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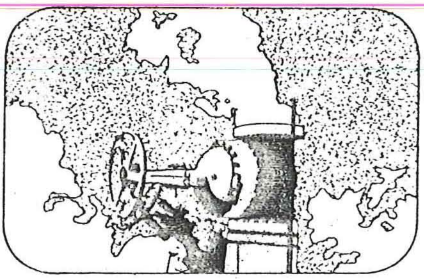

Geothermal Power, The Canadian Potential

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Summary

The technology to produce electricity from the natural heat of the earth was developed more than 70 years ago yet today total world production is less than 1500 Megawatts. Slow growth of geothermal electric generating capacity can be attributed partly to the former abundance of low-cost fossil fuel and, more recently, to the disproportionate allocation of funds to nuclear research.

Most of the earth's heat is too diffuse ever to be recovered by man. Only those rare thermal anomalies where high temperatures prevail within reach of drilling can be exploited for power production. Techniques for locating hidden geothermal reservoirs are only now being developed and there is an urgent need for new wells to test the validity of existing geological concepts and prospecting methods.

In 1972 the Department of Energy, Mines and Resources began an investigation of the geothermal resource potential of western Canada. Initial work included: 1) expansion of the regional heat flow program; 2) compilation of data on the distribution, age and petrochemistry of Quaternary volcanoes; 3) systematic sampling and chemical analysis of water from all known thermal springs.

Integration of this new data with existing geological and geophysical information on the crustal structure of the Canadian Cordillera indicates five broad thermal anomalies extending through west-central British Columbia and southern Yukon. They correspond to well-defined belts of Quaternary volcanoes including more than 100 post-glacial eruptive centres. Within these broad thermal zones specific targets based on local heat flow anomalies and spring water geochemistry are closely associated with those volcanic centres that have produced rhyolite or dacite domes and pumice. One of these (Meager Mountain) was selected for more detailed study, including the drilling of two 50m holes in 1974. Subsequently, this target was chosen as the focus of a more detailed geothermal resource evaluation commissioned by the British Columbia Hydro and Power Authority.

Introduction

Utilization of geothermal energy for generating electricity is not a new concept. The first turbines to use natural steam were put into operation in Larderello, Italy in 1904 and the field is still producing. Today more than a dozen nations have operating geothermal electric plants and world production is nearly 1500 Megawatts. The largest development, at the Geysers in Northern California, has an installed capacity of 550 Megawatts, enough to supply the total needs of San Francisco.

The spectacular success of geothermal power developments in the United States, Italy, Japan, New Zealand, Mexico and Iceland has placed it among the elite group of "alternate energy" sources that are expected to augment and eventually replace our diminishing reserves of fossil fuel. The appeal of geothermal energy lies in its apparent simplicity. Unlike nuclear reactors it does not require the development of a new and sophisticated technology and unlike coal-fired thermal plants and hydroelectric dams it presents little risk of environmental damage. Unfortunately, finding and harnessing geothermal power involves much more than drilling blindly into the earth.

The natural heat of the earth is produced by the decay of radioactive elements in the crust and mantle and, like these rare elements, most geothermal heat is too diffuse to ever be recovered and used by man. Over most of the earth the temperature increases only a few degrees centigrade per kilometre of depth but locally, where hot or molten rock has risen into the upper crust as plutons or breached the surface in volcanic eruptions the thermal gradient may be many times higher than normal. Only these rare "hot spots" where anomalously high temperatures exist at shallow enough depths to be reached by drilling can be classified as potential energy resources. But high temperature and shallow depth are only two of several criteria that must be met before heat can be extracted in commercial quantities. The reservoir rock must be permeable enough to allow adequate circulation of fluid and the fluid itself must be relatively free of corrosive salts.

Five types of geothermal reservoirs are commonly recognized: 1) molten rock, 2) hot dry rock, 3) dry steam, 4) hot water, 5) geopressured brine.

The feasibility of extracting energy from molten lava is in a very early stage of investigation. Similarly, the hot dry rock concept which involves the artificial fracturing of hot impermeable rock followed by injection of water to produce steam has yet to be demonstrated experimentally. The power potential of geopressured brines such as those of the Gulf Coast of the U.S. is enormous but development has so far been curtailed by failure to produce a conversion machine capable of withstanding the highly corrosive brines.

Only two types of reservoirs, dry steam and hot water have been brought into commercial production. Dry steam fields, as the name implies, produce superheated steam that can be fed directly into conventional turbines. Such fields (Larderello, Italy; Geysers, U.S.; and Matsukawa, Japan) are relatively efficient and the volume of condensate from the turbines is small enough to be reinjected thus minimizing environmental damage.

In hot water fields (Wairakei, N.Z.; Cerro Prieto, Mexico; Namafjall, Iceland) the pore fluid is water at a temperature below its boiling point at the hydrostatic pressure prevailing in the reservoir. When such water is brought to the surface in a well, part of it flashes to steam and the temperature of the water-steam mixture drops accordingly. The steam is separated and put through low pressure turbines. The hot water is usually discarded and may pose a disposal problem, not only because of the large amount of waste heat but also because of dissolved toxic salts.

Unlike petroleum reservoirs, which may persist in the earth for several geological epochs, geothermal reservoirs have a relatively short "shelf life". As soon as a thermal anomaly is introduced into the upper crust of the earth the heat begins to seep away to the surface along temporarily high thermal gradients. Thus the geological record abounds with "fossil geothermal systems" that long ago lost their heat. Active systems are rare and transient phenomena confined almost entirely to regions of late Tertiary and Quaternary tectonism.

Potential for geothermal power development in Canada is confined to the Cordillera. The shield and stable platform of the continental interior have uniformly low thermal gradients and no evidence of young tectonic or igneous activity. Similarly the Appalachian orogenic region of eastern Canada is geologically old, with no record of igneous activity younger than lower Cretaceous (±110 m.y.). In contrast, the Cordillera of British Columbia, Yukon and western Alberta is part of the seismically active Circumpacific orogenic belt in which young volcanoes, hot springs and zones of high heat flow attest to recent tectonic activity and local concentrations of heat in the earth's crust. It is tempting to equate the Canadian segment of the Pacific margin with that of the United States, Mexico or Japan, where geothermal power has been successfully developed, but there are important geological differences that make it impossible to project the geothermal resource potential from one segment of the Pacific margin to another. In assessing this potential the tectonic events of the last 10 to 15 m.y. are of greatest importance and it was during this time, from mid-Miocene to Holocene, that the tectonic setting of western Canada differed markedly from other parts of the Pacific margin.

Tectonic Setting

The distribution of earthquake epicentres in western Canada can be used to infer the present position and sense of movement between the continental margin and adjacent Pacific crust. The linear belt of epicentres extending northwest from the north end of Vancouver Island (Fig. 1) mark the trace of the Queen Charlotte transform fault (Wilson, 1965). Offsets on the Fairweather Fault, an extension of the Queen Charlotte Fault into Alaska, indicate right lateral displacements of as much as 150 miles since mid-Eocene time and strike slip movement of up to 21.5 feet during a single event on July 10, 1958 (Plafker, 1972). Where the coastline of North America turns west into the curving arc of the Alaska Peninsula the northwesterly moving Pacific crust again impinges on the continental margin and moves down a subduction zone beneath central Alaska and the Aleutian arc. The present dynamic relationship between western Canada and the adjacent Pacific crust does not appear to have changed significantly during the last 10 to 15 m.y.

Volcanicity

Volcanic activity in western Canada during the past 15 million years has been localized along five distinct linear belts (Fig. 1) that appear to be related to plate boundaries. The N-NW trending Pemberton volcanic belt of southern British Columbia is a late Miocene volcanic front related to an early stage of spreading from the Juan de Fuca – Explorer ridge system and subduction of Juan de Fuca plate. Garibaldi volcanic belt is a Quaternary front related to recent spreading from Juan de Fuca ridge. Anahim volcanic belt runs east-west between latitude 52° and 53° north and may be an expression of deep fracture zones along the northern boundary of the downgoing Juan de Fuca plate. The north-south trending Stikine volcanic belt of northern British Columbia is associated with rift structures that are believed to have opened in response to right lateral shear between the continent and Pacific crust (Souther, 1970). Wrangell volcanic belt of southern Alaska and southwestern Yukon lies above the Benioff zone associated with subduction of Pacific crust at the eastern limit of the Aleutian Arc system. The type of Quaternary volcanism in each of these belts differs according to the tectonic setting. Moreover the composition of lavas and style of eruption in each belt appears to have remained uniform not only during the Quaternary but also throughout the late Miocene, suggesting that the present tectonic framework has not undergone major changes during the last 15 million years.

The Pemberton volcanic belt (Fig. 1) is defined by a group of epizonal plutons and two deeply eroded cauldron complexes, Mt. Silverthrone and Franklin Glacier complexes (Ney, 1968) that lie along a NW trending belt extending from near the U.S. border east of Vancouver to King Island on the B.C. coast. Potassium-argon ages on four of these plutons range from 18 to 7.8 m.y. or approximately the same age as the late Miocene Plateau lavas of central British Columbia. The plutons are believed to be subvolcanic bodies associated with a Miocene volcanic front that was active during early stages of subduction of Juan de Fuca plate. With the notable exception of King Island, all the plutons and eruptive rocks are calc-alkaline, mainly granodioritic bodies and dacite ejecta, whereas the coeval plateau lavas are uniformly alkaline basalts, suggesting a paired relationship analogous to an arc, back-arc association.

The Miocene volcanic front is crossed at an acute angle by a line of approximately 32 Quaternary centres that comprise the Garibaldi volcanic belt. The few analyses available plot mainly in the calc-alkaline field of the alkali-silica diagram. Dacite and andesite are the predominant rock types, associated with minor rhyolite and high-alumina basalt. Mt. Garibaldi (Mathews, 1958) is an intraglacial dacite dome that erupted about 10,000 years ago. Other domes in the same belt, including Mt. Cayley and Meager Mountain, exhibit a similar degree of dissection and are considered to be approximately the same age. The youngest activity occurred less than 2.500 years ago from a vent near Meager Mountain. Explosive eruption of dacitic pumice produced a thick welded ash flow in upper Lillooet valley and a plume of air-fall pumice that settled over a wide area of southern British Columbia. The latter, called the Bridge River ash (Nasmith *et al.*, 1967) gives Carbon-14 ages of 2440±140 years B.P.

The Anahim volcanic belt runs approximately east-west along latitude 52°N and includes 37 Quaternary volcanic centres plus a large number of Miocene and Pliocene centres. The Quaternary centres have all produced alkali olivine basalt that forms small pyroclastic cones and thin blocky intravalley flows overlying even the youngest glacial features. Near the centre of the belt, north of Anahim Lake, the post-glacial cones are satellitic to three older, very large shield volcanoes comprising the Ilgachuz, Itcha and Rainbow ranges. The lower flows of each shield appear to be continuous with adjacent Plateau lavas that rest on sediments containing late Miocene or early Pliocene flora (Mathews and Rouse, 1963).

The relatively broad Stikine volcanic belt cuts diagonally across older, northwesterly-trending structures of the northern Coast Mountains and Intermontane Belt. Scattered within it are more than 50 post glacial eruptive centres plus at least as many of late Miocene to late Pliocene age. The lavas, like those of the Anahim belt, are mainly alkaline. Most of the Quaternary centres have been the locus of a single pulse of activity during which one or more small pyroclastic cones were built and a small volume of alkali olivine basalt issued to form thin blocky flows. The youngest dated eruption of this type issued from fissures in the central Coast Crystalline Complex near the southern end of the Stikine belt. The flows, which extend for 15 km along Lava Fork valley, have surrounded and charred trees, the stumps of which still project through the

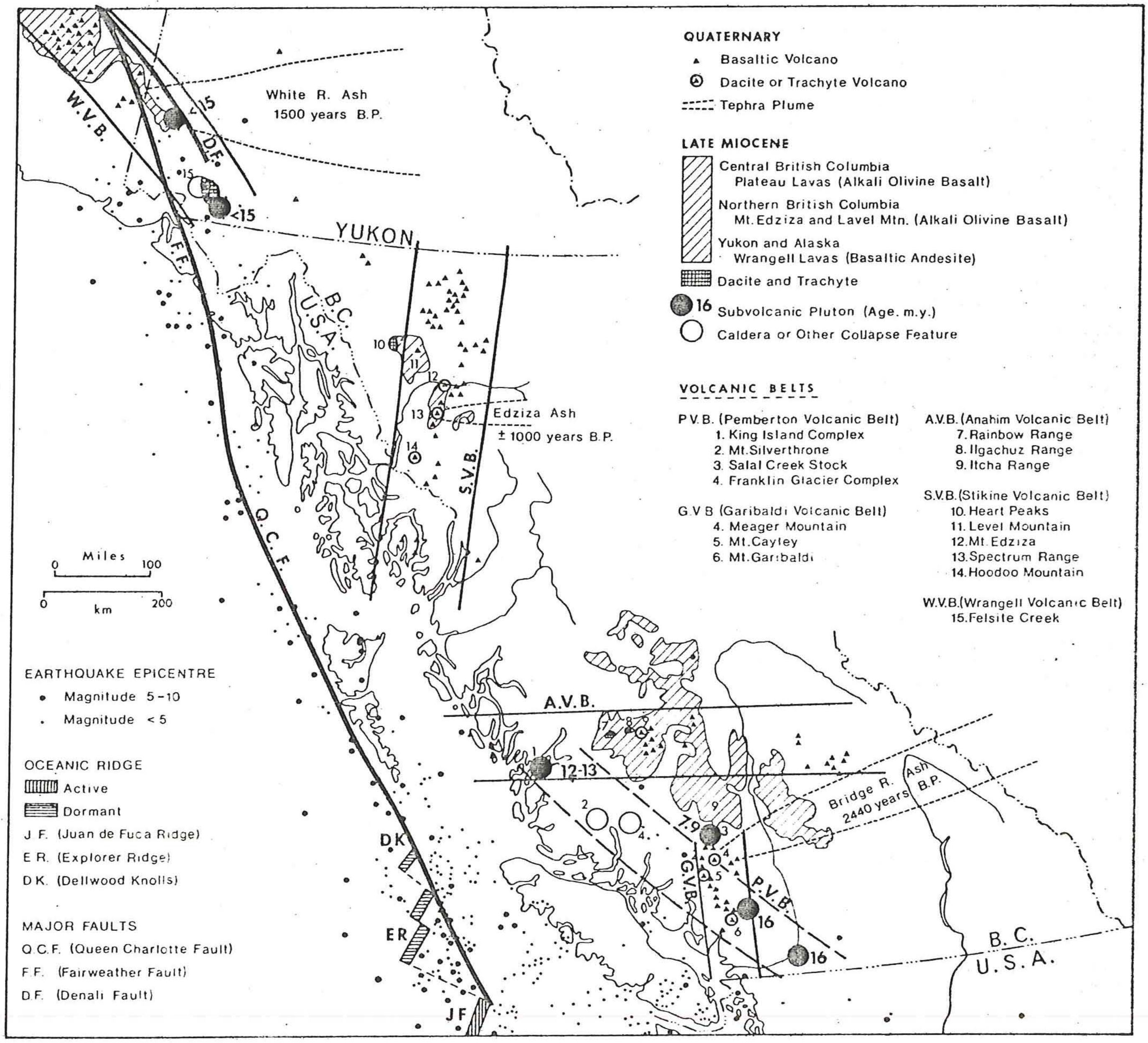

Figure 1
Schematic map showing the distribution of late Tertiary and Quaternary volcanic and plutonic rocks, oceanic ridges, earthquake epicentres and the inferred position of the Queen Charlotte — Fairweather transform fault system.

flow. Carbon-14 ages on these indicate that they were killed by the lava less than 200 years ago (E.W.T. Grove, pers. comm.). The slightly older Aiyansh flow and cinder cone also near the southern end of the Stikine belt, produced a total of 0.45 km^3 of basalt during two closely spaced pulses of activity about 220 years B.P. (Sutherland Brown, 1969). The Mt. Edziza - Spectrum Range complex, near the centre of the belt has a long, nearly continuous record of activity that spans most of post Miocene time. The earliest flows give K/Ar dates of nine m.y. whereas charred wood covered by tephra from satellitic cones gives a Carbon-14 age 1340 years B.P.

Most of the Edziza pile comprises alkali olivine basalt. The basalt, however, is interlayered with a significant volume of sodic rhyolite and peralkaline trachyte that form domes, flows, pumice and subvolcanic intrusions (Souther, 1973). The complex lies across a system of north-south trending normal faults and is bounded on the west by a rift valley that shows evidence of collapse during construction of the adjacent volcanic edifice (Souther, 1970). Level Mountain, 80 km northwest of Mt. Edziza comprises a large Miocene-Pliocene shield of mainly alkali olivine basalt, but small segments of rhyolite flows are exposed in the central part of the shield and large domes and subvolcanic intrusions of rhyolite and trachyte occur on adjacent Heart Peaks.

The Wrangell volcanic (Souther and Stanciu, 1975) belt runs across southwestern Yukon northwesterly into central Alaska. The lavas are predominantly basaltic andesites and andesites of the calc-alkaline rock series and, in Alaska, they range in age from Miocene to Recent. Explosive eruption of pumice from a vent near White River, Alaska (Lerbekmo and Campbell, 1969) produced two lobes of tephra, one of which extends northeast to the Arctic Ocean and the other eastward into Alberta. Tree-ring and Carbon-14 dates have established that the northern lobe is about 1500 years old and the eastern lobe 1200 years B.P. Only two small Quaternary centres are known in the Canadian part of he Wrangell volcanic belt. West of Kluane Lake the Wrangell Lavas comprise more than 5000 feet of flows and minor pyroclastic material. Though mostly flat lying the entire section is locally folded, overthrust by pre-Wrangell basement rocks and intruded by large plutons of porphyritic dacite. South of Kluane Lake, in the Alsek River area similar high-level plutons are associated with a volcanic-tectonic depression occupied by eruptive lava domes and surrounded by a thick apron of explosion breccia and welded ash flows.

Thermal Structure

Data on temperature distribution in the Canadian Cordillera are sparse and confined mainly to southern B.C. Existing heat flow and relevant geophysical data have been compiled and interpreted by Hyndman (1975) who defines a coastal zone 200 km wide of low heat flow separated by a narrow transition zone from a central belt of high heat flow. Steacy (1973), using gravity and seismic data, calculated crustal and mantle densities and depth to the M discontinuity across the southern Cordillera. He concludes that both crust and mantle densities must be relatively low under central B.C. and high beneath the coastal zone. The possibility that the low densities are due to thermal expansion is supported by the electrical properties. Caner (1969) has identified a zone that extends from near the Rocky Mountain Trench westward beneath central B.C. in which the lower crust and uppermost 10 to 25 km of mantle are highly conductive. He attributes this to hydration and high temperature, 750°C at 35 km, and concludes that the combined effect is sufficient to initiate partial melting in the conductive zone.

Hot Springs

Approximately 60 thermal springs are known in western Canada (Souther and Halstead, 1973). None are boiling and there are no associated fumeroles, mud pots or extensive alteration zones such as are commonly found near producing geothermal fields. Spring locations are shown on Figure 2.

On the basis of their geological association and water chemistry the springs have been broadly grouped into three classes (Souther, in press): 1) springs associated with deep flow systems in layered carbonate rocks. 2) springs issuing from fractures in granitic or metamorphic rocks of non-volcanic regions. 3) springs located in or near belts of Quaternary volcanism.

Springs in the Rocky Mountains of eastern B.C. and western Alberta are typical of the first class (Van Everdingen, 1972). They are linked to deep flow systems along intersecting thrust faults or along thrust faults and porous, mainly carbonate, aquifers. Meteoric water entering fractures in topographically-high recharge areas passes through flow systems controlled by geological structure and porosity and eventually discharges as springs at lower elevations. High local relief provides the hydraulic head that drives the system and the water temperature is simply a function of the depth of circulation and cooling rate on return to the surface. The Banff springs, for example, issue from several points along the trace of the Sulphur Mountain thrust fault. They are believed to originate from surface waters that have travelled down a secondary fault that intersects the Sulphur Mountain thrust at about 21,000 feet. At this depth, even in a region of low to moderate thermal gradient, the water will encounter temperatures of about 100°C or 50°C hotter than the hottest of the Banff springs. Springs of this class are dominantly of the calcium sulphate type with less than 50 ppm silica (Fig. 3). They indicate the presence of an unusually deep natural groundwater flow system but they are not indicative of thermal anomalies. In the far north some of these deep flow systems may have limited potential for space heating, but they have no potential for the production of power.

Springs of the second class are related to flow systems through more diverse rock types and this is reflected in the chemistry of their waters. Those issuing from other clastic sedimentary or volcanic terranes are predominantly of the calcium bicarbonate type whereas those issuing from granitic terranes are mostly chloride waters high in alkalis. Both total dissolved solids and silica are intermediate between the class 1 and class 3 springs. All of them are believed to be discharging from flow systems driven by differential hydraulic pressure rather than by thermal convection, however, some of the systems may be encountering relatively high temperatures at shallower depths than those associated with the class 1 springs. Many occur in or near potash-rich Tertiary plutons which have relatively high rates of radiogenic heat

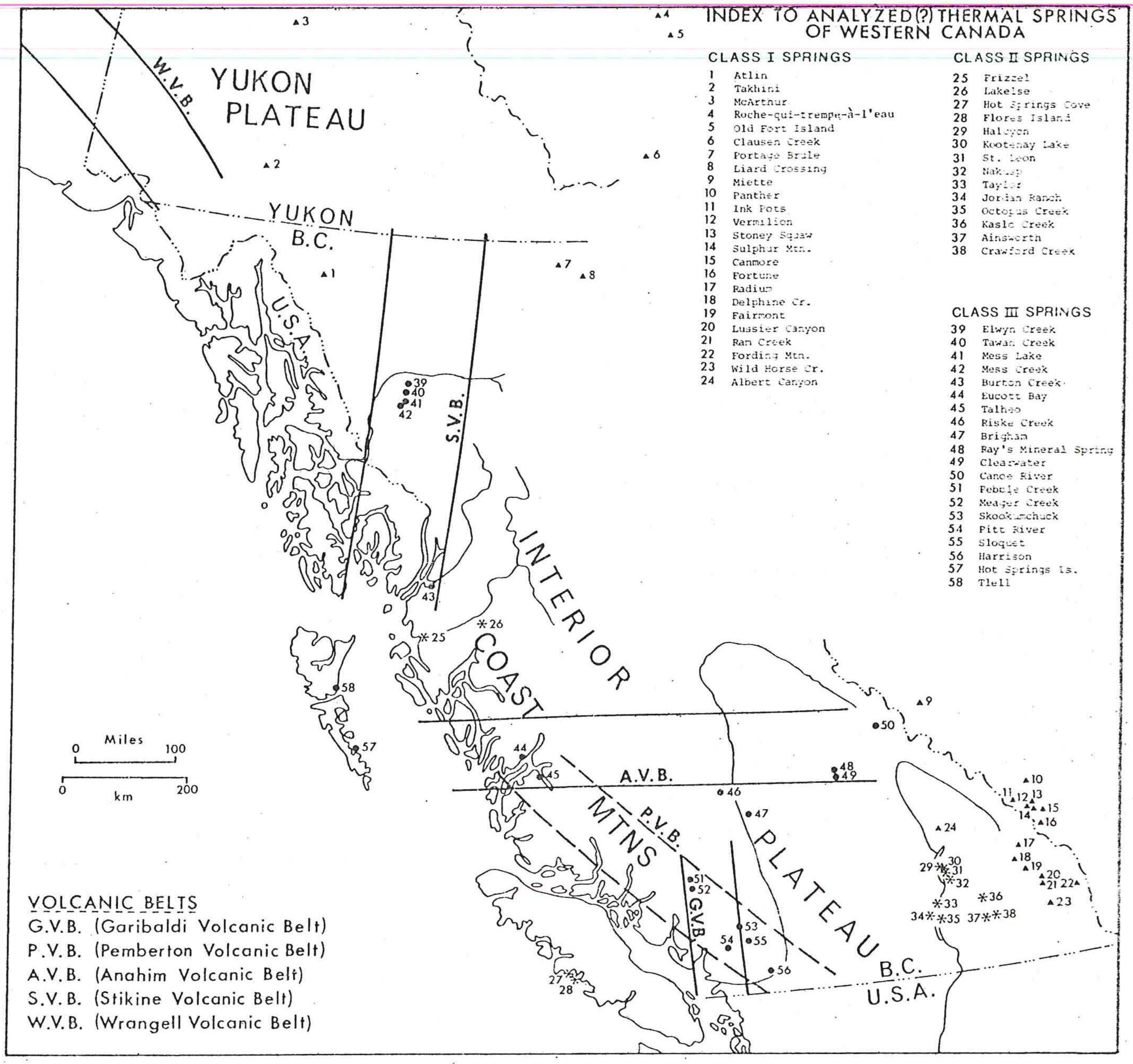

Figure 2

Map showing the distribution of thermal springs and their relationship to late Tertiary and Quaternary volcanic belts of western Canada. Springs listed above are those for which chemical data are available. A few additional springs have been reported in central Yukon and along the coast of B.C.

production (T. Lewis, pers. comm.) and correspondingly high thermal gradients. The springs of south central B.C., for example, are closely associated with Eocene syenite plutons. It is unlikely that any of the systems related to the class 2 springs is hot enough to be regarded as a potential geothermal power source; however, some may be suitable for non-power applications.

Springs of the third class are spatially related to belts of Quaternary igneous activity. Most yield alkaline waters of either bicarbonate or sulphate type with dissolved silica between 80 and 250 ppm. In south-central B.C. six groups of thermal springs lie along the same lineament as high level. Miocene, plutons (Figs. 1 and 2). The hottest of these issue from fractured granodiorite at several points around the periphery of Meager Mountain, a Quaternary dacite volcano from which the 2000-year-old Bridge River ash was erupted. A group of eight thermal springs lie along the east-west Anahim volcanic belt. The hottest in this group and the one with the highest silica content (115 ppm) issues from fractured granodiorite on Bentick Arm, near the 12 million year old. King Island syenite stock. Thermal springs within the north-south Stikine belt of Quaternary volcanoes are clustered around the Mt. Edziza volcanic complex. The waters are of the sodium bicarbonate type with a relatively high silica content (190 ppm). Of all the volcanic centres in the Stikine belt Mt. Edziza and adjacent Spectrum Range have produced the

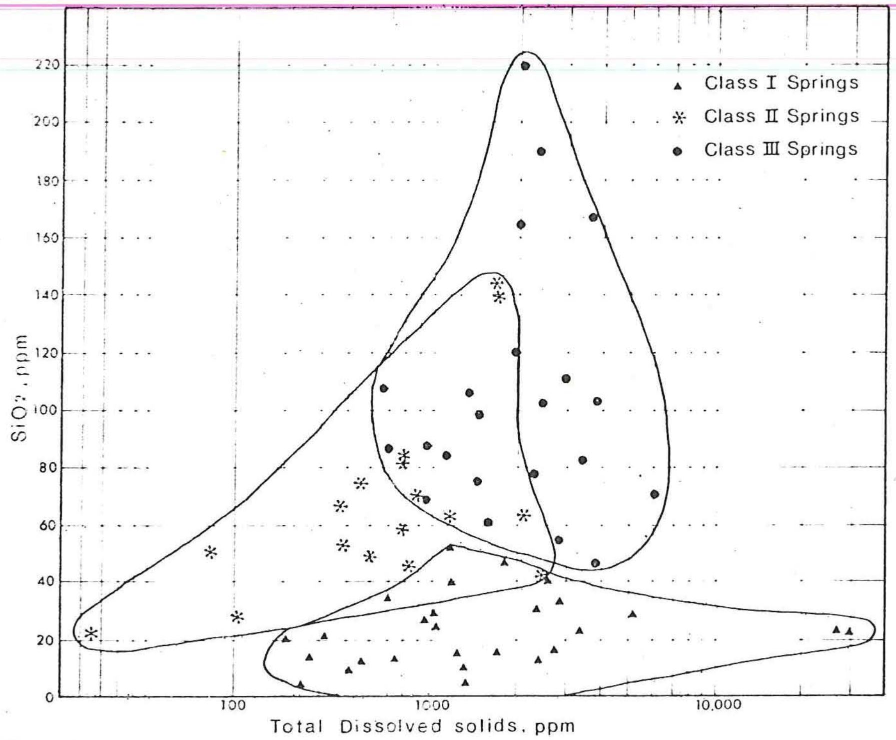

Figure 3
Plot of silica vs. total dissolved solids for 58 thermal springs in western Canada

only significant volume of siliceous lava that might be associated with subvolcanic intrusions.

The chemistry of thermal waters is influenced by temperature dependent reactions between water and rock (White, 1970). In rapidly flowing springs retrograde reactions may be slow enough to prevent re-equilibration of the water as it rises to the surface and cools. Thus spring water may inherit chemical characteristics established in the hottest part of the flow system and these in turn may be used to estimate subsurface temperatures. The amount of dissolved silica varies directly with temperature and provides the simplest means of identifying potential high temperature systems (Fournier and Rowe, 1966). An empirically derived Na-K-Ca geothermometer (Fournier and Truesdell, 1973) is also widely used. It provides not only a rough estimate of temperature, but also a means of discriminating between undiluted thermal waters and those mixed with cold groundwater (Fournier and Truesdell, 1973). Results of applying the silica and N-K-Ca geothermometers to thermal waters from western Canada indicate low or spurious temperatures for most of the class 1 springs and consistantly higher temperatures for the class 3 springs. The two highest temperatures indicated by both geothermometers are given by water from Tawah Creek and Meager Creek. Tawah Creek spring (silica 227°C and Na-K-Ca 177°C) is on the eastern flank of Mt. Edziza near the source of an approximately 1,000 year old plume of rhyolite pumice and Meager Creek spring (silica 228°C and Na-K-Ca 187°C) is on the south flank of Meager Mountain, the volcano from which the Bridge River dacitic pumice was erupted 2,440 years ago.

What next for Canada?

Exploration for geothermal energy in Canada has scarcely begun and any attempt to predict its future must be predicated largely on theoretical inference. The possibility of finding a dry steam field such as Larderello or the Geysers in Canada seems extremely remote. Such fields are invariably associated with surface leakage of steam or boiling water. Even the smallest surface expression of such thermal activity could not have gone unnoticed in the Canadian Cordillera where, for twenty years, an aggressive mineral exploration industry has used helicopters to scout the landscape for gossans.

It seems realistic to hope for the discovery of at least one hot-water field such as Wairakei (New Zealand) capable of supplying enough flash steam to generate electricity. Surface manifestations of such a field may not be very dramatic in the Canadian Cordillera where high relief and heavy precipitation favor deep circulation of cold groundwater and consequent dilution of rising thermal fluids. The most promising areas of search are broadly defined by the four belts of Quaternary volcanoes that extend across British Columbia and south-western Yukon. However, most of the eruptive centres in these belts have produced a single pulse of basaltic magma that must have been generated deep within the mantle. The fluid magma rose rapidly to the surface through relatively narrow conduit systems in which little of the thermal energy was trapped. The scores of isolated pyroclastic cones formed by this type of eruption in British Columbia are probably not associated with thermal reservoirs within the earth's crust. Only those few volcanoes with a record of repeated activity and those which have produced a significant volume of acidic magma have a reasonable chance of being underlain by an accessible thermal reservoir. Some of the centres within the southern Wrangell Belt, Mt. Edziza and Hoodoo Mountain of the Stikine Belt, the Ilgachuz, Itcha and Rainbow Ranges of the Anahim belt and the dacite domes, Mt. Garibaldi, Mt. Cayley and Meager Mountain of the Garibaldi belt could, on this basis, have some potential. Of these Mt. Edziza and Meager Mountain are the most likely targets. Both have erupted showers of acid pumice within the last 2,000 years. It is reasonable to suppose that this volatile-rich ejecta constitutes only a small proportion of the total volume of magma involved in the eruption and that subvolcanic masses of degassed magma or hot rock may be left beneath the volcanic edifice. It is significant that, of all the thermal springs known in western Canada, those near Mt. Edziza and Meager Mountain yield the highest estimates of subsurface temperatures using both the silica and Na-K-Ca geothermometers. Meager Mountain, because of its proximity to the city of Vancouver, is of particular interest and, in 1974 the Department of Energy, Mines and Resources drilled two test holes in the area. Both were abandoned when they encountered a copious artesian flow of 60°C water at less than 200 feet below surface. Further drilling and detailed geophysical investigations were subsequently undertaken by B.C. Hydro and Power Authority.

Development of geothermal power in Canada faces some unique and formidable obstacles. The high cost of geothermal exploration is aggravated by vast areas without roads, where aircraft provide the only means of transportation. Moreover, the regions of Canada with the greatest geothermal potential are also regions with substantial reserves of fossil fuel and hydroelectric power that can be developed without assuming the high capital risk inherent in geothermal drilling. However, the relatively small environmental impact of a geothermal development must be taken into account when considering the alternatives of flooding reservoirs for hydro or stripping coal for thermal plants.

There are few precedents to serve as a guide to geothermal exploration in Canada. We have no obvious surface expressions of thermal reservoirs so our search must be directed toward hidden targets defined only by geological concepts and by geochemical and geophysical anomalies that are believed to be temperature dependent. Reasonable first-order targets have already been identified but their true nature can only be confirmed by drilling. If the Canadian geothermal program is a serious effort to develop geothermal electric power capacity then it must be directed toward the siting and drilling of several deep holes. Any effort that stops short of drilling can do no more than produce another theoretical paper model and until several such models are actually tested there is no justification in using them to assess our potential geothermal resource.

Realization of Canada's modest geothermal potential will be possible only if governments are prepared to support the search either through large scale participation or through the enactment of new legislation that will encourage the investment of private risk capital in geothermal exploration and development programs.

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