Introduction to Interior Alaskan Hot Springs:
slightly modified from Kolker (2008)

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INTRODUCTION

Over 30 hot springs occur in the Central Alaska Hot Springs Belt (CAHSB), a vast low-temperature geothermal regime which is unlike most Alaskan hot springs in that they are not related to an active volcanic center. Given the absence of magma, the most plausible heat source is radiogenic heat from high U, Th plutons.

Geothermal systems have been classified in a variety of ways. Most authors distinguish between "convective" and "conductive/static" types (e.g., Rybach, 1981). Convective type systems are classified either as "magmatic" (related to abnormal heat flow caused by young intrusions <1 Ma, Cathles et al., 1997) or "deep circulation" (resulting from deep circulation of meteoric water along subvertical fault/fracture zones, typically in regions of high heat flow). Static or conductive type systems are characterized by a thermal regime due to conduction alone, either in deep aquifers or sedimentary basins, and usually in a low permeability environment. Convective type hot springs systems also occur in areas of elevated natural radioactivity (e.g., Pocos de Caldas, Brazil; Ramsar, Iran; and Paralana, Australia). Observations of fossil hydrothermal activity in high heat-producing granites (e.g., Durrance, 1985) suggest that such activity could be cyclic and effectively short-lived.

One potential source of confusion in distinguishing among these types is that *all* convective hydrothermal systems (magmatic, deep circulation, or radiogenic) require vertical permeability pathways of closely-spaced fractures and/or faults that enable groundwater to efficiently convect through or around the heat source. However, the faults associated with geothermal systems that have derived their heat solely by deep circulation are typically active, broad-scale (>100 km long surface expression) normal faults in extensional settings. The predominant geological features of the different types of convective hydrothermal systems are given below.

Table IHS 1. Characteristics of geothermal systems derived from various sources.

Hot springs type	**Tectonic Setting**	**Geologic Features**	**Surface expressions and reservoir temperatures**	**TDS (mg/L)**
Radiogenic	Unspecified	High heat producing (HHP) granitoids + fracture/fault permeability	Low (<90 °C) temperature hot springs, estimated reservoir Ts 95-130 °C*	Low (<5000)
Volcanic / Magmatic	subduction zones, rift zones, hot spots	Young (<1 ma) volcanic fields + fracture/fault permeability,	Fumaroles, boiling springs, , reservoir Ts up to 350°C	Medium to High (5,000-15,000)
Deep circulation	Extensional basins, shear zones, and/or broad-scale rift zones	*Active*, large normal faults (>100 km), high regional heat flow (60-100 □ W/m^3), crustal thinning	Moderate- to high-T (90-150 °C) hot springs in topographic lows, reservoir Ts to 260°C	High (>10,000)

Thermal gradient measurements indicate that the regional gradient for the CAHSB province is fairly average; around 30 C/km (Erkan et al., 2007). Nearly all of the hot springs areas of the CAHSB are in or near granitoid plutons of Cretaceous to early Tertiary age. Thermal upwelling in the CAHSB often occurs at pluton-country rock contacts, and many of the hot springs have a linear surface expression, suggesting structural control. However, few significant faults have been identified in the immediate vicinity of any of the hot springs. While intrusive bodies of a variety of types and ages are present along the CAHSB, geothermal activity is restricted to plutons of late Cretaceous and early Tertiary granite and mid-to late Cretaceous syenite. These all contain anomalous concentrations of U and Th. Localized high heat flow in upper crustal area containing radioactive granites could explain the discrepancy between measured thermal gradients and measured heat flow.

CAHSB PLUTONS

The location of hot springs in the CAHSB clearly shows a positive correlation with Cretaceous-age and/or Tertiary-age plutonic rocks (Figure IHS-1). Note that only hot springs-associated plutons are shown on this map. There are many additional plutons that lack hot springs! Thirty out of the 31 CAHSB springs (97%) occur inside or at the margin of a pluton. Of those, 16 hot springs (52%) occur inside or at the center of a pluton, and 14 are located at the margins of the pluton. The one hot spring that does not occur in or at the margins of a pluton is Hutlinana hot springs. This is about 10 km from the nearest known intrusive rocks.

Uranium-Thorium-rich plutonic rocks are a well-established feature of the western CAHSB (Miller, and Bunker, 1975). Kolker et al (2007) suggested that an anomalously radioactive body within a composite pluton at Chena Hot Springs was at least partially responsible for the development of hydrothermal convection at that location. All across the CAHSB, there is evidence for anomalous radioactivity in the vicinity of hot springs related to plutons of Cretaceous to Tertiary age.

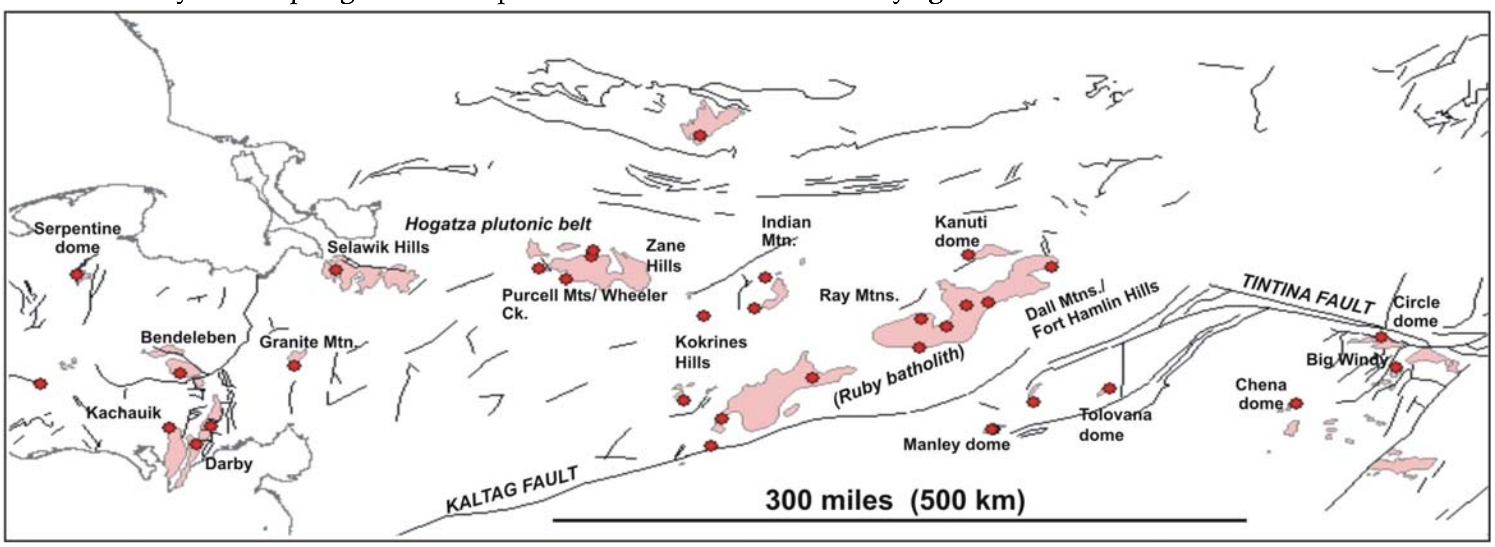

Figure IHS-1. Simplified map of CAHSB region, showing hot springs and plutons, pluton common names, and major faults, adapted from Biekman, 1998. Few of the faults shown are active, and only plutons near hot springs are shown. Modified from Kolker (2008).

Numerous studies between 1951 and 1975 attempted to locate commercial-grade uranium deposits in the CAHSB region, primarily in the U, Th-enriched alkaline plutonic rocks of west-central Alaska . Airborne radiometric surveys found radiometric anomalies associated with CAHSB plutons, especially in the western part of the belt (e.g., Eakins, 1977). Mineralogical and petrological studies confirmed that the Cretaceous-age and/or Tertiary-age plutonic rocks were the source of the U and Th anomalies (e.g., Wallace, 1979). In general, radioactive elements were found to be disseminated throughout CAHSB granitic bodies (Eakins 1977; Wallace, 1979). More recent investigations found U concentrations up to 97 ppm and Th up to 2910 ppm Th in a particular CAHSB pluton (Zane Hills, Solie, 1993)

Interior Alaska experienced three major plutonic episodes: mid-Cretaceous, late Cretaceous, and early Tertiary. In general, the early Tertiary intrusions contain high concentrations of Sn, U, and F (Newberry, 2000), as does the mid-Cretaceous (105–115 ma) Ruby batholith. The Ruby batholith is a northeast-trending body of peraluminous granite, comprised of more than a dozen individual plutons (Barker, 1991). The early Tertiary igneous rocks in Interior Alaska are bimodal: biotite monzogranite and syenogranite, intruded by aphanitic to diabasic-textured basalt dikes or sills.

RADIOACTIVE HEAT PRODUCTION OF GRANITIC ROCKS

The principal primary source of the radioactive elements U, Th and K are felsic igneous rocks. The average U concentration for felsic igneous rocks is 4 ppm; in Thorium it is 18 ppm (Wedepohl, 1969). For comparison, the average U concentration for sedimentary rocks it is 1.3.-3.2 ppm U; for mafic igneous rocks it is 0.8 ppm U (Eakins et al., 1977). Radioactive heat production in granitic rocks comes from the decay of long half-life radioactive isotopes K^{40}, U^{235}, U^{238}, and Th^{232}. Anomalous concentrations of radioactive elements in granites of southwest England were shown to cause high heat production and considerable post-magmatic hydrothermal convection (Fehn, 1985). Durrance (1985) suggested that HHP granites go through a several million year cycle of: heating by radioactive decay with minimal conductive heat loss; inflation due to heating; inflation-induced fracturing; convective groundwater circulation; and finally deflation and cooling due to efficient convective cooling. At least four such cycles are identified by radiometric dating for granites of Cornwall, England (Stone & Exley, 1985). Additionally, heat production in granites may induce fracturing by thermal expansion (Durrance, 1985), providing the vertical permeability required as circulation pathways for convecting fluids.

Anomalously radioactive (high heat-producing) plutonic bodies occur throughout the world. These plutons are typically highly evolved, granite, alkali granite, syenite, pegmatite and (or) related rock types. Many of these regions also have low-temperature thermal areas, but only limited studies have shown the correlation between radioactive granitic bodies and active hydrothermal circulation. Brugger et al. (2005) attributed the heat driving the Paralana hot springs (PHS) system, South Australia, to a zone of anomalously high heat flow attributed to high concentrations of radioactive elements in a nearby plutonic body.

Table IHS 2 gives U and Th data for some Interior Alaskan hot-springs associated plutons and their host rocks. The mean U concentration for CAHSB plutons is 24 ppm, with a range from 5 (Tolovana pluton) to 127 (Purcell Mts. Pluton). The mean Th concentration is 87 ppm, with a range from 22 (Indian Mountain pluton) to 454 (Zane Hills pluton). Heat production (A) can be calculated from radioelement concentration (after Rybach, 1981):

$$A\ (\mu W/m^3) = 10^{-5}\rho\ (9.52cU + 2.56cK + 3.48cTh,$$

where A = heat production, c = radioelement concentration (U and Th in ppm, K in %), and ρ = rock density.

Table IHS 2: U and Th contents and heat production (HP) of some hot spring associated- plutons.

Hot Spring	Pluton	No. samples	Ave U (ppm)	Max U (ppm)	Ave Th (ppm)	Max Th (ppm)	HP (mW/m^3)
Circle	Circle Tertiary	36	16±9	52	50±18	88	8±3
Chena	Chena Tertiary	19	12±3	75	37±10	48	6±1
Tolovana	Tolovana	13	5±2	12	19±5	26	3±1
Manley	Manley	6	9±7	17	65±62	165	9±8
SURROUNDING ROCKS		15	1.3±0.2	1.5	3.5±0.5	4.2	~0.5

EVALUATION OF THE DEEP CIRCULATION HEAT SOURCE MODEL

CAHSB fluids are convective (Erkan et al., 2007), which suggests that vertical permeability pathways of closely-spaced fractures and (or) faults are present to enable groundwater convection through or around the heat source. However, this does not mean that CAHSB fluids are 'deep-circulation' type. There are several problems with the latter interpretation. The first is that the tectonic setting of Central Alaska – dominated by fault-bounded crustal blocks rotating in response to movement along strike-slip faults – does not provide the same type of deep fault pathways that extensional settings do. There are also very few hot springs associated with the large-scale strike-slip faults in the area. The smaller faults that bound the crustal blocks in Central Alaska are also rarely associated with hot springs. The small-scale fractures and localized faults that are observed in CAHSB plutons and at the pluton-hornfels contacts show no evidence of penetrating to deep crustal levels. Instead, such fractures and faults are probably of a variety of origins, including that indirectly related to movements on the Tintina and Denali fault systems.

Hence, fractures and faults are clearly providing the vertical permeability required as circulation pathways for convecting fluids – but they may not be the sole phenomenon operating in the CAHSB system. Unfortunately, geologic maps are not available beyond a 1:1,000,000-scale for much of the CAHSB. According to this regional map (Fig. IHS-1), 15 out of the 32 hot springs are located on or near mapped faults, though there is no indication of the age of activity of those faults. This number should be considered as a minimum considering the poor exposure of structural features and lack of field studies in Interior and Western Alaska. In the few areas where detailed maps are available, small faults controlling the geothermal upwelling have been identified. For example, Kolker et al. (2007) argued that Chena hot springs is related to intersecting, high-angle, strike-slip faults, but there is no evidence for recent activity along those faults. The amount of lateral displacement along the Chena hot springs faults are <3 km, which is miniscule compared to the faults with tens to hundreds of km displacement in other "deep circulation" systems.

Moreover, there is little evidence that the small-scale faults in and near CAHSB plutons are active. Active faults are far more important hydraulic conduits than inactive ones (Barton et al., 1995). In geothermal systems, this is even more true due to self-sealing processes from hydrothermal alteration and deposition. In the CAHSB, active faults would have to be held open by shear stresses operating within rotational blocks (Interior Alaska). However, the locations of CAHSB hot springs do not coincide with the zones of seismic activity that mark the boundary of rotational blocks in Interior Alaska (Ratchkovski and Hansen, 2002).

The second problem with the 'deep circulation' hypothesis is that there is no evidence to suggest that the geologic provinces that comprise the CAHSB are high heat flow provinces. 'Deep circulation' type hot springs typically occur in regions of high heat flow. Thermal gradient measurements indicate relatively normal regional conditions (28-40 °C/km; average ~33 °C/km). However, none of the measured heat flow points are near CAHSB plutons or hot springs. The highest measured thermal gradients (32-40 °C/km) are from wells at the western end of the Seward Peninsula, in the Purcell Mountains, and at Eielson Air Force base near Fairbanks – but all are 30 km or farther from the closest hot springs. Thermal gradient measurements from near Chena Hot Springs also indicate a fairly normal gradient in the wells drilled outside of the thermal upwelling zone (28-34 °C/km, Erkan et al., 2007).

While thermal gradient measurements are relatively average for crustal heat flow, heat flow measurements in some parts of the CASHB are higher than average (80-100 mW/m^2). This discrepancy indicates that there could be substantial local variation and that heat flow could be anomalous in localized areas. Since heat flow is a function of thermal gradient and conductivity, this implies either (1) the CAHSB has anomalous thermal rock conductivity; (2) while regional heat flow is average, there are localized sources of anomalous heat flow. There is absolutely no basis for hypothesis (1). If (2) is true, then regional extension and/or crustal thinning cannot be the mechanism of heat, since that would cause a regional widespread heat anomaly. The limited nature of the thermal anomalies argues for a shallow rather than deep source.

U, TH CONCENTRATIONS IN CAHSB PLUTONS

Figure IHS-2 shows U and Th concentrations of CAHSB plutons vs. plutons from elsewhere in the United States. The Idaho batholith is a large complex of Late Cretaceous to early Tertiary granitoid bodies covering approximately 15,400 square miles in central Idaho. The Idaho batholith hosts a number of non-magmatic fracture-controlled hydrothermal systems (Druschel and Rosenberg, 2001), thought to be of the 'deep circulation' type. The Sierra Nevada batholith is a complex of late Jurassic (160−150 Ma), and Late Cretaceous (100−85 Ma) intrusive bodies. It is not associated with geothermal activity, though unrelated magmatic hydrothermal systems do occur nearby. The New England high-heat producing (HHP) granites were once investigated as a potential source of low-temperature geothermal energy (Costain et al., 1980); however permeability limitations in this tectonically quiet area preclude the development of hot springs systems. Compared to other plutonic bodies in the U.S., even the HHP granites of New England, CAHSB plutons contain highly anomalous concentrations of U and Th.

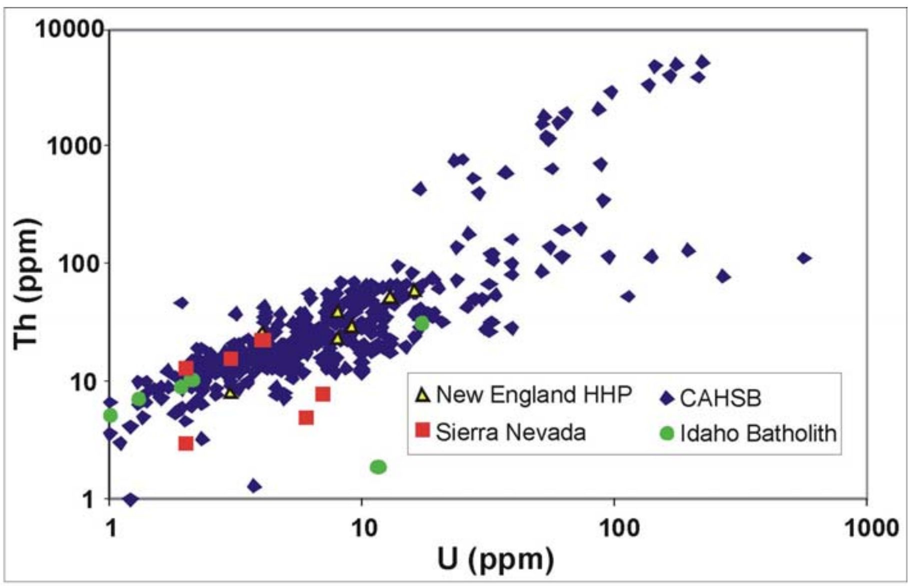

Figure IHS-2: U and Th contents of CAHSB-related and other plutons, modified from Kolker (2008).

The variability in the U, Th data is probably due to the inhomogeneous distribution of these elements in a given body. Significant variation in U and Th concentrations within plutons has been documented by most workers (e.g., Jones and Forbes, 1976; Arth et al., 1989). Figure IHS-2 shows a near-linear correlation between U and Th in concentrations below 10 and 80 ppm respectively, but at higher concentrations U and Th behave differently. The two distinct trendlines at high concentrations may reflect post-emplacement U redistribution into quartz veins and other secondary deposits. Another source of variability may be focus of the studies themselves: vein samples may have been favored by some studies but rejected by others.

The heat generation of CAHSB plutons ranges from 3 to 45 μW/m^3, with an average of 12 μW/m^3. If values from plutons with standard deviations >100% are excluded, the average is 8 μW/m^3. This is four to six times the average of 2 μW/m^3 for granitic rocks (Rybach, 1981). This places all the CAHSB hot springs-associated granites in the category of high-heat-producing (HHP) granites.

CAHSB fluids are different from magmatic and deep-circulation type hot springs in terms of fluid chemical characteristics. The low surface temperatures (<90 °C, average 55 °C, near-neutral pH) low concentrations of total dissolved solids (TDS, average <2000), and other characteristics of the CAHSB resembles better the radiogenic Paralana hot springs fluids in South Australia, which are characterized by low-surface temperatures (average 57° C), near-neutral pH (7–8), and average TDS of 1144 mg/L.

Chloride concentrations in geothermal fluids are often used in ratios with other elements in the interpretation of water chemistry, the most conservative element in geothermal waters (Nicholson, 1993). In magmatic hydrothermal systems, Cl is thought to be introduced through crystallization of the associated magma, and in deep circulation systems Cl is thought to derive directly from the deep reservoir. Arehart et al (2003) used Cl/B and Cl/Li ratios in geothermal fluids to distinguish between magmatic-driven and extension-driven (‘deep circulation’ type) geothermal systems in the Great Basin. Cl/B and Cl/Li ratios of CAHSB fluids resemble neither magmatic nor deep circulation type systems (Fig. IHS-3). Cl concentrations in CAHSB fluids are lower than fluids from both other types of systems, but Li and B are lower by several orders of magnitude. This defines a separate trend for CASHB systems, which fits data from the radiogenic geothermal system at PHS.

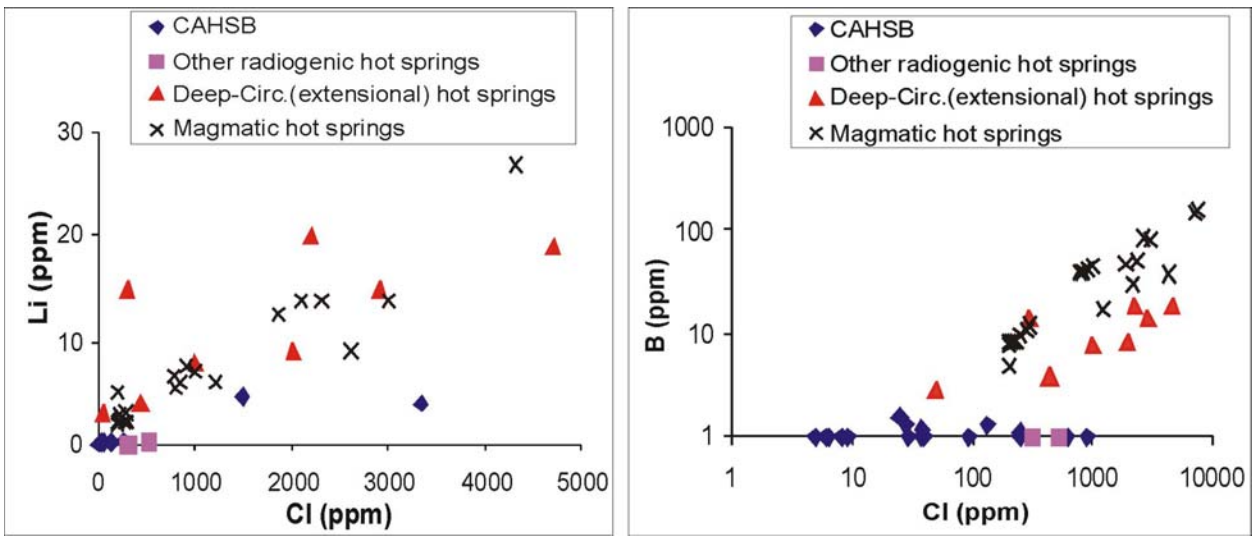

Figure IHS-3: Cl vs. Li and B concentrations for CAHS plotted against data from radiogenic, magmatic, and deep-circulation (extensional) hot springs systems. Data from Kolker et al. (2007), Brugger et al. (2005), Arehart et al. (2003). Modified from Kolker (2008).

Whether CAHSB plutons generate a sufficient amount of heat to drive the observed geothermal activity depends in large part on the assumed volume of the pluton. Depending on the volume assumption, five of the CAHSB plutons could generate heat equal to or in excess of what is required to heat CAHSB fluids to estimated reservoir temperatures; whereas 9 CAHSB plutons do not generate sufficient heat. That is, most of the plutons do not supply sufficient radioactive heat production to account for CONTINUOUS HOT SPRINGS ACTIVITY.

However, radiogenic hydrothermal systems do not appear to operate continuously in radioactive granite terrains; rather, they occur in discrete pulses when conditions are favorable for circulation and then terminate. For example, ore deposits in SW England, Nigeria, and in the Bohemian massif of Germany, appear to be related to extinct radiogenically-derived hydrothermal systems that were caused by circulation tens of millions of years after intrusions were emplaced (Dill, H., 1985; Fehn, 1985). Durrance (1985) suggested that anomalously radioactive granitic bodies go through a several million year cycle of: heating by radioactive decay with minimal conductive heat loss; inflation due to heating; inflation-induced fracturing; convective groundwater circulation; and finally deflation and cooling due to efficient convective cooling (Fig. IHS-4). HHP granites buried under “caps” of sedimentary rocks in the northeastern U.S. do appear to have caused anomalous heat flow, but not robust hydrothermal activity (Costain et al., 1980). This could be because permeability in this tectonically quiet region is not sufficient for the development of hydrothermal convective systems. In the CAHSB, it appears that the active convective hydrothermal systems developed not very long ago, and that the convective heat loss by hydrothermal circulation will continue until it has drawn the bulk of radiogenic heat away from the plutonic body.

Hence, it would appear that in Alaska the combination of high-heat-producing granites of 60-100 Ma and the active structural setting of these plutons create a combination of heat and permeability favorable for the development of low-temperature hot springs *at the present time*.

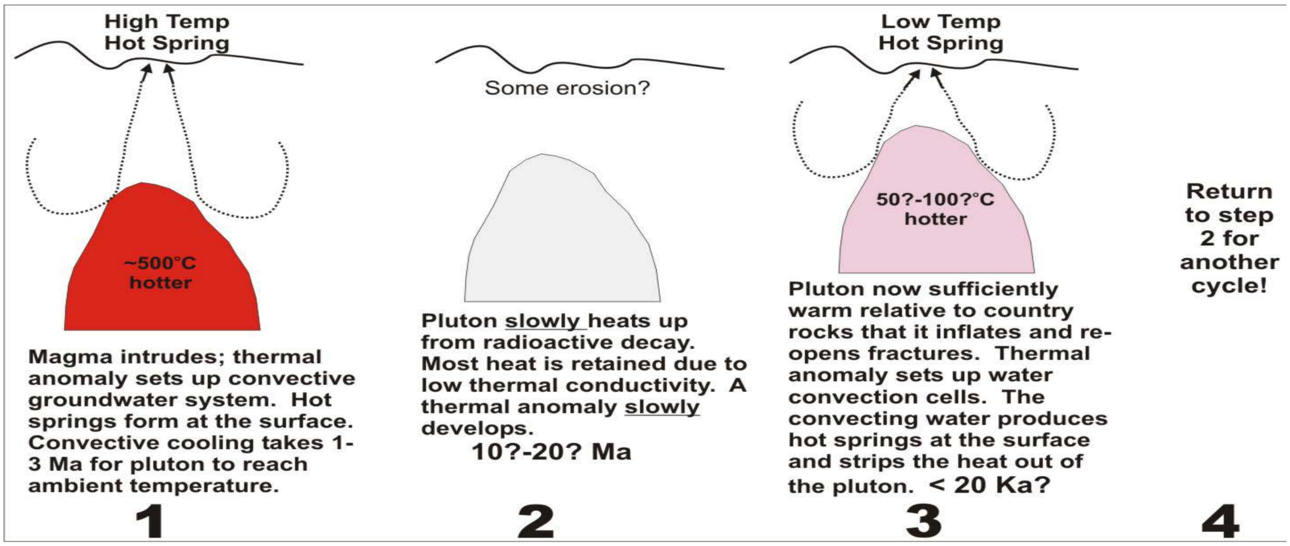

Figure IHS-4: Cartoon of geothermal system cycle related to U-, Th-rich pluton

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