arnorsson (1985):

1) A huge mass flow rate of spring;
2) Low pH of water relative to the water salinity (water containing chloride concentration less than 100 ppm should have pH between 6 and 7);

3) Variation in oxygen and hydrogen isotopes;
4) Calcite unsaturation;
5) A high concentration of silica relative to discharge temperature.

As seen from Table 5, for the spring waters in Darchula, Jumla, Jomsom, Rior, and Surai Khola whose chloride concentration is less than 100 ppm, the pH value is 7 or above. Table 5 also shows that these waters are supersaturated or nearly saturated with respect to calcite.

TABLE 5: Characteristic data for the unmixed springs of Nepal

Location	Cl (ppm)	pH	log Q/K (calcite)	SiO_2 -CO_2 (hot & cold)
Darchula				
Sribagar	18.51	7	n.d.	
Chamliya	10.69	7	n.d.	
Jumla				
Dhanchauri	82	7	a.s	
Tila Nadi	45	>7	n.d.	
Jomsom	95.92	7.7	s.s.	
Chilime	a.s.	6.14	a.s.	
Rior	14.04.	8.5.	a.s.	small
Surai Khola	3.19	8.9	s.s.	small
Tatopani	555.2	7.1	s.s.	
Mayangdi	350.9	8.2	s.s.	small
Sadhu Khola	286	7.09	a.s.	

s.s. = supersaturated; a.s. = almost saturated; n.d. = not determined

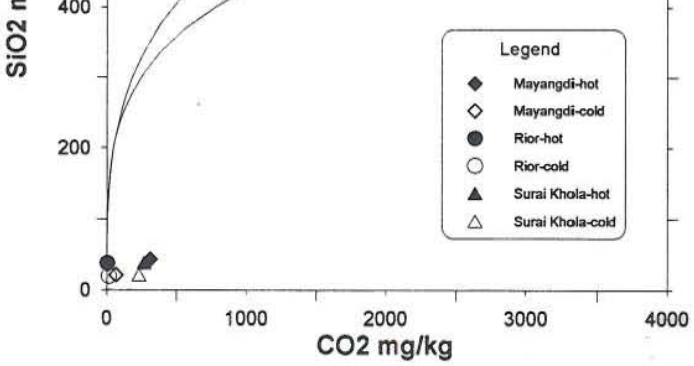

FIGURE 9: Silica vs. carbonate diagram for some thermal springs

Moreover, the differences in carbonate content between hot and cold water for the springs in Mayangdi, Rioand Surai Khola are quite low (Figure 9). For the springs in Tatopani-Mustang, Mayangdi and Sadhu Khola, whose chloride concentrations are more than 100 ppm, the waters are calcite saturated or almost saturated. Furthermore, the flow rates of these springs are not high (Table 2).

Isotopic studies in central Nepal showed that increase of water temperature from about 20 to 70°C is reversely correlated to tritium concentration from 55 to 7 T.U. This dependence could either be caused by a different transit time of the one-age-component water or mixing of two water components: one hot water presumably without tritium, and the second, a young cold water. The case for mixing appears less speculative from

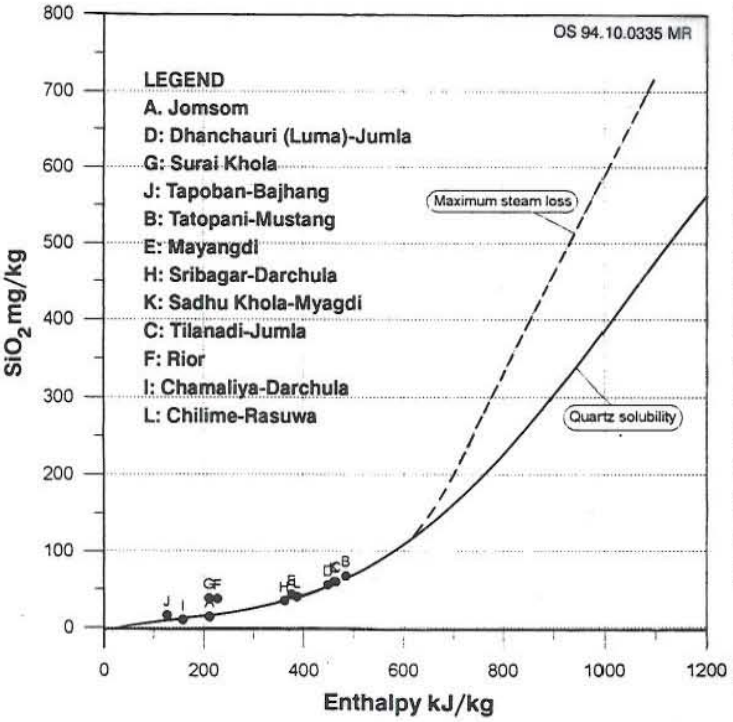

FIGURE 10: Silica-enthalpy diagram for various geothermal springs

the tritium data (Grabczak and Kotarba, 1985).

A silica-enthalpy graph was plotted for various thermal springs in Nepal (Figure10) mainly to see if there is some mixing. It shows that the springs in Rior and Surai Khola (located in the Main Boundary Fault of recent origin) are in equilibrium with chalcedony and all the rest are in full equilibrium with quartz. In other words, there is no difference between the initial and the present enthalpy of the hot water component. All these results suggest that there is no mixing taking place between the geothermal and cold groundwater.

5.2 Estimation of subsurface temperatures

A Na-K-Mg plot for spring waters from different places in Nepal is presented in Figure 11. As can be seen, the spring waters are all shifted, to varying degrees, towards the magnesium corner. This points to extensive interaction of the spring water with rock at comparatively low temperatures because the concentrations of Mg are relatively high in low temperature waters.

Attainment of equilibrium in the reservoir depends on a number of factors, such as the nature of the host rock, the temperature of the reservoir at a particular temperature, kinetics of the particular reaction and the concentration of the indicator elements in the water (Arnorsson et al., 1983b). In the present case many of the thermal waters are not found to be in equilibrium. The Sadhu Khola, Dhanchauri-Luma and Rior spring waters seem to be in or near equilibrium with several minerals at temperatures of 120°C, 100°C and about 50°C respectively. These temperatures agree fairly well with those determined using silica and Na/K geothermometers (Table 6).

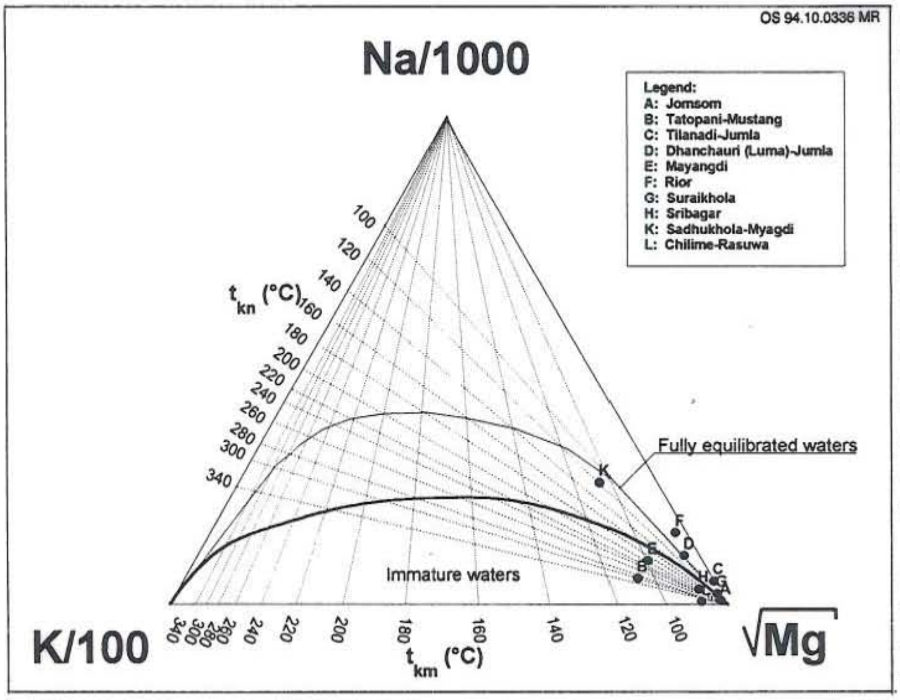

FIGURE 11: Diagram for the evaluation of Na-K and K-Mg equilibrium temperature of the thermal springs

TABLE 6: Geothermal temperatures of some springs estimated from various geothermometers

Location	Surface temp. (°C)	Geothermometer temperat. (°C)			Na-K-Mg temperat. (°C)	Log Q/K temperat. (°C)	CL-SO_4-HCO_3 indications
		SiO_2	Chalcdony	Na/K			
Darchula							
Sribagar	57-73	86.2			*	80-120	
Chamaliya	warm	37.6			*		
Jumla							
Dhanchauri-Luma	24	106.9		88.2	100	120	Peripheral
Tila Nadi	36-42	110.6			*	80-100	Steam-heated?
Jomsom	21	50.3			*	140-160	Peripheral
Tatopani-Mustang	71	115.4			*	140	Mature
Sadhu Khola	69	109.8		115.3	120	120-170	Mature
Rior	33		54.2	52.3	*	150	Steam-heated?
Surai Khola	37		50.1	100.4	*	90-130	Peripheral
Mayangdi	40	89.8			*	60-80	Peripheral
Chilime	55	92.1				140-160	Peripheral
Bajhang-Tapoban	warm	55.1			*		

The plots of log *Q/K* versus temperature curves for thermal waters for various locations in Nepal are presented in Figures 12 and 13. The spring waters of Jomsom, Sadhu Khola, Tatopani-Mustang, Chilime, Sribagar, Dhanchauri and Tila Nadi are in equilibrium and all the other spring waters undersaturated with the most common hydrothermal alteration minerals. The intersection of various mineral curves stretches over a range of temperatures, making it difficult to draw any definite conclusion about the most probable reservoir temperature. However, this temperature range is helpful to confirm the validity of the temperatures calculated from other geothermometers. Where such intersections appear at two places with a large difference in temperature, the values nearer to those obtained by silica and Na/K geothermometers are considered best. Lack of apparent equilibrium with respect to many minerals at a particular temperature is common in mixed waters and surface waters.

A Cl-SO_4-HCO_4 diagram for various thermal springs of Nepal is shown in Figure 14. It seems that the spring waters from Tatopani-Mustang and Sadhu Khola-Myagdi are chloride waters (relatively mature), and those of Jomsom, Dhanchauri-Luma, Mayangdi, Surai Khola and Chilime are representative of the waters with high CO_2 reactivity. The springs of Tila Nadi - Jumla and Rior plot cose to the SO_4 corner to represent steam-heated character. However, their respective pH values of about 7 and 8.5 makes them unlikely to be pure steam-heated waters.

5.3 Evaluation of reservoirs

The oxygen-18/16 and deuterium ratios of water samples from 36 hot springs in the central part of Nepal, and the tritium activity of 14 of them show 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 as shown in Figure 15 by the equation line and all the springs tested have tritium activity between 7 and 68 T.U. However, nearly all points for Seti Khola are regularly displaced, with mean deuterium excess equal to 14.8‰ (local meteoric line?). Also three points for Tatopani-Myagdi show a slight positive oxygen-18 shift (about 0.7‰) which could be suspected to result from isotopic exchange (Grabczak and Kotarba, 1985).

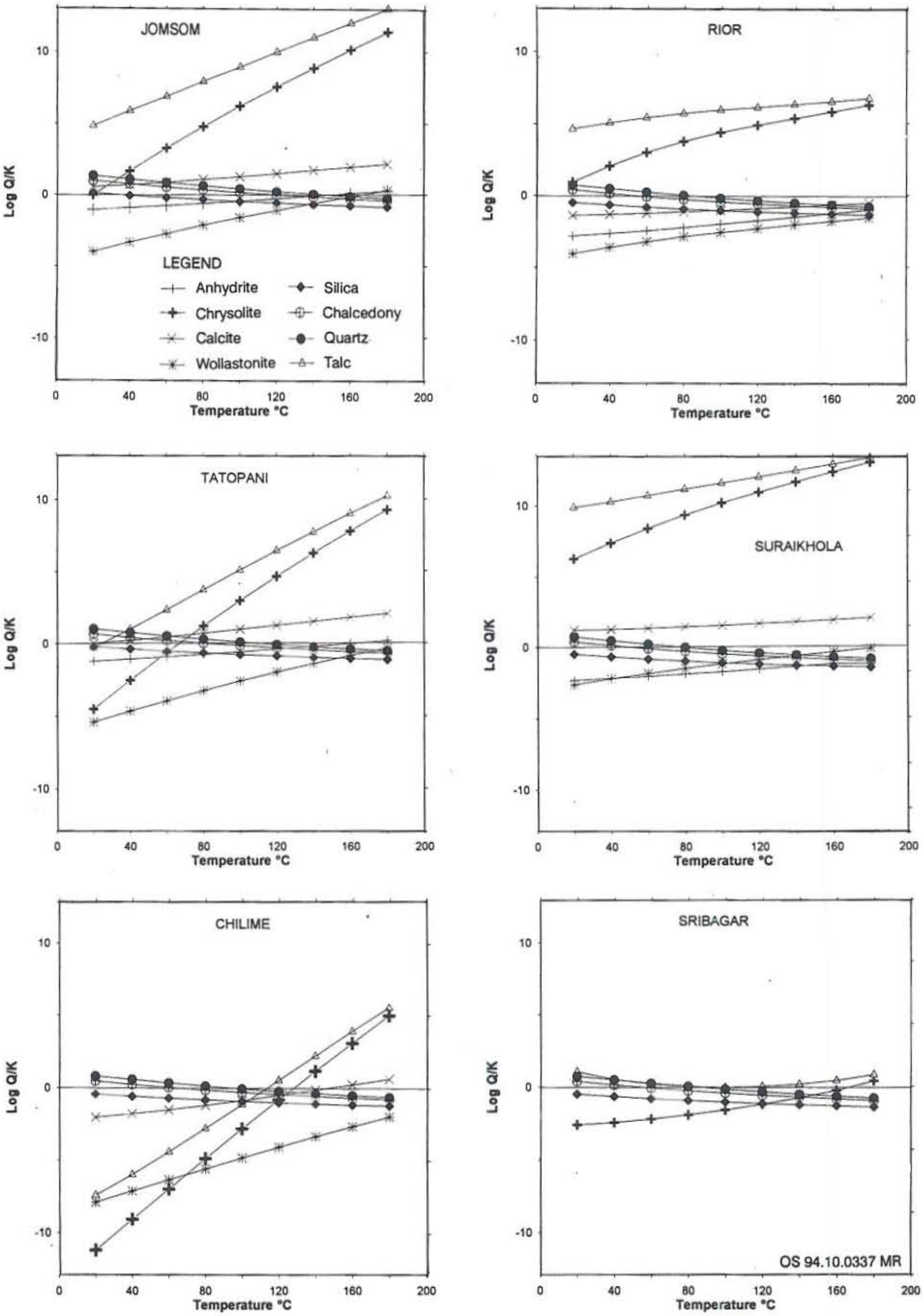

FIGURE 12: Log Q/K for minerals vs. temperature for six different geothermal springs in Nepal

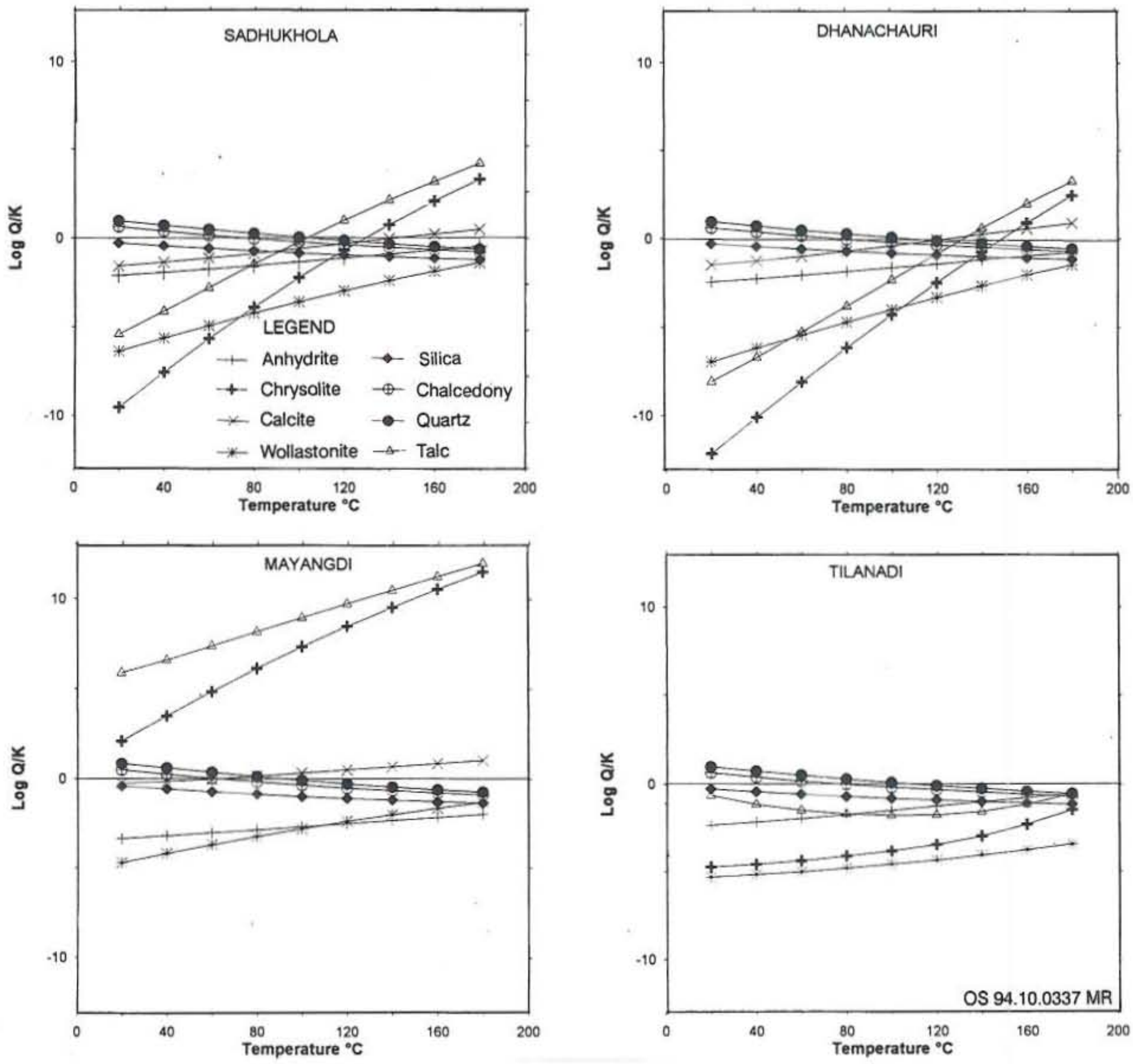

FIGURE 13: Log Q/K for minerals vs. temperature for four different geothermal springs in Nepal

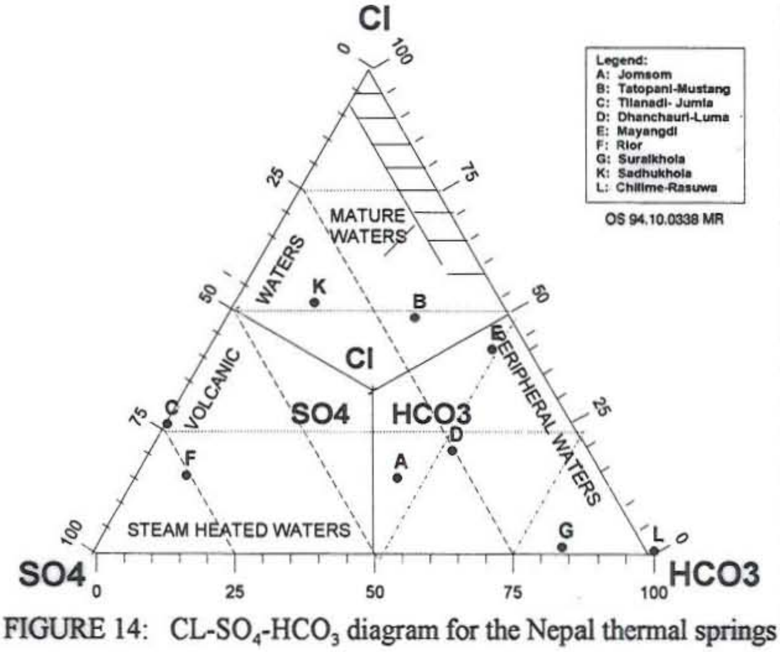

FIGURE 14: CL-SO_4-HCO_3 diagram for the Nepal thermal springs

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 water from two different sources is present: a mixture of an old tritium-free water and a young water containing tritium. If the tritium content is appreciable and constant in time, the young water is well mixed in the aquifer with old water and the size of the reservoir masks any fluctuations in recharge (Nuti, 1991). The above study result does not indicate whether the tritium is

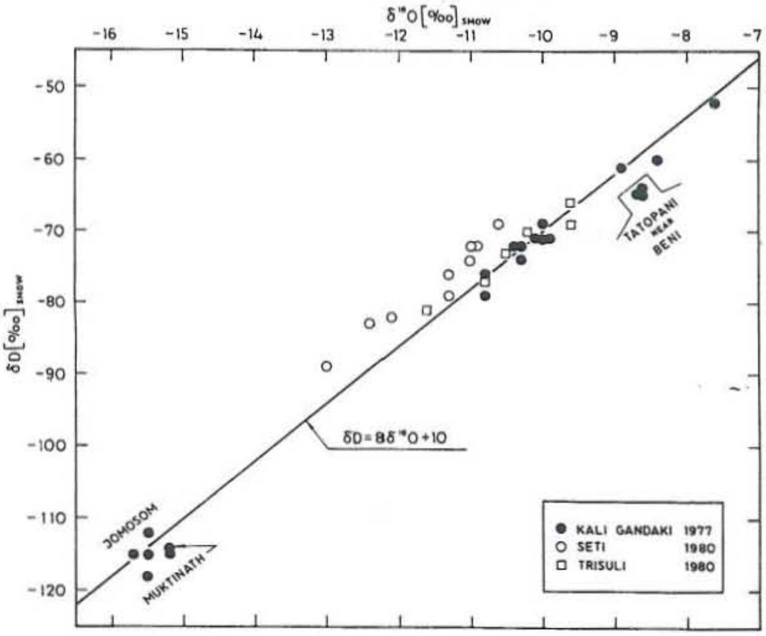

FIGURE 15: $\delta^{18}O$ - δD correlation of analysed waters (Grabczak and Kotarba, 1985)

variable or constant in time. However, since the waters are found to be unmixed, the relatively high chloride content of Sadhu Khola, Tatopani- Mustang and Mayangdi lying in the central region suggests that the waters are fairly mature. This is possible only if the size of the reservoir is large as interpreted above. Hence the studies indicate that there is possibly a large geothermal reservoir in the Sadhu Khola - Jomsom area in the central region of Nepal.

6. CONCLUSIONS AND RECOMMENDATIONS

1. Analysis based on the limited data available on the hot springs of Nepal indicate that the waters of the thermal springs of Jomsom, Tatopani-Mustang, Mayangdi, Sadhu Khola-Myagdi, Darchula (Sribagar and Chamaliya), Bajhang (Tapoban), Jumla (Tila Nadi and Dhanchauri-Luma) and Chilime are fully in equilibrium with quartz. Also that the waters of the springs in Rior and Surai Khola are in equilibrium with chalcedony. None of these thermal springs are mixed with cold groundwater.

2. The waters of the thermal springs in Jomsom, Rior, Tatopani-Mustang, Surai Khola, Chilime, Sribagar-Darchula, Sadhu Khola and Dhanchauri-Jumla are nearly in equilibrium with common hydrothermal alteration minerals.

3. Geothermometers show that the subsurface temperatures in Darchula, Jumla, Jomsom, Tatopani-Mustang, Sadhu Khola, Rior, Mayangdi, Chilime and Bajhang-Tapoban are in the range of 85 to 115°C.

4. Most of the thermal spring waters are peripheral and those at Tatopani-Mustang and Sadhu Khola are mature according to Giggenbach's (1991) classification based on the concentrations of the major anions, Cl^-, SO_4^{2-} and HCO_3^-.

5. There is apparently a large geothermal reservoir in the Sadhu Khola - Jomsom area in the central region of Nepal.

6. The use of geothermal resources can play a significant role in Nepal for a wide range of economically productive purposes and for reducing environmental pollution in the northern colder areas.

7. Many of the geothermal springs in Nepal are yet unexplored. Detailed scientific studies should be conducted on them. Investigative exploration (drilling) and reservoir estimation should be made of the thermal areas that have potential use, particularly in the central part of Nepal where accessibility is comparatively good and population density relatively high.

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