

Isotope hydrogeology and geothermometry of the Mount Meager geothermal area

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A survey of stable and radioactive environmental isotopes has been carried out in order to investigate the recharge, thermal history, age, and geothermometry of the thermal waters at Mount Meager, British Columbia, a Quaternary volcano that is currently the site of active exploration for geothermal resources. Isotope determinations include ^{18}O , ^2H , and ^3H in precipitation, thermal and cold groundwaters, and glacier ice; ^{13}C and ^{14}C in dissolved inorganic carbon; ^{18}O and ^{34}S in dissolved sulphate from thermal and cold groundwaters; and ^{13}C and ^{18}O in hydrothermal calcite crystals. Major ion analyses were performed on thermal and cold spring waters.

Precipitation data are used to define the local meteoric waterline and to document the altitude effect on waters recharging the geothermal system, demonstrating that there are two hydrogeologically separate reservoirs recharged at different altitudes. Both pools of geothermal waters have experienced shifts of between +0.5 and +2.5‰ in $\delta^{18}\text{O}$ values, indicating a limited degree of ^{18}O exchange with hot silicate minerals.

Tritium contents indicate that these waters recharged prior to 1955. ^{13}C contents of dissolved inorganic carbon and hydrothermal calcites from drill core document contamination of the thermal waters with "dead" volcanogenic CO_2 plus carbon exchange with fracture calcite, which precludes the possibility of "dating" the thermal waters using ^{14}C .

Several chemical and isotopic geothermometers are used to estimate the maximum temperatures experienced by the thermal waters. The fractionation of ^{18}O between SO_4^{2-} and H_2O in these waters gives calculated maximum temperatures of less than 140°C. The Mg-corrected Na–K–Ca geothermometer shows excellent correlation with the $\text{SO}_4\text{--H}_2\text{O}$ estimates with maximum temperatures of less than 140°C. Fractionation of ^{13}C and ^{18}O in the systems $\text{CaCO}_3\text{--CO}_2$ and $\text{CaCO}_3\text{--H}_2\text{O}$ using hydrothermal calcites and borehole fluids also offers no indications of subsurface temperatures in excess of 140°C. Silica geothermometer results are not reliable because of equilibrium with amorphous silica phases in the subsurface.

It is concluded that these thermal waters are not deeply circulating and have not experienced temperatures in excess of 140°C.

Une étude d'isotopes stables et radio-actifs naturels examine la recharge, l'histoire thermique, l'âge et la géothermométrie des eaux thermales du Mont Meager, Colombie-Britannique, un volcan quaternaire, site des recherches de ressources géothermiques. Les déterminations isotopiques comprennent le ^{18}O , le ^2H et le ^3H dans les précipitations, les eaux de ruissellement, les eaux souterraines ou froides ou thermales et la glace de glaciers; le ^{13}C et le ^{14}C dans le carbone inorganique dissout le ^{18}O et le ^{34}S dans le sulfate de solution provenant des eaux souterraines ou thermales ainsi que le ^{13}C et le ^{18}O dans les cristaux de calcite hydrothermale. Les analyses chimiques ont été faites des eaux de source froides et thermales.

Les données obtenues des précipitations et des eaux de source froides ont été utilisées afin d'enregistrer l'effet de l'altitude sur les eaux rechargant un système géothermale, démontrant qu'il existe deux réservoirs peu profondes et hydrogéologiquement indépendants qui sont rechargés à des altitudes différentes. Les deux réservoirs d'eaux géothermales montrent une modification du rapport $^{18}\text{O}/^{16}\text{O}$ correspondant à +0,5 à 2,5‰, indiquant un échange restreint de ^{18}O avec des minéraux de silicate chauds.

Les teneurs en ^3H indiquent que ces eaux ont rechargés avant 1955. Les teneurs en ^{13}C du carbone inorganique aqueux et des calcites hydrothermales provenant des carottes montrent que les eaux thermales sont contaminés de CO_2 volcanique "mort" et d'un échange de carbone avec du calcite secondaire de fissures. Donc, il est impossible de dater les eaux thermales utilisant le ^{14}C .

Plusieurs géothermomètres chimiques et isotopiques sont utilisés pour estimer les températures maximales des eaux thermales. La fractionation du ^{18}O entre le SO_4^{2-} et le H_2O dans ces eaux indique des températures maximales de moins de 140°C. Le géothermomètre Na–K–Ca corrigé avec Mg montre de bonnes corrélations avec les estimations du $\text{SO}_4\text{--H}_2\text{O}$, indiquant une température maximale de 140°C. La fractionation du ^{13}C et du ^{18}O dans les systèmes de $\text{CO}_2\text{--CaCO}_3$ et de $\text{H}_2\text{O--CaCO}_3$ utilisant la calcite hydrothermale et les eaux provenant des puits ne montre pas d'indice des températures de plus de 140°C. Les résultats du géothermomètre de silice ne sont pas fiables à cause de l'équilibre établi avec les phases de silice amorphe souterraines.

Donc, ces eaux thermales ne circulent pas à profondeur et n'ont pas subi des températures plus de 140°C.

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Introduction

The potential for geothermal power production in western Canada was recognized in 1973 when the Geological Survey of Canada and the British Columbia Hydro and Power Authority began reconnaissance programs to locate geothermal anomalies (Souther 1975). The main focus of interest was Mount Meager (Fig. 1), which last erupted 2440 years ago (Nasmith *et al.* 1967) leaving a steep geothermal gradient to which an abundance of hot springs bears witness.

To realize this geothermal potential, an integrated program of drilling and geophysics was initiated in 1974 and has since delineated three thermal anomalies on the flanks of the volcanic complex (Fig. 2) (Nevin Sadlier-Brown Goodbrand Ltd. 1975, 1977, 1979). Artesian water temperatures up to 65°C and dry rock temperatures up to 202°C have been recorded in the southern anomaly (Fairbank *et al.* 1980).

In 1977, an investigation was begun to elucidate the origin and flow path of the geothermal waters through the use of environmental isotopes (Michel and Fritz 1978, 1979). It included determinations of ^{18}O , ^2H , and ^3H contents in thermal, precipitation, and runoff waters and "dating" using ^{14}C in dissolved carbonate. Following these studies, it was felt that a full-scale investigation of the isotope hydrogeology of the Mount Meager thermal waters would provide a more comprehensive understanding of the hydrogeological regime, thermal history, and reservoir temperatures of the geothermal waters. Therefore, in 1979 a program was undertaken by the University of Waterloo to sample and analyze precipitation, runoff, cold spring waters, and thermal waters of Mount Meager for stable and radioactive environmental isotopes and geochemistry.

The main focus of the study was threefold: (a) a detailed investigation of the recharge environment and subsurface flow path of the thermal waters through analyses of ^{18}O , ^2H , and ^3H concentrations; (b) determination of residence times of the thermal waters, through the use of tritium and ^{14}C ; and (c) the application of a series of geothermometers aimed at determining reservoir temperatures.

Geology

The Mount Meager volcanic complex is located 20 km north of Vancouver, British Columbia at the northern end of the Cenozoic Garibaldi Volcanic Belt (Fig. 1), which comprises late Tertiary to Quaternary basaltic to rhyolitic volcanics (Lewis and Souther 1978). The Garibaldi Belt is considered to be a northward extension of the western United States High Cascades, which include the Mount Baker and Mount St. Helens volcanic centers. Regional basement rocks include

metasediments, granodiorites, diorites, and gneisses of the Mesozoic to Tertiary Coast Range Plutonic Complex. To the east of the Garibaldi belt and trending northwest is the Pemberton Belt of late Tertiary and Quaternary quartz monzonite plutons (Lewis and Souther 1978). The Pemberton Belt intersects the Garibaldi Belt at the Salal Creek pluton in the vicinity of Mount Meager (Fig. 1). Both belts are related to subduction of the Juan de Fuca Plate. The presence of several additional thermal springs and seeps along the Lillooet Valley between Mount Meager and Harrison Lake suggests that a major fault roughly follows the axis of the Pemberton Belt.

The Mount Meager complex consists of a series of predominantly andesitic and dacitic flows and breccias of Quaternary age overlying metavolcanics and meta-sedimentary basement rocks of pre-Tertiary and Quaternary periods (Read 1979). The volcanic pile is directly underlain by a basal breccia representative of an explosive eruption that led to extensive fracturing of the local basement rocks. The most recent stage of volcanic activity at Mount Meager was the eruption of the Bridge River Ash from a vent on the northeast flank of Plinth Peak; the ash has been dated at 2440 ± 140 years BP (Nasmith *et al.* 1967).

Thermal springs

The hot springs of southwestern British Columbia can be divided into two groups. The Harrison, Sloquet, and Skookumchuck Hot Springs (Fig. 1) are related to the Pemberton Belt and issue from Tertiary intrusive rocks or from basement rocks proximal to the intrusives along the Lillooet Valley fault system. This fault system has apparently provided the fracture permeability required for deep circulation of meteoric waters. The second group includes the Mount Meager and Mount Cayley Hot Springs (Souther 1980), which are related to the centers of Quaternary volcanism. The Pebble Creek Hot Springs, which occur at the intersection of the Garibaldi Volcanic Belt and the Pemberton Belt, appear related to both groups of thermal springs.

Along Meager Creek are three sites where thermal waters discharge (Fig. 2). The Meager Creek Hot Springs, at 45–55°C, represent the principal discharge where as many as 21 individual vents have been identified in an area of approximately 1200 m². They contribute to a measured discharge rate of ~40 L/s (Lewis and Souther 1978), issuing into sinter-lined pools in coarse fluvial sand and gravel deposits on the south side of Meager Creek. The Placid Hot Springs, at 45°C, with an estimated combined flow of less than 2 L/s, emanate from the gravel and boulder bank of Meager Creek approximately 1 km upstream from the Meager Creek Hot Springs. About 5 km farther up-

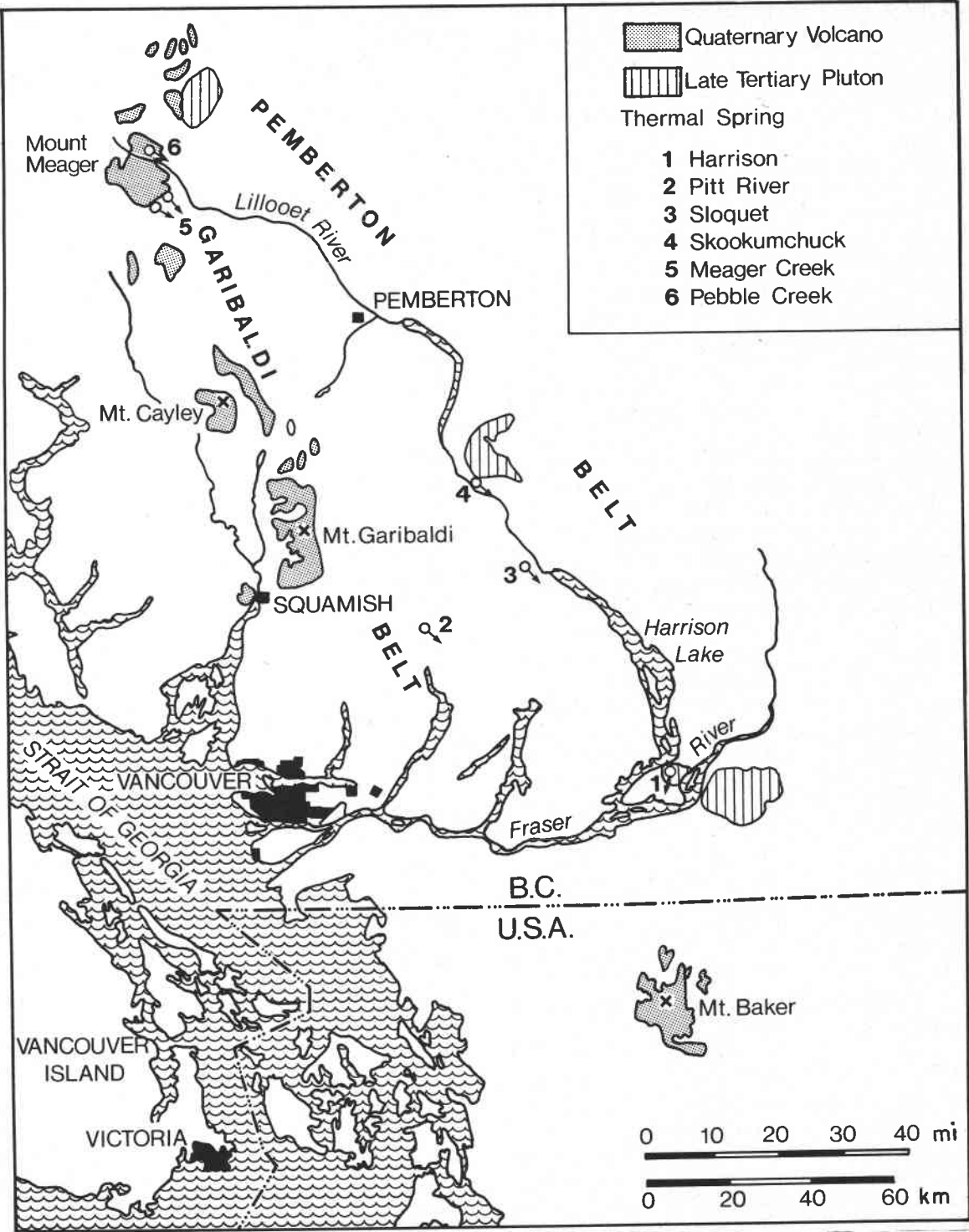


FIG. 1. Location of Mount Meager and its relation to the Garibaldi Volcanic Belt and the Pemberton Plutonic Belt.

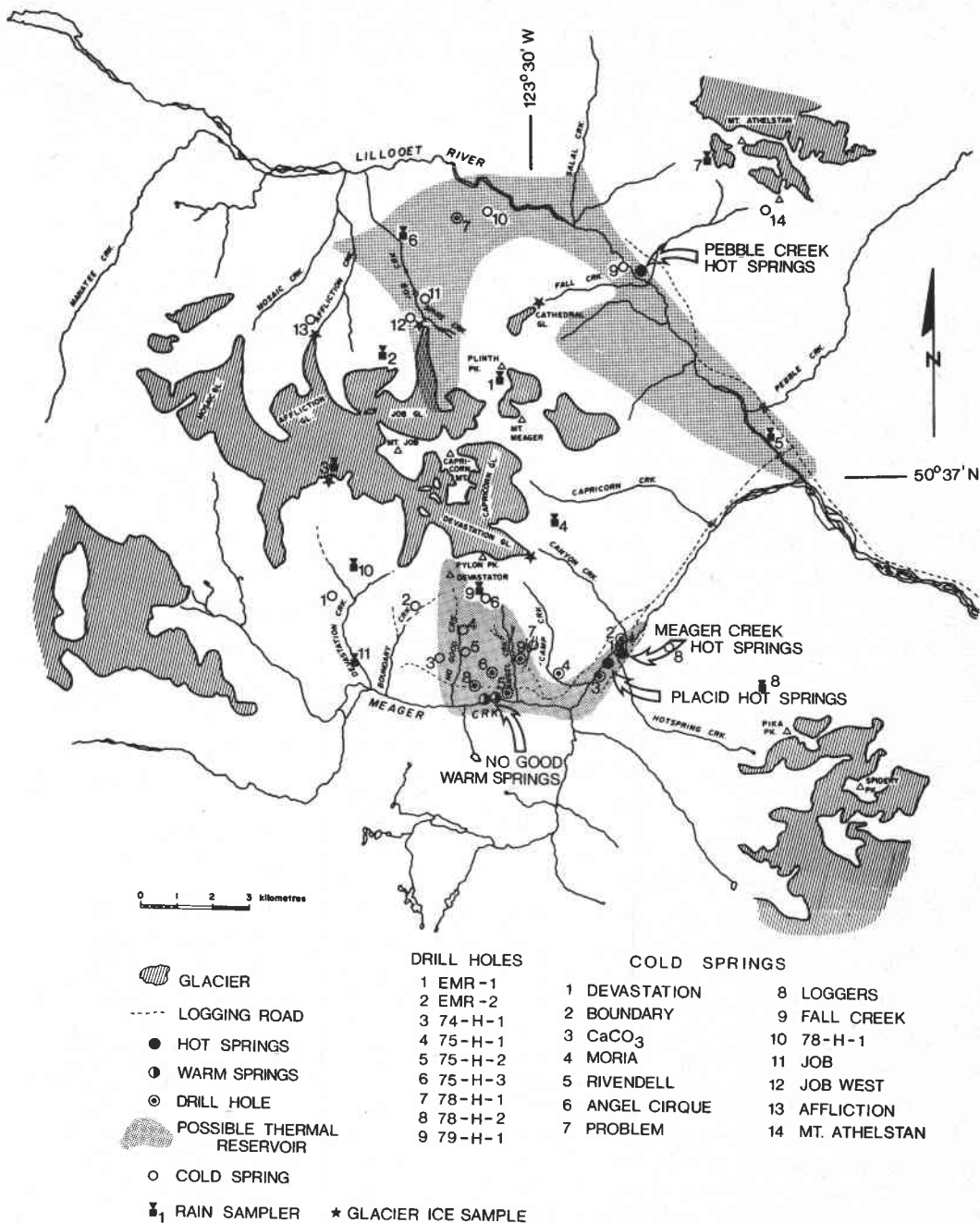


Fig. 2. Site map of the Mount Meager complex showing locations of thermal and cold springs, boreholes, glaciers, rain sampling stations, and access routes. Thermal anomalies shown are based on resistivity survey (Nevin Sadlier-Brown Goodbrand 1979).

stream, six vents (No Good Warm Springs) discharge 20–40°C water at less than an estimated 4 L/s.

The Pebble Creek Hot Springs discharge 55–60°C water at between 5 and 10 L/s into an ochre- and sinter-lined pool on a bedrock bench on the northeast side of the Lillooet River. In addition, several related

thermal seeps, depositing aprons of calcite and algae, discharge from the face of this bench.

The Meager Creek thermal waters are dominated by a sodium-chloride chemistry with Na⁺ and Cl⁻ concentrations averaging about 400 and 550 ppm, respectively (Table 1), and are oversaturated with respect to amor-

TABLE 1. Chemical and

Sample		Date	Temp. (°C)	pH	Ca ²⁺ (ppm)	Mg ²⁺ (ppm)	Na ⁺ (ppm)	K ⁺ (ppm)
Hot springs								
Meager Creek	main vent	June/79	50.1	6.54	81.9	26.2	439	45.5
	vent #19	June/79	49.8	6.24	78.0	24.5	440	50.0
Placid		Aug./79	45.1	5.89	114	27.6	433	53.5
	vent #1	June/79	38.8	6.47	—	—	—	—
No Good	vent #1	Aug./79	40.4	6.34	77.0	17.0	360	35.0
	vent #2	June/79	29.5	6.82	75.6	13.7	175	22.4
Pebble Creek	main vent	June/79	59.8	6.88	32.7	4.73	426	13.8
	vent #7	June/79	56.5	6.85	—	—	—	—
	vent #7	Aug./79	57.0	6.60	35.3	5.11	419	14.1
Drill holes								
EMR-1		Aug./79	58.4	6.06	107	36.2	424	48.4
74-H-1		Aug./79	52.3	6.23	223	90.3	2390	98.1
75-H-1		Aug./79	10.1	7.70	32.9	18.0	23.0	6.93
79-H-1		Sept./79	28	6.12	210	43.1	9.10	6.82
Cold springs								
Boundary #4		Aug./79	4.5	8.31	12.2	5.42	4.84	0.54
Moria #1		Aug./79	8.5	7.91	110	38.5	4.50	3.31
CaCO ₃ #1		June/79	5.6	7.71	—	—	—	—
#3		June/79	5.6	7.62	98.6	12.5	3.20	1.75
#4		June/79	6.2	7.50	—	—	—	—
Angel Cirque #1		Aug./79	0.3	8.72	—	—	—	—
Problem #1		June/79	9.0	7.65	106	44.9	11.9	5.00
Fall Creek #1		Aug./79	3.9	5.92	5.40	2.60	6.00	1.80
78-H-1 spring #1		June/79	4.6	7.18	3.50	1.01	16.0	0.67
Mt. Athelstan #1		Aug./79	1.2	8.48	—	—	—	—
Runoff								
Job Creek (at Job Glacier)		June/79	5.1	7.3	—	—	—	—

phous silica. The Placid Hot Springs and No Good Warm Springs have essentially the same chemistry as the Meager Creek Hot Springs, a possible indication that they emerge from the same geothermal reservoir.

The Pebble Creek Hot Springs, unlike the Meager Creek thermal waters, are dominated by a sodium-bicarbonate chemistry with concentrations of Na⁺ and HCO₃⁻ of about 400 and 750 ppm, respectively. Also, unlike the Meager Creek thermal waters, these waters are supersaturated with respect to calcite and undersaturated with respect to amorphous silica. The contrasting chemical natures of the Pebble Creek and Meager Creek thermal waters suggest that they may have unrelated flow paths and that at least two independent sources of thermal waters exist (Hammerstrom and Brown 1977).

Cold springs

Cold springs in the Mount Meager area range in altitude from 564 to 1875 m (Fig. 2), issuing in most cases from unconsolidated soil, gravel, and ash deposits. Temperatures range from -0.1 to 9°C and chemistries, although generally quite low in total dissolved

solids (TDS), can be quite variable, with Ca²⁺ concentrations between 3.5 and 110 ppm and HCO₃⁻ between 2.70 and 594 ppm (Table 1). Cold springs with high bicarbonate concentrations are precipitating calcite tufa, as is the case at the CaCO₃ Cold Springs where supersaturated spring waters cascade over 20 m of hillside, forming an intricate network of terraced calcite pools.

Sampling and analysis

All analyses were performed in the Environmental Isotope Laboratory and the Aqueous Geochemistry Laboratory at the University of Waterloo, Ontario.

Isotope samples

¹⁸O, ²H, and ³H contents were determined for all thermal waters, as well as for cold springs, glacier ice, snow, and rainfall. ¹⁸O and ²H contents were determined by equilibration with CO₂ and by uranium reduction, respectively. Results are expressed as per mil differences (δ¹⁸O‰ and δ²H‰ from SMOW (Standard Mean Ocean Water) with analytical precisions of ±0.15 and ±1‰, respectively. Tritium (³H) concentrations

carbon-13 analyses

Fe _{tot} (ppm)	Mn ²⁺ (ppm)	SiO ₂ (ppm)	SO ₄ ²⁻ (ppm)	Cl ⁻ (ppm)	HCO ₃ ⁻ (ppm)	TDS (ppm)	δ ¹³ C _{DIC} (‰ PDB)	δ ¹³ C _{CO₂} (‰ PDB)	log pCO ₂
0.12	0.64	162	122	528	443	1848	-6.1	-9.5	-0.77
0.20	0.08	142	130	605	437	1907	-7.3	-9.7	-0.48
0.35	0.76	138	174	674	398	2013	—	—	—
—	—	—	—	—	404	—	-7.6	-11.3	-0.81
0.70	1.27	125	114	405	409	1544	—	—	—
0.25	0.84	101	69.0	196	382	1035	-8.4	-14.0	-1.24
0.13	0.19	79.0	288	83.3	763	1679	-4.6	-8.2	-0.79
—	—	—	—	—	771	—	-6.3	-9.9	-0.55
0.10	0.15	67.5	316	62.4	735	1655	—	—	—
0.14	1.20	155	182	571	526	2049	-6.2	-8.4	-0.16
0.16	0.67	104	2370	2640	1270	9188	-4.9	-7.4	-0.05
0.10	0.50	15.5	22.6	0.56	233	353	-10.7	-19.8	-2.42
35.5	0.85	23.8	16.1	0.89	974	1266	-7.0	-9.2	-0.24
Δ 0.1	0.01	6.0	2.02	0.2	66.3	97	-6.1	-16.3	-3.59
Δ 0.1	0.03	6.7	124	0.34	395	682	-5.0	-14.5	-2.43
—	—	—	—	—	370	—	+0.5	-10.1	-2.26
Δ 0.1	0.05	8.9	8.95	0.8	370	504	—	—	—
—	—	—	—	—	351	—	-3.0	-12.0	-2.14
—	—	—	—	—	2.70	—	-7.2	-18.1	-4.58
Δ 0.1	0.05	10.9	36.1	0.8	594	809	-2.8	-12.0	-1.99
Δ 0.1	0.05	52.8	8.55	0.8	36.8	114	-8.6	-9.8	-1.45
Δ 0.1	0.05	36.5	3.48	0.8	40.8	102	-13.9	-22.2	-2.66
—	—	—	—	—	12.0	—	-6.8	-17.4	-4.49
—	—	—	—	—	44.7	—	+0.2	-8.9	-2.81

were determined on non-enriched water samples and are expressed as tritium units (TU, 1 TU = 1 ³H × 10⁻¹⁸ H); unless otherwise indicated they have an analytical precision of ±10 TU.

For analysis of ¹³C and ¹⁴C dissolved carbonate was precipitated in the field from solution as BaCO₃ by the addition of NaOH and hydrous BaCl₂. ¹³C analyses were done on CO₂ evolved through reaction with H₃PO₄ and results are reported in the δ¹³C‰ notation and refer to the PDB standard (rostrum of *Belemnitella americana* of the Peedee Formation) with a reproducibility of ±0.5‰. ¹⁴C activities were determined by liquid scintillation counting on benzene produced from the sample and are expressed as pmC (percent modern carbon), where 100 pmC is defined as 95% of the National Bureau of Standards (NBS) oxalic acid standard and corresponds to wood grown in 1850 in a pollution-free environment.

Dissolved sulphate was co-precipitated with BaCO₃ as BaSO₄ in the manner described above. BaCO₃ was then removed by acidification with ~10% HCl. Sulphate samples were converted to CO₂ for ¹⁸O analysis accord-

ing to the graphite reduction method described by Holt (1977). Analyses are reported as δ¹⁸O‰ SMOW with a reproducibility of better than ±0.5‰ (Feenstra 1980). ³⁴S concentrations in sulphate were analyzed by using SO₂ gas produced by the thermal decomposition of BaSO₄ (Rafter 1957). Values are reported as δ³⁴S‰ CDT (Cañon Diablo troilite) with a reproducibility of ±0.3‰.

Calcite was collected from sinter deposits at the mouths of hot and cold springs as well as from hydrothermal deposits in drill core. Samples have been analyzed for their ¹⁸O and ¹³C concentrations by conversion to CO₂ through acidification with 100% phosphoric acid at 50°C. The resulting analyses are both expressed relative to PDB with an analytical precision of better than ±0.2‰.

Chemistry samples

At all chemistry sample sites, temperature, field pH, and field alkalinity measurements were recorded. Water samples were filtered through a 0.45 μm pore diameter filter paper and collected in two 250 mL bottles, one of

which was acidified to below pH 3 for heavy metal analysis. Water samples for silica determinations were diluted with deionized water to prevent precipitation of amorphous silica. Charge balance calculations demonstrated that all analyses have a discrepancy of <8% between anion and cation equivalence concentrations.

Results and discussion

Stable isotope hydrogeology

In a normal, non-thermal groundwater, the ^{18}O and deuterium contents are not affected by geochemical or biological processes. They closely reflect, in most cases, the average annual temperature of the recharge area and hence can be used as tracers for the origin of groundwater.

In geothermal areas, this is not necessarily possible because oxygen exchange between minerals and water at elevated temperatures often results in an ^{18}O enrichment in the water due to high concentrations of ^{18}O in most rocks (Craig 1963; Epstein and Taylor 1967). The "meteoric relationship" between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ is then no longer obeyed. However, because deuterium is not affected, the original meteoric waters can be identified (Arnason 1976). Furthermore, the magnitude of the ^{18}O shift often reflects the magnitude of the geothermal resource (Truesdell and Hulston 1980).

A detailed analysis of ^{18}O and deuterium abundances in meteoric and non-thermal groundwaters can then greatly contribute to the understanding of the origin of geothermal waters and the environment through which they have passed. The following discussion includes, therefore, data on local precipitation, cold spring waters, and thermal waters. Attempts are made not only to describe the origin of subsurface waters but also to comment on their residence times.

Precipitation data collected in this and previous studies at Mount Meager (Michel and Fritz 1978, 1979) plot close to a meteoric waterline defined on the basis of samples collected at Mount Meager, where $\delta^2\text{H} = (6.98^{18}\text{O} - 8.1)\text{‰}$. Normal, cold groundwater will fall on this line, whereas thermal waters may be displaced to the right (Fig. 3). Note that this line is quite different from a meteoric waterline obtained on samples collected since 1975 at Victoria, British Columbia, where $\delta^2\text{H} = (7.78^{18}\text{O} - 0.6)\text{‰}$. The difference may be due to local influences that, at this time, cannot be defined.

An important aspect of ^{18}O and ^2H contents in precipitation is their altitude dependence. In alpine environments, one observes a decrease of 0.15–0.5‰ in ^{18}O per 100 m rise in altitude with a corresponding decrease for deuterium (Gat 1980). At Mount Meager, the altitude effect is approximately –0.25‰ per 100 m rise for ^{18}O , and can provide rough estimates of the relative altitude of recharge for various groundwaters.

Cold springs in the Mount Meager area have been

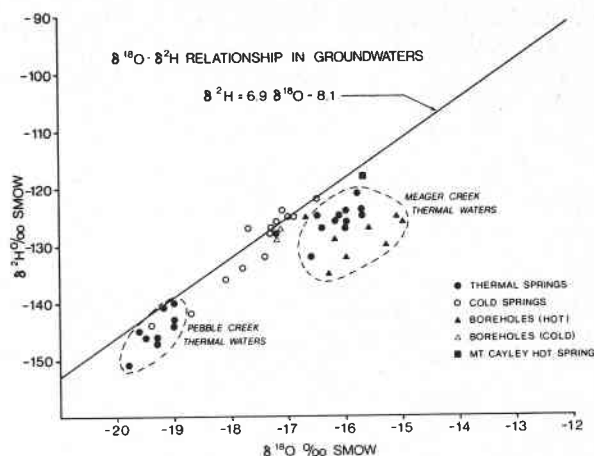


FIG. 3. Relationship between ^{18}O and ^2H in thermal and cold groundwaters. Cold spring waters fall very close to the local meteoric waterline whereas thermal waters are shifted to more positive $\delta^{18}\text{O}$ values because of exchange with hot silicate minerals.

sampled at altitudes ranging between 564 and 1875 m during spring and later summer sampling trips. The high-altitude springs show a seasonal fluctuation of up to 3‰ in $\delta^{18}\text{O}$ values and the low-altitude springs have variations over the sampling period close to the analytical error of $\pm 0.15\text{‰}$ (Table 2).

The high-altitude cold springs discharge from very limited, shallow flow systems of short residence time whereas the low-altitude cold springs discharge mixed waters from larger hydrogeological systems of longer residence time. Because these low-altitude discharges show little seasonal fluctuation, they should represent the average annual $\delta^{18}\text{O}$ values of the meteoric waters that recharge their systems. These non-fluctuating springs discharge below ~1200 m elevation and, therefore, recharge must occur above this level where meteoric waters have average annual $\delta^{18}\text{O}$ values of –17.0 to –18.0‰. The lowest $\delta^{18}\text{O}$ values of glaciers on Mount Meager are also in this range and it can be assumed that it closely approximates the lowest average ^{18}O contents to be expected from larger hydrogeologic systems originating on Mount Meager.

Thermal waters do not usually plot on the meteoric waterline because of exchange with ^{18}O in reservoir rocks: the ^{18}O content of granites and granodiorites is generally of the order of +8–+9‰ SMOW (Epstein and Taylor 1967), and sedimentary rocks may be as high as +30‰, representing a significant enrichment over most meteoric waters.

Exchange with these oxygen reservoirs explains the observations by Craig (1963, 1966), who reported positive ^{18}O shifts of 3–4.5‰ magnitude for the Steamboat Springs and Lassen Park thermal waters and

5–7‰ for steam at Larderello, Italy and Hekla, Iceland. Hulston (1976) reported positive shifts of about 5‰ in ^{18}O in the thermal waters from boreholes at El Tatio, Chile. Shifts of this magnitude are not observed for the Meager Creek and Pebble Creek Hot Springs, which are enriched by 0.5–1.5‰ over local meteoric waters. Borehole samples show enrichments of up to 2.5‰ (Fig. 3; Table 2). One should also note that the ^{18}O enrichment in the Pebble Creek Hot Springs is at most 0.5‰ and may be less, considering the uncertainties associated with the definition of the local meteoric waterline. This indicates that these thermal waters have been in contact with rocks at either lower temperatures or for shorter periods than is the case at other geothermal systems, possibly due to more shallow circulation, which may involve some mixing of cold and warm waters. One has to note that oxygen exchange during short contact times with igneous rocks only becomes significant at temperatures above approximately 150°C (Truesdell and Hulston 1980). The difference between thermal springs and boreholes at Meager Creek shows that some mixing with local meteoric waters may occur, which is more significant in the free flowing springs than in the partially cased boreholes.

The original $\delta^{18}\text{O}$ value for the thermal waters can be deduced from the $\delta^2\text{H}$ values, which indicate that the Meager Creek thermal waters had an original $\delta^{18}\text{O}$ value of about –17.0 to –18.0‰. This is close to the value for the low-altitude cold springs, which discharge isotopically constant water thought to represent the average annual precipitation and glacial meltwater input at the higher elevations of Mount Meager.

The Pebble Creek thermal waters have much lower ^{18}O contents and, corrected for a positive shift, average between –19.5 and –20.5‰. This enforces the observation made on the basis of chemical data that the Meager Creek and Pebble Creek thermal waters discharge from quite separate geothermal pools. The more negative values for the Pebble Creek thermal waters correspond to a significantly higher altitude recharge zone. Unfortunately, with the data available, the location of the recharge area for this system cannot yet be defined, but is almost certainly not on Mount Meager.

Tritium

Tritium (half-life = 12.43 years) is produced naturally in the atmosphere by the bombardment of nitrogen with cosmic radiation, and its natural abundance in precipitation is believed to be between 5 and 20 TU (Brown 1961). However, between 1952 and 1964, upper atmospheric testing of thermonuclear bombs resulted in abnormally high amounts of tritium entering the hydrosphere. Thus, the absence of tritium in natural groundwaters can identify waters that entered the flow system prior to about 1952.

Precipitation samples collected between 1977 and 1979 at Mount Meager have tritium levels of the order of 20–70 TU with an unweighted average of 47 TU. Cold springs contain just slightly less tritium, ranging from 79 TU to the detection limit and averaging 33 TU (Table 2). However, the information that exists on the seasonal variations in tritium fallout at Mount Meager is limited, and without long-term sampling it is impossible to differentiate older from younger waters with certainty, especially since in these regions modern precipitations can again have very low tritium contents. Furthermore, glacial meltwaters are essentially tritium free (Table 2) and their input into these flow systems must also be known in order to date the waters.

The Pebble Creek thermal waters consistently show tritium concentrations near the detection limit, whereas the Meager Creek thermal waters in the springs and boreholes show an apparent variability ranging between detection limit and 58 TU, averaging 21 TU (Table 2). These small amounts of tritium can be attributed to mixing with modern near-surface waters. This implies that the thermal waters are tritium free and, therefore, more than 25 years old. The Pebble Creek thermal waters experience less mixing with very young waters, possibly because they issue from fractured bedrock 15 m above river level rather than from fluvial sands and gravels as do the Meager Creek Hot Springs.

The carbon system— ^{14}C and ^{13}C

When atmospheric ^{14}C enters the hydrosphere as dissolved atmospheric or soil $^{14}\text{CO}_2$ and becomes isolated from these sources, then radioactive decay reduces the activity of the ^{14}C , providing a method for age dating. However, because of contributions of “dead” carbon from dissolution of carbonates along the flow path and from incorporation of volcanogenic CO_2 , the activity of ^{14}C in dissolved inorganic carbon (DIC) from geothermal areas can be significantly decreased without radioactive decay. In a previous study (Michel and Fritz 1978), ^{14}C activities below 5.6 pmC were found (Fig. 4; Table 3) and the calculated $\delta^{13}\text{C}$ values of CO_2 in equilibrium with water were close to volcanogenic CO_2 . Thus carbon exchange with hydrothermal carbonate minerals and (or) contamination by volcanogenic CO_2 were suspected. A survey of $\delta^{13}\text{C}$ in aqueous carbonate was thus undertaken (Table 1; Fig. 4), and results support the suggestion that volcanogenic CO_2 has indeed equilibrated with these thermal waters (see below). Therefore, ^{14}C exchange is undoubtedly taking place and ^{14}C cannot be used to determine residence times.

If mixing of ^{14}C -free thermal waters with near-surface cold groundwaters takes place then contributions from ^{14}C -rich soil CO_2 will be recorded. This explains the data obtained for No Good Warm Spring 2,

TABLE 2. Environmental isotope data

Sample	Elev. (m)	Date	Temp. (°C)	$\delta^{18}\text{O}$ (‰ SMOW)	$\delta^2\text{H}$ (‰ SMOW)	^3H (± 10 TU)
Hot springs						
Meager Creek main vent	602	Oct./77	—	-15.8	-121	11
main vent		Feb./78	—	-16.0	-126	17
main vent		Mar./78	—	-15.7	-125	—
main vent		Dec./78	—	-16.2	-126	29
main vent		June/79	50.1	-16.4	-127	19
main vent		Aug./79	54.2	-15.7	-124	3
vent #2	602	Feb./78	—	-16.6	-132	58
vent #2		Mar./78	—	-16.0	-127	—
vent #3	602	Mar./78	—	-15.7	-125	34
vent #15	595	June/79	—	-16.5	-125	—
vent #15		Aug./79	49.2	-15.8	—	—
vent #17	587	June/79	—	-14.6	—	24
vent #17		Aug./79	49.3	-15.8	—	—
vent #17	587	June/79	49.8	-16.4	—	36
vent #19		Aug./79	51.2	-16.2	—	13
Placid vent #1	617	Aug./79	45.1	-16.0	-124	0
vent #3		Aug./79	41.0	-15.1	—	—
vent #5		Aug./79	46.0	-16.1	—	0
No Good vent #1	686	June/79	38.8	-16.1	-125	—
vent #2	686	June/79	29.5	-17.2	-128	—
vent #2		Aug./79	29.9	-16.5	—	38
Pebble Creek main vent	564	Oct./77	—	-19.0	-140	—
main vent		Feb./78	—	-19.3	-146	23
main vent		Mar./78	—	-19.0	-143	—
main vent		Oct./78	—	-19.8	-151	—
main vent		Dec./78	—	-19.3	-147	—
main vent		June/79	59.8	-19.5	-146	20
main vent		Aug./79	59.1	-19.3	—	—
vent #2	562	Feb./78	—	-19.0	-144	—
vent #2		Mar./78	—	-19.2	-141	—
vent #2		June/79	—	-18.0	—	23
vent #2		Sept./79	—	-18.9	—	0
vent #7	549	June/79	56.5	-19.6	-145	2
vent #7		Aug./79	57.0	-19.5	—	16
Boreholes						
Depth (m)						
EMR-1 45	587	Feb./78	—	-15.6	-127	33
EMR-1		Mar./78	—	-15.7	-125	—
EMR-1		Oct./78	—	-16.0	-132	—
EMR-1		Dec./78	—	-16.3	-135	26
EMR-1		June/79	58.5	-16.2	-126	7
EMR-1		Aug./79	58.4	-16.1	—	39
EMR-2 118		Mar./78	—	-16.2	-129	19
74-H-1 347.5	640	Oct./77	—	-15.1	-125	—
74-H-1		Feb./78	—	-15.3	-130	—
74-H-1		Mar./78	—	-15.0	-126	13
74-H-1		June/79	50.5	-15.6	-127	0
74-H-1		Aug./79	52.3	-15.3	—	23
75-H-1 91.4	789	Aug./79	10.1	-17.2	-128	31
PDH-78-3 61.0	480	Sept./78	—	-17.2	-129	16
79-H-1 60-68	823	Aug./79	—	-17.1	—	44
79-H-1		Sept./79	28.0	-16.7	-125	35
Cold springs						
Devastation	1188	June/79	10.0	-17.1	-124	—

TABLE 2. (Concluded)

Sample	Elev. (m)	Date	Temp. (°C)	$\delta^{18}\text{O}$ (‰ SMOW)	$\delta^2\text{H}$ (‰ SMOW)	^3H (± 10 TU)
Boundary #3	1204	Aug./79	4.5	-16.7	—	—
#4		Aug./79	4.5	-17.1	—	51
CaCO ₃ #1	945	June/79	5.6	-17.4	-132	43
#3		June/79	5.6	-17.3	-128	
#4		June/79	6.2	-17.3	-127	42
#4		Aug./79	6.9	-17.2	-126	52
#6		Aug./79	10.0	-17.0	—	25
#7		Aug./79	10.0	-17.7	—	—
Moria #1	1143	Aug./79	8.5	-17.5	—	34
#3		Aug./79	10.0	-17.4	—	—
Rivendell #1	975	Aug./79	10.0	-17.3	—	—
#2		Aug./79	10.0	-17.3	—	—
Angel Cirque #1	1661	June/79	2.0	—	-136	24
#1		Aug./79	0.3	-16.5	-122	4
#2		June/79	2.0	-18.1	—	—
#2		Aug./79	2.0	-16.4	—	22
#4		Aug./79	2.0	-17.3	—	—
#7		Aug./79	-0.2	-16.1	—	—
Problem #1	1151	June/79	9.0	-17.7	-127	54
#1		Aug./79	10.0	-17.0	-125	13
#2		June/79	10.0	-16.9	-125	23
#2		Aug./79	10.0	-17.2	—	—
Loggers #1	823	Aug./79	5.0	-17.7	—	—
Fall Creek #1	564	Aug./79	3.9	-17.0	—	79
#4		Aug./79	5.0	-16.9	—	—
78-H-1 #1	728	June/79	4.6	-18.1	-136	—
#1		Aug./79	10.0	-18.0	—	—
#3		June/79	10.0	-17.4	—	—
Job #1	1448	June/79	10.0	-17.8	-134	40
Job (west)	1524	Sept./79	10.0	-15.8	—	—
Affliction	1494	June/79	10.0	-18.7	-142	213
Mt. Athelstan #1	1875	June/79	5.0	-19.4	-144	29
#1		Aug./79	1.3	-17.1	—	—
#2		Aug./79	1.2	-16.8	—	28
Glacier ice						
Job (south)	2075	Sept./79	<0	-14.9	—	0
Devastation (east)	1830	Aug./79	<0	-16.0	—	0
Cathedral	1220	Aug./79	<0	-17.4	—	—
Job (north)	1220	Aug./79	<0	-15.5	—	—
Affliction	1400	Aug./79	<0	-16.1	—	11

NOTES: Dash indicates no data were available. Boreholes: depths are total depths except for 79-H-1 (60–68 m), which is an artesian zone; elevations are collar elevations.

which discharges at a much lower temperature with lower total dissolved solids (TDS) and higher tritium values than the Meager Creek Hot Springs (Tables 1, 2). The ^{14}C activity for these waters is 19.8 pmC (Fig. 4).

^{13}C in aqueous carbonate

In most geothermal systems, a significant CO_2 gas phase is present that controls the ^{13}C of the DIC. We can calculate the ^{13}C for the equilibrium $\text{CO}_2(\text{g})$, which can be used to identify the sources of this gas providing it is an open system with respect to this gas.

The per mil difference in ^{13}C between $\text{CO}_2(\text{g})$ and each of H_2CO_3 , HCO_3^- , and CO_3^{2-} is represented by the temperature-dependent isotope fractionation factors between $\text{CO}_2(\text{g})$ and carbonic acid (Vogel *et al.* 1970), $\text{CO}_2(\text{g})$ and bicarbonate (Mook *et al.* 1974), and $\text{CO}_2(\text{g})$ and carbonate (Thode *et al.* 1965). Using these fractionation factors and the molar concentrations of each carbonate species as determined by WATEQF (a FORTRAN version of the WATEQ PL1 water analysis program, Plummer *et al.* 1976) an isotope mass balance equation can be written to determine the value of $\delta^{13}\text{C}$

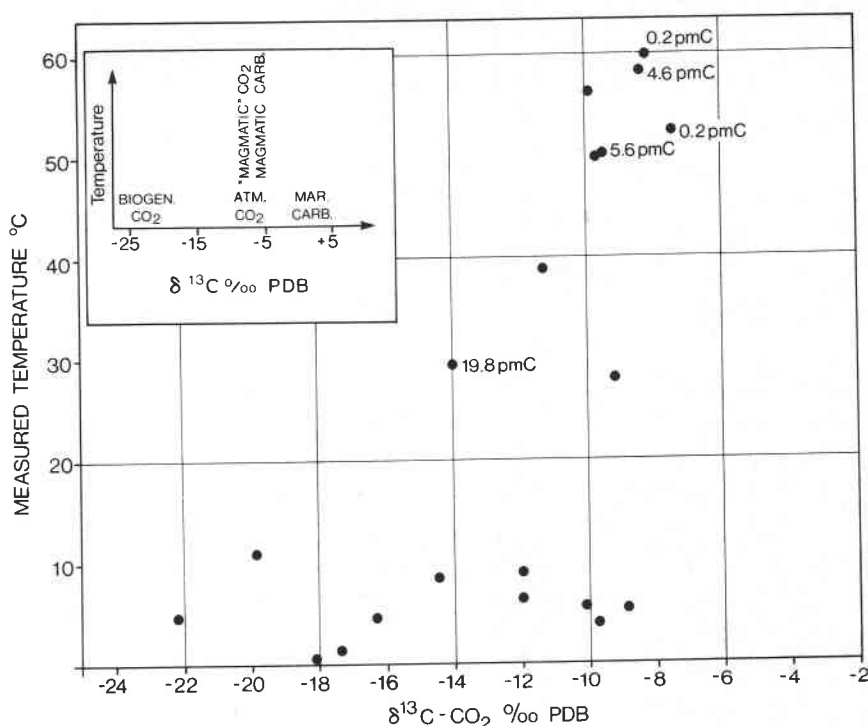


FIG. 4. Relationship between discharge temperature and the calculated $\delta^{13}\text{C}$ of the CO_2 gas phase for thermal and cold spring waters. The inset shows common sources of CO_2 . Results for ^{14}C analyses are shown for all samples tested.

TABLE 3. ^{14}C activities and $\delta^{13}\text{C}$ values for major thermal discharges

Sample	Date	^{14}C (pmC)	$\delta^{13}\text{C}$ (‰ PDB)
Hot springs			
Meager Creek main vent*	Feb./78	5.6	-5.2
Pebble Creek main vent*	Feb./78	0.24	-4.6
No Good vent #2	Aug./79	19.8	-8.4
Drill holes			
EMR-1*	Feb./78	4.6	-7.0
74-H-1*	Feb./78	0.19	-5.3

*Michel and Fritz (1978).

for the CO_2 gas phase in equilibrium with the water sample (Deines *et al.* 1974).

The results of these calculations are tabulated in Table 1 and are graphically represented in Fig. 4 where calculated $\delta^{13}\text{C}$ values of the carbon dioxide are compared with discharge temperatures. The inset in this figure shows the various sources that can contribute to the carbon pool of a groundwater. It is noteworthy that little or no difference in ^{13}C content exists between atmospheric CO_2 (which has, however, a ^{14}C activity equivalent of ≈ 100 pmC) and mantle-derived CO_2 (which is free of ^{14}C).

The values of $\delta^{13}\text{C}$ for $\text{CO}_2(\text{g})$ calculated for the

Meager Creek Hot Springs and thermal borehole waters vary between -7.4 and -9.9 ‰ (Table 1; Fig. 4), which is very close to the range of volcanogenic CO_2 (Barnes *et al.* 1978). This could indicate that they have equilibrated at some time with this source of carbon dioxide. Any component of modern biogenic or atmospheric CO_2 that may exist in the recharging water would be masked by this source of "dead" CO_2 . The cold springs at Mount Meager have much lower $\delta^{13}\text{C}$ values and thus experienced quite a different carbonate evolution. They show little influence of volcanic carbon dioxide and are dominated by biogenic or soil CO_2 and possibly some carbonate dissolution. This explains the scatter of $\delta^{13}\text{C}$ of DIC values for the cold springs and the generally high pH's and low $p\text{CO}_2$ values. Multiple CO_2 sources are recognized for the warm springs (No Good Warm Springs 1 and 2, Table 1; Fig. 5) on the basis of their carbon isotopic compositions, which are intermediate between those of the volcanogenic carbon dioxide and soil CO_2 .

Partial pressure of CO_2 in equilibrium with the water, calculated following procedures outlined by Deines *et al.* (1974), can be used to substantiate this interpretation. Atmospheric CO_2 concentration is very low ($p\text{CO}_2 = 10^{-3.5}$ atm) whereas biogenic CO_2 in soil horizons has higher partial pressures ($p\text{CO}_2 = 10^{-1}$ to $10^{-2.5}$ atm) due to oxidation of organic matter by

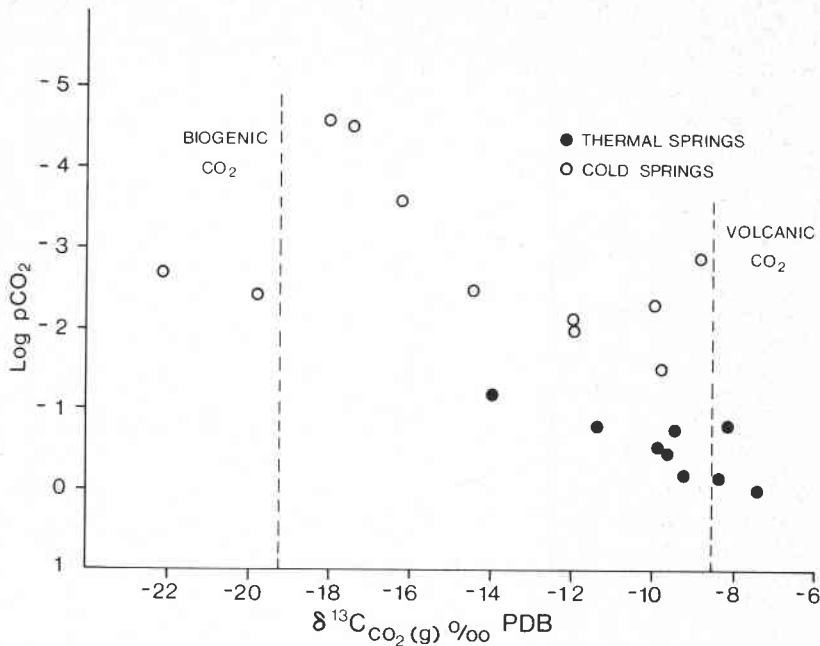


FIG. 5. Relationship between the calculated $p\text{CO}_2$ and the $\delta^{13}\text{C}$ of the CO_2 is shown for all groundwaters sampled. Demonstrated are the relative contributions of biogenic and volcanogenic carbon dioxide to the different spring waters.

micro-organisms and root respiration. Volcanogenic CO_2 , however, can constitute up to 95% of a geothermal gas (Ferrara *et al.* 1963). Figure 5 demonstrates that the hot spring samples tend to have high concentrations of $\text{CO}_2(\text{g})$, reflecting a dominantly volcanogenic source, whereas cold springs have much lower CO_2 partial pressures.

Geothermometry

In the exploration for geothermal resources, the only direct method of determining subsurface temperatures is through downhole measurements. However, to get estimates of subsurface temperatures without the commitment that drilling involves, attempts have been made in the past two decades to develop a series of chemical and isotopic geothermometers requiring only laboratory analysis of geothermal fluids or gases (Fournier and Rowe 1966; Fournier and Truesdell 1973; McKenzie and Truesdell 1976; D'Amore and Panichi 1980).

Fundamental to the application of most geothermometers is an assumption that the thermal waters have experienced little or no mixing with other waters of a different chemical or isotopic nature. Isotope data provide evidence that both the Meager Creek and Pebble Creek thermal waters have experienced some mixing. However, the chemical load of the thermal waters is much higher than the load carried by cold spring waters (Table 1). Therefore, minor mixing with shallow groundwaters of low major ion concentrations should

not significantly affect temperature estimates for major hot springs and boreholes.

The Na-K-Ca geothermometer

Fournier and Truesdell (1973) published a semi-empirical relationship between the concentration ratios of Na^+ , K^+ , and Ca^{2+} in the geothermal fluids and the geothermal reservoir temperature, considering these ions to participate in equilibrium alterations of alkali minerals in the host rock. Furthermore, Fournier and Potter (1979) suggested that magnesium also plays an important role in these alteration reactions and must be taken into account. They presented appropriate correction procedures for data obtained with the Na-Ca-K geothermometer.

This approach was applied to chemical data obtained in this study (Table 1) and yielded a range of subsurface temperatures for the Meager Creek thermal waters of 77–99°C and for the Pebble Creek thermal waters of about 105°C (Table 4).

Silica geothermometer

The increased solubility of quartz and its related polymorphs at elevated temperatures has been well documented (Kennedy 1950; Kitahara 1960; Morey *et al.* 1962; Fournier and Rowe 1962; Fig. 6). In geothermal systems this relationship can be used to estimate subsurface temperatures, provided the concentrations of silica in solution at the discharge point are due only to an

TABLE 4. Compilation of geothermometer temperature estimates

Sample	Measured discharge temp. (°C)	$\delta^{18}\text{O}_{\text{SO}_4}$ (‰ SMOW)	$\text{SO}_4\text{--H}_2\text{O}$ $\delta^{34}\text{S}_{\text{SO}_4}$ (‰ CDT)	T (°C)	Mg-Na- K-Ca (°C)	$\text{H}_2\text{O-}$ CaCO_3 (°C)	CO- CaCO_3 (°C)	Silica	
								Chalc. (°C)	Qtz. (°C)
Hot springs									
Meager Creek main vent vent #19	50.1	+2.1	+7.2	98	77	—	—	147	164
	49.8	*	+9.1	*	82	—	—	136	156
Placid	45.1	—	—	—	94	—	—	134	153
No Good	38.8	-0.3	+7.4	121	96	—	—	126	148
vent #1	29.5	-1.0	+6.5	116	99	—	—	111	137
vent #2	59.8	-5.3	+13.7	136	105	48	79	95	124
Pebble Creek main vent vent #7	56.5	-5.3	+14.3	135	104	—	—	87	118
Drill holes									
EMR-1	58.5	+3.7	+7.1	87	64	—	—	142	160
74-H-1	50.5	+6.3	+9.1	73	40	—	—	113	138
75-H-1	10.1	—	—	—	46	—	—	18	40
79-H-1†	28	*	—	*	85	—	—	37	74
	45	—	—	—	—	40	82	—	—
	53	—	—	—	—	20	111	—	—
	75	—	—	—	—	41	118	—	—
	92	—	—	—	—	86	67	—	—
	102	—	—	—	—	40	123	—	—
	128	—	—	—	—	95	70	—	—
	132	—	—	—	—	36	98	—	—
	131	—	—	—	—	45	136	—	—

NOTE: Dash indicates geothermometer not applied.

*Inconsistent results.

†Sample from 60-68 m = artesian water; all other samples for 79-H-1 are fracture calcites.

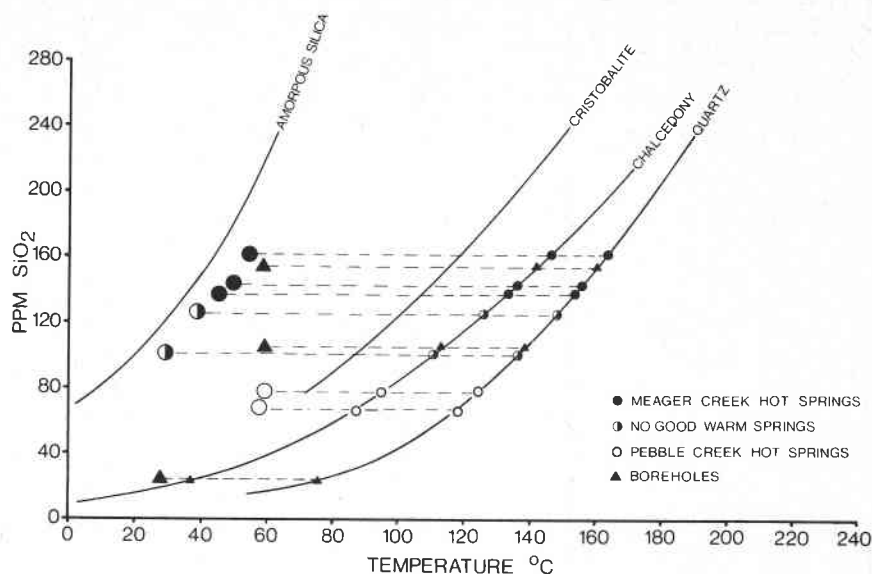


FIG. 6. Solubility of quartz and its polymorphs from 0–200°C. Large symbols denote discharge temperatures; small symbols denote geothermometer estimates assuming equilibrium with chalcedony or quartz. Solubility data: amorphous silica (Kitahara 1960); cristobalite (Fournier and Rowe 1962); chalcedony (Fournier and Rowe 1966); quartz (Morey *et al.* 1962; Kennedy 1950).

equilibrium between the water and quartz or chalcedony reservoir temperatures.

The Meager Creek and Pebble Creek thermal waters have relatively high concentrations of silica in solution, which render somewhat more optimistic temperature estimates than do the other geothermometers. It is interesting to note, however, that the waters discharging from the Meager Creek, Placid, and No Good thermal springs and the EMR-1 and 74-H-1 drill holes are all near saturation with respect to amorphous silica (Fig. 6), which is being deposited at the discharge points in all cases. The close correlation between the silica contents of these discharges and the solubility line of amorphous silica suggests that these waters are in equilibrium with an amorphous silica phase in the near-surface environment rather than with quartz or chalcedony at depth. In such a case, the temperature estimates do not reflect subsurface temperatures and cannot be valid.

However, silica concentrations in the Pebble Creek thermal waters are considerably lower than expected for amorphous silica equilibrium (Table 1; Fig. 6), implying equilibrium with chalcedony or quartz at depth, and thus these calculated silica temperatures may be valid. They agree well with other estimates that indicate that temperatures in the Pebble Creek system are between about 100 and 135°C.

The sulphate–water geothermometer

The distribution of ^{18}O between dissolved sulphate and water is temperature dependent (Lloyd 1968;

Mizutani and Rafter 1969; Mizutani 1972) and has been determined experimentally to be governed by the following equation, which is graphically presented in Fig. 7:

$$1000 \ln \alpha_{\text{SO}_4/\text{H}_2\text{O}} = 3.251(10^6/T^2) - 5.1$$

This relationship has been proven to be a reliable geothermometer provided equilibrium between SO_4^{2-} and H_2O has been obtained within the geothermal reservoir. McKenzie and Truesdell (1976) estimated that it would take 2 years at 300°C and 18 years at 200°C and pH 7 for 99.9% isotopic exchange. One can thus assume that isotopic equilibrium exists between the two phases because tritium data indicate the water ages to be greater than 30 years for the thermal waters. Also, re-equilibration due to cooling during ascent of the geothermal fluids is, therefore, unlikely.

This geothermometer can be sensitive, however, to new inputs of sulphate during ascent of the waters. A survey of the distribution of ^{34}S values in the dissolved sulphate from all major hot springs was attempted in order to establish whether more than one input of sulphate existed. The $\delta^{34}\text{S}$ values for the Meager Creek thermal waters fall within a range of 6.5–9.1‰ and the Pebble Creek thermal waters fall within a range of 13.7–14.3‰ (Table 4). The 6‰ difference between these two ranges indicates quite different sulphur geochemistry in the reservoirs. However, the narrow range of values for each thermal pool (± 1.5 and ± 0.5 ‰ for Meager and Pebble Creek thermal waters, respectively)

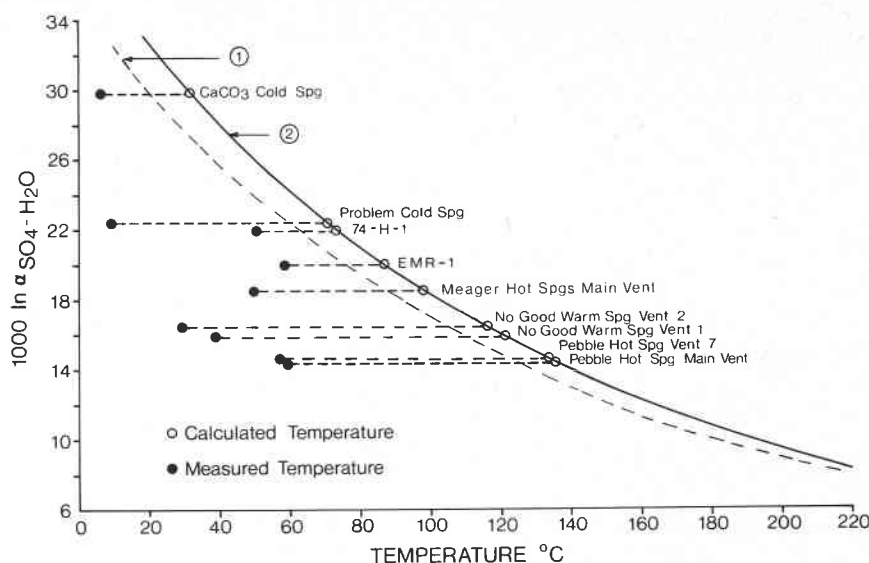


FIG. 7. ^{18}O fractionation between sulphate and water. Measured temperatures are for point discharges; calculated temperatures are estimates of subsurface equilibria. Line 1 is based on data by Mizutani and Rafter (1969); line 2 refers to the equation given by Lloyd (1968).

represents a significant degree of consistency, which almost certainly implies that no sulphate sources were available during ascent of the thermal fluids. Precipitation of gypsum and other sulphates from solution would have no measurable effects unless most of the aqueous sulphate were removed. Furthermore, chemical data show that these waters are strongly undersaturated with respect to gypsum (Clark 1980) and, therefore, only the dissolution of earlier gypsum could alter the sulphate content of these waters. Remobilization of such sulphate could influence the temperature estimates to some degree but without specific data it is not possible to state whether they would increase or decrease.

The sulphate–water fractionation factors were determined from ^{18}O measurements on sulphate and water and have been plotted on the fractionation curve in Fig. 7 to determine the temperature of equilibration for each sample. Measured water temperatures and calculated reservoir temperatures are compared, showing the calculated temperatures to exceed the measured temperatures, indicating cooling during ascent. The calculated values indicate that the temperatures that exist at the depths reached by flow systems analyzed in this study are unlikely to be in excess of 140°C .

The calcite–water geothermometer

Fractures in drill cores are commonly coated with calcite. If this calcite is in isotopic equilibrium with the water, the temperature-dependent ^{18}O fractionation between the two can, under favourable circumstances, be used to substantiate the temperatures derived from other geothermometers. However, the oxygen exchange

between water and calcite takes place between an aqueous and a solid phase and, as a consequence, the calculated temperatures will reflect equilibrium at the sampling point and not in the reservoir.

Furthermore, it assumes that the isotopic composition of the water is known. For “old” calcites, such as collected from fractures in boreholes, the $\delta^{18}\text{O}$ value of the precipitating groundwaters may differ from present ones and, therefore, these temperatures may be rather unreliable.

The experimentally derived equation defining the equilibrium exchange reaction is graphically shown in Fig. 8 and given by O’Neil *et al.* (1969) as:

$$1000 \ln \alpha_{\text{calcite-water}} = 2.78(10^6/T^2) - 3.39$$

Samples of calcite from Mount Meager include sinter deposits from both hot and cold springs and calcite crystals taken from fractures in drill core. Their ^{18}O and ^{13}C contents are summarized in Table 5. Calculated and measured temperatures are shown in Fig. 8.

Measured temperatures for drill hole 79-H-1 were actual rock temperatures encountered during drilling and the waters used for the calculations were from an artesian zone at 60–68 m depth. The samples from depths of 185.5 and 262.5 m were euhedral crystals up to 0.5 cm in size, reflecting a hydrothermal precipitation for which calculated temperatures are in good agreement with the Mg–Na–K–Ca geothermometer. The remaining drill-hole samples were generally aphanitic calcite with associated quartz and clay, possibly related to past events rather than representing recent hydrothermal

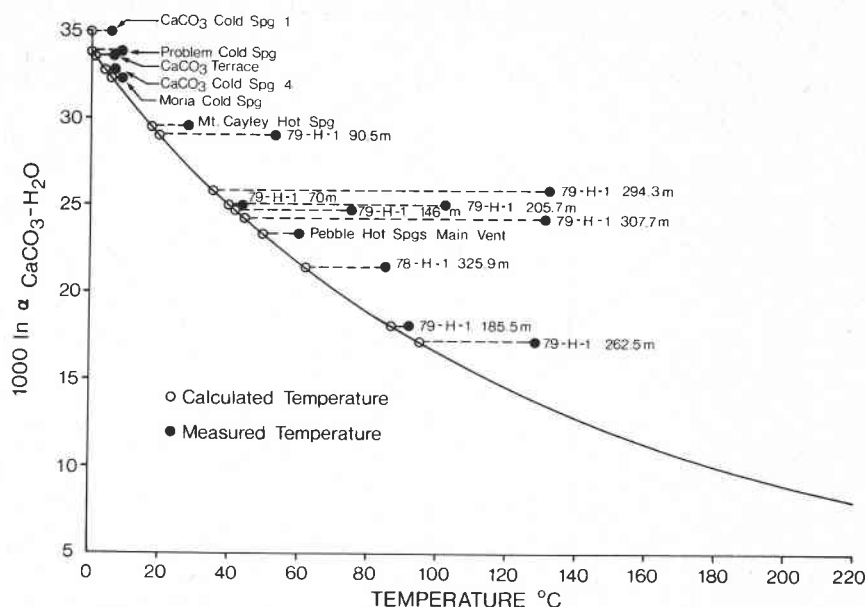


FIG. 8. ^{18}O fractionation in the calcite–water system (O'Neil *et al.* 1969). Measured temperatures for borehole 79-H-1 samples are temperatures encountered during drilling.

TABLE 5. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ composition of calcite precipitates at spring vents and in drill core

Sample	$\delta^{13}\text{C}$ (‰ PDB)	$\delta^{18}\text{O}$ (‰ SMOW)
Hot springs		
Pebble Creek main vent	-3.4	3.6
Cold springs		
Boundary Creek #4	-8.2	7.0
CaCO ₃ #1	+2.3	17.5
#4	-1.1	15.4
Terrace	-0.3	15.9
Moria #1	-3.5	14.7
Rivendell #2	-3.2	14.9
Problem #1	-0.5	16.1
Drill core		
79-H-1		
70	-5.8	8.2
90.5	-8.0	12.3
146	-8.0	7.9
185.5	-4.2	1.2
205.7	-8.2	8.3
262.5	-4.9	0.4
294.3	-6.9	9.0
307.7	-8.9	7.4
78-H-1		
325.9	-6.2	3.0

seems to be the case as indicated by the discrepancy between their measured and calculated temperatures.

The carbon dioxide – calcite geothermometer

This geothermometer is based upon the temperature dependence of the ^{13}C fractionation in the exchange reaction between $\text{CO}_2(\text{g})$ and CaCO_3 . It is presented here to substantiate the temperatures derived from the sulphate–water geothermometer and is possibly more reliable than the $\text{H}_2\text{O} - \text{CaCO}_3$ geothermometer because the carbon source was probably not subject to changes in isotopic composition as would be expected for the water in the system. However, calculated temperatures again reflect the location of equilibration with calcite and not the locus of sampling.

The equilibrium exchange reaction equation has been determined experimentally (Bottinga 1968) to be:

$$1000 \ln \alpha_{\text{CO}_2-\text{CaCO}_3} = 2.9880(10^6/T^2) + 7.6663(10^3/T) - 2.4612$$

The results of these calculations are presented in Fig. 9, and are based on $\delta^{13}\text{C}$ of CO_2 values listed in Table 1 and the calcite data of Table 5.

The calculated temperatures for the hot springs and calcite precipitates in drill hole 79-H-1 demonstrate that, in most cases, ^{13}C equilibrium between $\text{CO}_2(\text{g})$ and CaCO_3 does not exist at the measured temperatures but may reflect conditions deeper in the system. However, an error may also be introduced by assuming that $\text{CO}_2(\text{g})$ of a single isotopic composition ($\delta^{13}\text{C}$ of $\text{CO}_2 = -9.2\text{‰}$ PDB; Table 1) has equilibrated with all the precipitated

deposits. If they were not in contact with circulating hydrothermal fluids and they could not equilibrate with them, their temperatures would not necessarily be expected to reflect an equilibrium precipitation. Such

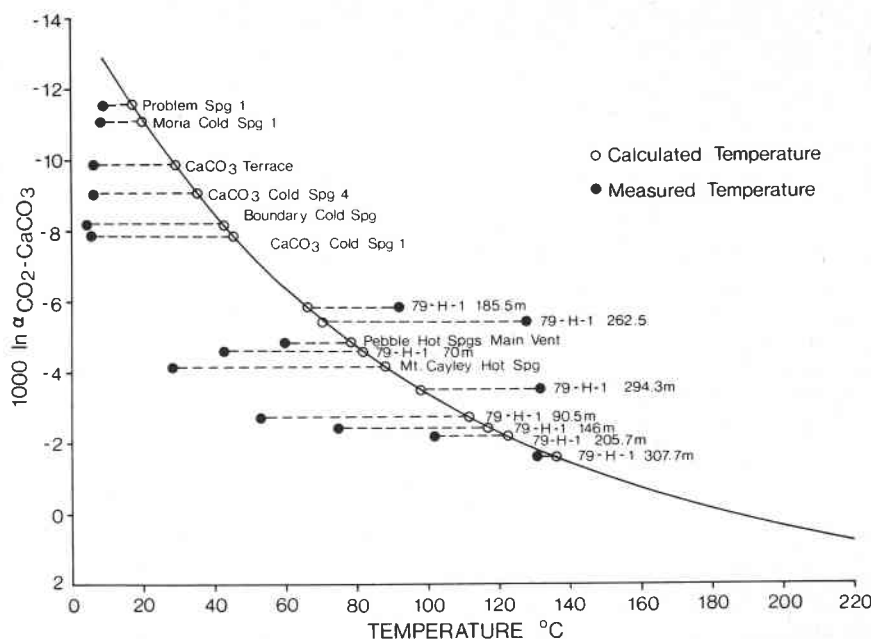


FIG. 9. ^{13}C fractionation in the calcite – carbon dioxide system (Bottinga 1969). Measured temperatures for borehole 79-H-1 samples represent temperatures encountered during drilling.

calcite minerals sampled. Mixing between aqueous carbonates from different sources before discharge would also invalidate this geothermometer. Nonetheless, the data from the bottom of borehole 79-H-1 show good agreement and there are again no indications that temperatures in excess of 140° exist in the systems sampled to data.

Summary and conclusions

Chemical and environmental isotope data indicate that the Meager Creek and the Pebble Creek thermal waters discharge from different geothermal systems. The Meager Creek thermal waters, corrected for a positive shift in ^{18}O contents, have an isotopic composition similar to the average annual precipitation above 1200 m elevation on Mount Meager. The Pebble Creek thermal waters, also corrected for a positive ^{18}O shift, are considerably more depleted in ^{18}O and ^2H than the Meager Creek thermal waters, reflecting a different recharge zone at higher elevations, not on the Mount Meager complex.

The majority of cold springs at Mount Meager discharge from seasonally variable, shallow flow systems and show a correlation between altitude and lighter isotope contents. The lower altitude cold springs, including the CaCO_3 and Problem Cold Springs, are unique in that they show no seasonal variation and hence discharge flow systems of sufficient circulation time to ensure mixing of seasonally varying meteoric waters. They discharge below 1200 m elevation, so the ^{18}O and

^2H contents of these waters must represent the average annual precipitation falling above this altitude. Their isotopic composition is identical to the corrected composition of the Meager Creek Hot Springs, implying recharge in similar environments.

Most cold groundwaters collected for this study contain measurable amounts of tritium, which shows that a large proportion of these waters is less than about 20 years old.

Tritium contents in the thermal waters are considered to be due to the small degree of mixing with shallow groundwaters and hence the thermal waters are thought to be tritium free. Their age would thus exceed approximately 30 years. ^{14}C activities in the thermal waters are very low and not related to the "age" of these waters but to the admixture of volcanogenic, ^{14}C -free carbon dioxide. A survey of $p\text{CO}_2$'s for thermal waters and $\delta^{13}\text{C}$ values for dissolved bicarbonate and calcite precipitates also demonstrates the dominance of volcanogenic CO_2 in these waters over other carbon sources.

The Mount Meager thermal waters have experienced ^{18}O shifts of between +0.5 and +2.5‰. These shifts are less than those found at many commercial geothermal fields, indicating shorter residence times and (or) lower subsurface temperatures in the systems sampled.

Reservoir temperature estimates from the geochemical and isotopic geothermometers consistently indicate that the known Meager Creek and Pebble Creek thermal waters have experienced only moderate heating. Offering the most confidence in their estimates are the

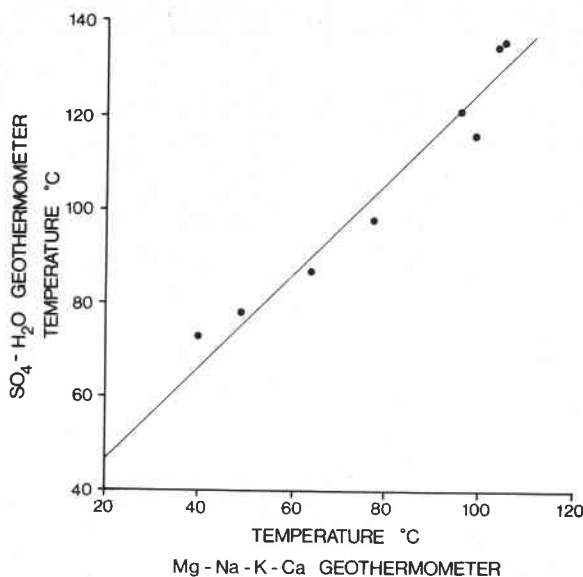


FIG. 10. Correlation between the sulphate-water and Mg-Na-K-Ca geothermometers. The line has a slope of one and intercepts the y-axis at about 25°C.

Mg-Na-K-Ca and the $\text{SO}_4\text{-H}_2\text{O}$ geothermometers. An excellent correlation exists between the estimates obtained with these geothermometers (Fig. 10), although the $\text{SO}_4\text{-H}_2\text{O}$ estimates are consistently 20–30° higher than the Mg-Na-K-Ca estimates. The reason for this discrepancy is not known, but slightly better results would have been obtained if an equation developed by Mitzutani and Rafter (1969) had been used. This was not done because their experimental range did not reach the low temperatures considered here. Maximum temperatures in the system sampled would be 140°C. This is further supported by the $\text{H}_2\text{O-CaCO}_3$ and $\text{CO}_2\text{-CaCO}_3$ geothermometers, which gave an estimated maximum temperature for the deepest sample in drill-hole 79-H-1 of approximately 140°C. This is roughly correlative with downhole temperatures measured during drilling. Other calcites from higher intervals gave similar or lower temperature estimates, reflecting either the lack of isotopic equilibrium with the water sampled, or variable temperature regimes, or both. All chemical and isotopic geothermometers consistently indicate that neither the Meager Creek nor Pebble Creek thermal waters sampled for this study have encountered rocks with temperatures in excess of 140°C.

Isotopic and chemical evidence further indicates that the Meager Creek and Pebble Creek thermal waters are part of separate, shallow circulating geothermal systems. However, these data do not deny the possible existence of deeper flow systems that have no surface expression in this region and that could not be sampled for this study. They also do not preclude the possibility

that a more significant heat source exists at greater depths beneath Mount Meager. Discharging gases of an apparent volcanic origin may be related to such a heat source.

Recently, a newly drilled geothermal well has encountered temperatures close to 250°C at an approximate depth of 2400 m (Geothermal Resources Council 1981). This indicates that indeed a significant heat source may exist, which would support the conclusion that the chemistries and isotopic compositions of the springs sampled for this study do not reflect the resource potential at Mount Meager.

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