

Epithermal Mineral Deposits within Geothermal Systems

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ABSTRACT

Epithermal mineral deposits generally form from meteoric waters within large geothermal systems. Many large hot spring-type gold deposits occur within fossil geothermal systems. These deposits exhibit widespread hydrothermal alteration that is a direct indication of the size and temperature of the paleo geothermal system. Mineral exploration utilizes minor element chemistry and alteration mineral zonation to locate source areas of paleo fluid flow, where the highest-grade precious metal deposits are often found. These same tools have been used to discover hidden geothermal systems, though not always by intent. These tools were used to discover many gold deposits including Sleeper, Wind Mountain, and a small deposit in the Willard District in Nevada. Our team focused principally on advanced argillic alteration zones, created by upwardly mobile geothermal vapors, principally H₂S (partially sourced from destruction of gold bisulfide complexes after gold deposition) to target drilling. The Wind Mountain and Willard deposits occur adjacent to active geothermal fields. The Nevada team also discovered several new geothermal fields, including Tungsten Mountain and McGinness Hills. The processes and methodologies for these discoveries were very similar. Many of the same vapors released in forming mineral deposits, such as H₂S, Hg, various S compounds, organic and other materials leached from country rock are common in natural geothermal systems. If mineral explorers can find new geothermal fields with rock alteration, it seems probable that geothermal exploration models and methodologies could be improved to help discover totally blind geothermal systems.

1. Introduction

I started my career in 1974 as a field chemist for the Amax Geothermal Group analyzing water samples on-site at geothermal projects. This was done to monitor chemical and physical changes to samples, which often occur enroute to the laboratory. Within 24 hours many samples formed precipitates and nearly all released a vapor phase (largely CO₂) which we also analyzed. We were studying water chemistry to make better chemical geothermometers and better understand limitations on silica and fluorine to target heat flow and exploration drilling.

I later switched to mineral exploration and looked for porphyry and epithermal gold deposits. In 1981, I visited the Borealis gold deposit in Nevada and recognized alteration very similar to geothermal projects. The old term “hot spring-type” gold deposit remains valid, but they are often categorized under new names reflecting physical and genetic characteristics. Gradually we incorporated a large volume of geochemical and physical process information into predictive exploration models. This body of knowledge grew painfully slow for several decades until recent years when laboratory work and detailed geologic models enabled estimates of depth ranges for deposit formation, gold metal carriers, maximum solubility conditions, deposition mechanisms and zonation of ore stage and peripheral alteration minerals (Wood, 2020 and 2022).

2. Epithermal Gold Exploration

In the early 1980's we applied our rudimentary geologic knowledge of geothermal systems to epithermal gold exploration in Nevada. This focused on “hot spring-type” alteration associated with regional scale deep penetrating fault zones, where large meteoric water reservoirs could circulate deeply over large areas. Many of these structures hosted deep intrusions and more shallow volcanic centers associated with broad advanced argillic (illite-clay-silica) alteration zones. This led to the discovery of the Sleeper gold deposit (Wood, 1996 and 1988; Wood and Hamilton, 1991). At Sleeper, banded chalcedony-adularia-electrum veins formed at temperatures as low as 100°C, locally with bonanza grades exceeding 60 oz/t gold. Sleeper briefly became the highest-grade open pit gold mine in the world, producing about 2.2 million ounces of gold. This discovery added extensively to understanding the geologic process which formed the deposit and added to the exploration model and discovery methodology. The Sleeper deposit formed in a shallow intrusive environment around a volcanic vent. These rocks are not strongly mineralized but were important as part of the heat source that drove an extensive hydrothermal system of meteoric water that formed the deposit. The age of the deposit is about 16.1 Ma as indicated by K/Ar and laser fusion $^{40}\text{Ar}/^{39}\text{Ar}$ dating, with a small second stage at about 14 Ma (Conrad and McKee, 1995). It is generally believed the period of main stage gold mineralization lasted about 0.6 million years (Ferdock et al., 2005). This was a period of extensive hydrothermal brecciation related to near surface boiling. Dating of alteration zones indicate that the geothermal system lasted, at least episodically from about 18 Ma, and gradually cooled down at about 5.4 Ma as indicated by deposition of alunite (Conrad et al., 1993). This long-lived geothermal activity resulted in many overprinting episodes of alteration that have brought into question some early age dates and fluid inclusions used in temperatures of formation estimates (Nash et al., 1989).

Armed with more advanced exploration models the search continued for large advanced argillic (illite-clay-silica) alteration zones. These were ranked by their size, chemistry and gold endowment with pervasive gold values deemed more important, indicating possible bulk mine potential and higher-grade structures where bonanza gold may occur of secondary importance. This led to the discovery of the Wind Mountain deposit in 1988, which contained 13.7 million tons of rock averaging 0.72 g Au/t and 11.4 g Ag/t (Wood, 1991). This occurred within a sub-economic resource of about 58 million metric tons in strongly altered rock. An unaltered bed sampled distally from the orebody was dated at 4.8 ± 0.9 Ma by a $^{40}\text{Ar}/\text{Ar}^{39}$ method and the deposit was considered slightly younger by Rhodes (2011). Although it is difficult to correlate stratigraphy in this area due to alteration and structure, the deposit is not likely to be much older than this date and is probably a fossil portion of the adjacent San Emidio geothermal field. Pipe scale from the active geothermal system contained low-level gold values (Joe Kizis, President, Rio Fortuna Inc., personal

communication 2023). Another smaller gold resource was discovered on the pediment of the Willard District, adjacent to a diatreme and within an active geothermal field. This deposit was dated at about 6.1 Ma (Seedorff, 1991; Figure 1).

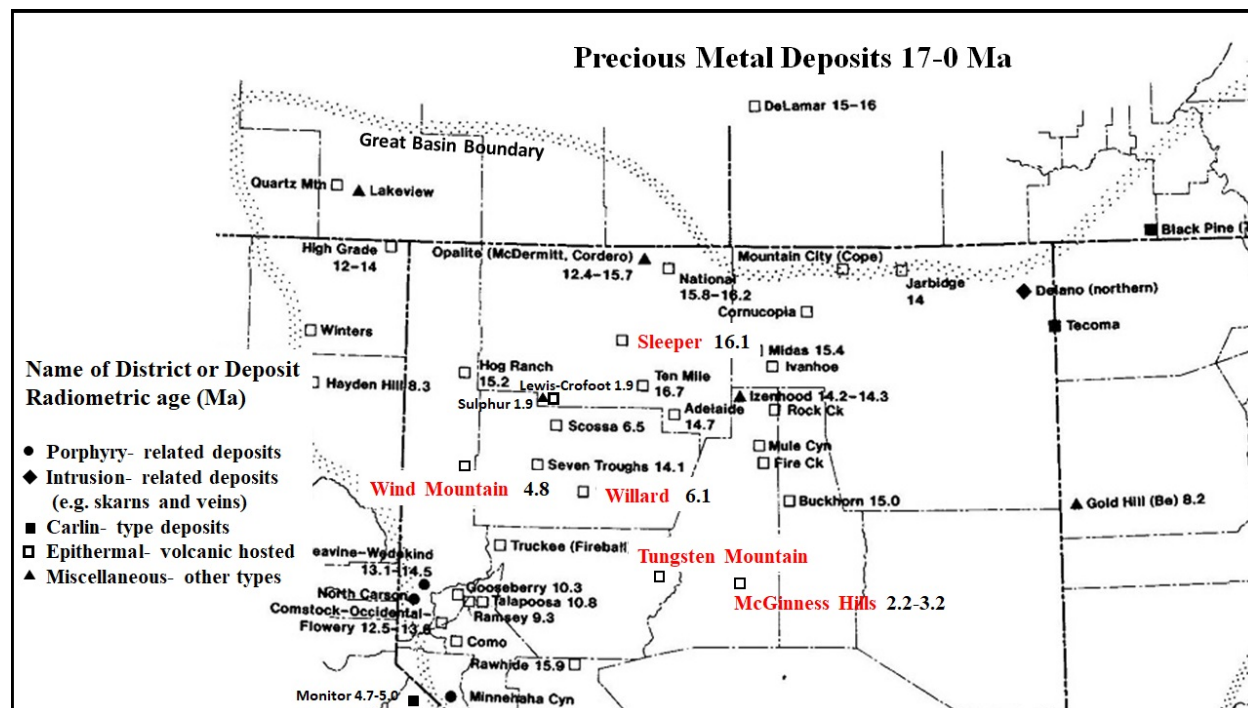


Figure 1: Gold deposits in Northern Nevada less than 17 million years old (modified from Seedorff, 1991).

3. Geothermal Discoveries Using Metal Exploration Methods

The Tungsten Mountain project, located about 60 miles east of Fallon in Churchill County, Nevada had a weak discontinuous gold anomaly with values locally exceeding 0.1g Au/t extending about 300 m along the edge of a range front. This area exhibited locally strong advanced argillic alteration, cut by fractures partly filled with calcite veins and minor chalcedony. This alteration appeared to extend under pediment alluvial cover towards a major fault zone. An IP-resistivity survey indicated a large conductive area with moderate chargeability, which was interpreted as strong clay alteration with pyrite. In 2002 and 2003, this target was tested with 17 drill holes which encountered intensely bleached and argillized volcanic rocks with stratiform layers of opal and chalcedony containing up to 5 percent pyrite. These horizons were locally cut by single stage hydrothermal breccias, covering an area of about 2 km². Silica zones contained low-level gold, but rarely exceeded 0.15g Au/t and no high-grade veins were found along structures. This alteration may not seem exciting, even to most mineral explorers, but it is similar to rocks 200 m from the Sleeper orebodies. Unfortunately, gold and other gradients were very weak and high volumes of hot water severely hampered drilling as we stepped outward from the range front. We were using a reverse circulation drill set up for geothermal drilling with set casing and a blow-out preventer. Unfortunately, high water volumes “drowned-out” the air-hammer and holes had to be completed with a tricone bit. Cold water was pumped down the holes to prevent water from flashing up the

hole when changing rods. Weak gold gradients and several holes with flashing hot water resulted in discontinuing the project.

The McGinness Hills project in Lander County, Nevada exhibited hydrothermal alteration and patchy low-level gold over an area of about 16 km². Here, hypogene alunite was dated at 34.8 ±1.7 Ma, a younger phase of adularia vein material was dated at 3.2 ±0.4 Ma and adularia in a hot spring sinter was dated at 2.2 ±0.4 Ma, all by K/Ar determinations (Casaceli et al., 1986). Previous workers drilled 41 exploration holes at McGinness Hills from 1982 to 1996. This drilling encountered strong alteration with low-level gold. Extensive sampling identified a 5 km long and 2.5 km wide gold-bearing zone. Our target was to test major controlling structures deeper under and adjacent to the sinter mound down to the Tertiary unconformity and a covered area to the south. During 2003 and 2004, 26 drill holes followed alteration gradients and encountered extensive alteration with 3 to 7 percent pyrite. Pervasive gold grades were generally less than 0.1g Au/t and a few faults had grades up to 2.1g Au/t. Gold values were weakly encouraging and would warrant follow-up, but many holes encountered extremely hot water and deep vein mining looked unattractive.

Water samples and temperature data from Tungsten Mountain and McGinness Hills were given to the Nevada Bureau of Mines and Geology, so the properties could be explored for geothermal potential.

4. Nevada Geothermal Exploration Lessons

The Basin and Range province in Nevada has been a very active thin crust extensional structural environment, especially for the past 20 million years. The source areas of volcanic and geothermal activity occur along deep penetrating extensional basin-and-range and subsidiary faults throughout Nevada. Metal explorers often focus on intrusions and volcanic centers as sources for metals and heat. These display characteristic magnetic anomalies and magnetite destructive alteration with higher salinity fluid inclusions and pathfinder geochemistry more anomalous in sulfur, mercury, tellurium, potassium, and sometimes base metals. Large deep penetrating fault zones are sometimes overlooked by metal explorers. These can host numerous intrusions, dike swarms, and localize larger zones of high heat flow and deep circulating meteoric water. They can form natural convection cells much larger than can be attributed to a single intrusion and can leach more metals from country rocks and deposit them close to the surface in hot spring-type alteration zones. At Sleeper, major structures localized intrusions, a volcanic center, and allowed deep circulation of meteoric water into areas of high heat flow. Age dates tell us that favorable structures and geothermal systems have been active for long periods of time, locally exceeding 10 million years, with composite alteration zones often exceeding 100 km³ (Wood, 2022). They often display multiple ages of hydrothermal alteration and multi-stage breccia formation in boiling zones. These formed from episodic geothermal activity related to active and inactive periods of fault movement. Without active faulting, geothermal systems will seal themselves off at depth by clay alteration. They are often covered in basins by clay-rich lake beds. Clay alteration and the variable availability of groundwater often create conditions of episodic water flow, vent area migration, overpressurization and hydrothermal breccia formation through time. Through fluid inclusion studies we know the depositional temperatures of ore stage and alteration minerals and we can follow mineral zonation into metal depositional environments. The volume and complexity of

hydrothermal breccia can be used to find fluid up-flow areas and boiling horizons. Rock and vein textures and silica polymorphs are windows into dynamic conditions of hydrothermal fluids.

Geothermal systems and hot spring-type gold deposits exhibit essentially the same features. A distinction is that most geothermal systems do not contain much gold and the largest hot spring-type gold deposits tend to be fossil deposits formed in large long-lived geothermal systems. The only difference between many epithermal mineral deposits and geothermal alteration zones is the economic minerals. In Nevada, precious metals and lithium are the most sought-after hot spring related deposits, but deposits of hydrothermal clay, sulfur, mercury, pyrite, alum, and tungsten have also been prospected. The source waters are the same – meteoric water as indicated by very low salinity fluid inclusions. In most cases the source economic minerals are leached from country rock. Cool, low oxygen groundwater can become an enhanced leachate when heated, especially when pH conditions are in disequilibrium with host rocks or when reactive host rocks are encountered. The limitation of a mineral deposits size is probably the mineral availability within the hydrothermal system. The main stage of gold mineralization at Sleeper occurred in several pulses over a period of about 0.6 million years and probably occurred when the hydrothermal cell was near its maximum volume and experiencing boiling. By this time the hydrothermal system leached and deposited nearly all the available gold and only minor gold was deposited after this time.

Any soluble economic elements in basement rocks can potentially be leached by geothermal water and form mineral deposits. In general, meteoric water is near neutral in pH but it will react with alkaline or acid host rocks and change pH. Large packages of similar rocks tend to buffer groundwater chemistry and hydrothermal systems. When water is heated significantly it becomes a better solvent. At high temperatures it can hydrolyze, turn alkaline and become a powerful leachate. Geothermal fluids are often rich in sulfur, which can form strong acids. Metal bearing fluids moving into different pH conditions will react with host rocks and may deposit minerals. Fluid chemistry often changes with temperature and pressure, boiling and release of gas phases. When geothermal water reaches structures open to the surface both temperature and pressure drop, resulting in rapid cooling to near 100°C and atmospheric pressure (release of a vapor phase) and rapid deposition of constituents in solution. Most banded vein textures indicate a rapid cyclical deposition. In very deep structures lithostatic load and hydrostatic pressure can inhibit boiling, allowing minerals in solution to migrate closer to the surface. The Beowawe geysers in Eureka County, Nevada, prior to plugging, would flash upward tens of meters on low-pressure days, but only a couple of meters on high-pressure days, demonstrating their sensitivity to small atmospheric pressure changes. Geothermal water migrating to the surface often changes chemistry and equilibrium as it moves toward the surface, experiencing pressure drops, losing a vapor phase, boiling, and precipitating elements and compounds that have reached saturation.

5. Models and Methods for Geothermal Exploration

It stands to reason that if a mineral explorer can find blind geothermal systems by accident, geothermal explorers armed with modern theories and tools should be more successful. In the 1980s we only explored for mineral deposits where evidence of mineralization was exposed at the surface. Today we are exploring for almost blind deposits. The Tungsten Mountain and McGinness Hills geothermal projects were only recently discovered, even though boiling water occurred within 100 m of the surface, indicating how well clay and silica capping can hide both heat and

water. Nevada contains many areas of seismic and geothermal activity and probably contains many more geothermal systems hidden under lakebeds within the basins.

Geothermal systems are generally confined to structures and power production requires both heat and water. Small geothermal systems are commonly associated with shallow intrusions in volcanic environments. Larger geothermal systems generally occur where groundwater can circulate deep (± 2 km) into zones of high heat flow within large regional fault zones. The best geothermal exploration targets are where a large groundwater reservoir occurs within deep penetrating structures in a “deep reservoir environment” (Figure 2). In Nevada, areas of dry high heat-flow may be more common than high temperature geothermal systems. Successful geothermal exploration should target favorable deep penetrating structures with high heat flow, in areas where Tertiary basins host large reservoirs of groundwater. Many of these basins are grabens bounded by large fault zones. Major fault structures that cut thick sections of brittle volcanic rock are more likely to host permeable geothermal reservoirs suitable for power production. These targets are also more likely to be concealed by thick sections of young lake beds that can cap a “deep geothermal reservoir environment” (Figure 2). If a dry system were discovered, this environment would have a higher probability of nearby groundwater suitable for injection.

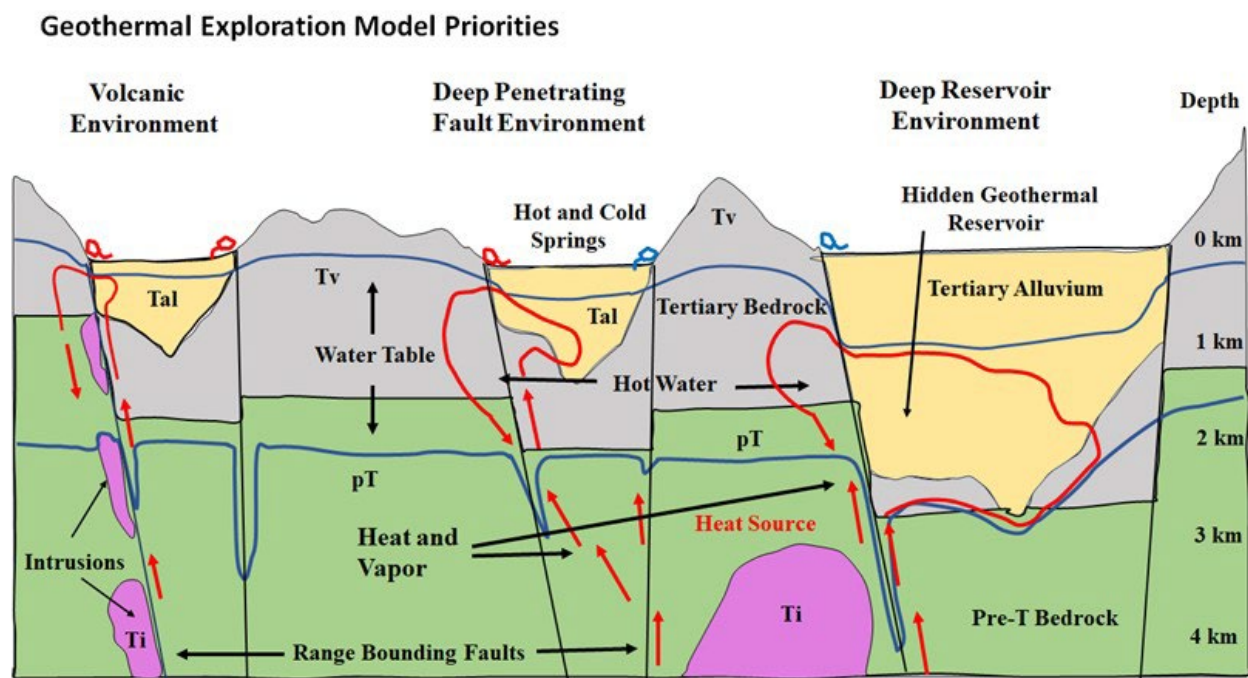


Figure 2: Nevada Geothermal Exploration Environments.

Successful exploration of new regions for well-hidden geothermal systems requires a general understanding of the process that forms them. It is important to look at targets through the mind’s eye, visualize the dynamic process and not leave all data processing to machines. A geothermal system may be active for 10 million years or more, migrate 10 km or more within a structural network, and exhibit dozens of alteration minerals and rock textures, which can define

hydrothermal conditions spatially and through time. They often occur in areas of active faulting, and large water reservoirs are essential for economic production. Much of Nevada's groundwater occurs in fault-controlled reservoirs along range-fronts, while valleys are often filled with impermeable clay-rich lake beds. Many of these fault zones are more than a kilometer wide, as at Sleeper, and are often interconnected with a regional network of other structures. These faults are large enough to provide adequate reservoir capacity and often strongly fracture Tertiary volcanic sections adding to potential reservoir capacity (Figure 2). Pre-Tertiary basement rocks are generally much less permeable, and upwardly mobile fluids often depressurize flowing into the Tertiary unconformity, a common horizon of mineral deposition and initial boiling. This horizon is often very permeable, hosting regional conglomerates, broken volcanic rocks, open space, and considerable groundwater. At geothermal targets it should be tested where it intersects high-angle structures, especially in areas of high heat flow. Nevada's Basin and Range province provides excellent targets for hidden deep groundwater reservoirs. In general, fractures are more open and permeable within 1 km of the surface and become progressively less open to depths below 2 km, due to lithostatic load and hydrostatic conditions. Brittle rocks at depths above 2 km are favorable reservoir targets. Large open spaces can exist below 2 km, but they are held open by water under very high pressure. A deep geothermal system would boil in fractures open to the surface, but this is often suppressed by the hydrostatic head of groundwater and natural impermeable caps. It is important to map the structural architecture of the target area and drill test the most favorable structure at the most favorable elevation.

Regional exploration methods generally begin with regional portfolios of available maps of known geothermal resources, structure, seismic and other data to study and prioritize prospective areas. This may include hyperspectral imaging to look for favorable alteration zones and alteration products. This type of imaging can save time and expense in regional surveys and help focus field examinations in the most productive areas. Airborne geophysical and radiometric surveys can aid exploration in both exposed and covered areas. Most of these anomalous areas have probably been examined by previous explorers and new exploration regions may be alluvial covered, with no near surface water or heat signature (Faulds et al., 2021). It is important to look for new targets with a more trained eye for what could be hiding under cover or between datapoints.

At the prospect scale more focused discovery methods can be employed. Where no surface indications of geothermal activity are present, passive seismic surveys utilizing geophones and a recording base station may be a useful tool for initial targeting. Active fault movements are often associated with areas of high heat flow. Measuring fault movements can often identify water lubricated faults and the top and base of water tables. Once a seismic target is identified, other methods can be employed to help refine the target for drilling. Metal explorers would look for evidence of favorable attributes of a deep geothermal system. Large alteration zones will only exist if hydrothermal fluids experienced boiling and acid alteration near the surface. In deeper systems favorable alteration would likely be confined to fractures, exhibiting small areas of structurally controlled alteration, hydrothermal breccias and fracture coatings of epithermal mineral products like illite, clay, silica, adularia, calcite, anhydrite, buddingtonite, gypsum, zeolite, alunite, etc. Evidence of vapor stage alteration may also be present. In most cases hot vapors would condense in faults and create acid and clay-like alteration products. These would look superficially like white clay, with vapor stage minerals like native sulfur, cinnabar and small amounts of many other minerals. Condensate and alteration mineral assemblages are often too fine grained to recognize visually and appear as just minor bleaching or clay alteration. XRF (X-ray fluorescence) and NIR

(near-infrared) spectrometers can be very useful in identifying mineralogy in these zones. Geothermal systems trapped at depth may only exhibit vapor transport to the surface during periodic fault movements. Vapors escaping through fractures and condensing can accumulate in perched groundwater in faults forming distal anomalies of sulfur, sulfur compounds, mercury, selenium, boron, ammonium salts, organic material, and other materials leached from country rock. There would likely be trace elements unique to the system that could aid targeting. Areas of hot dry rock may lack enough water to form recognizable anomalies, but measurement of total vapor pressure and individual gases may reveal the hidden heat source. Organic vapors are often common above an active hydrothermal cell. Ammonia replaced potassium in late-stage adularia at Sleeper, forming buddingtonite. Geothermal systems readily leach sulfur from country rocks and through the process of sulfidation form pyrite where iron minerals are present. Pyrite may form banded veins and fracture coatings in iron-rich fluids. In low iron environments abundant sulfates will often be deposited. Sulfidation and oxidation of iron minerals are both magnetite destructive processes identifiable with magnetic surveys. Zones of intense hot-spring-type alteration are often surrounded by pyritic zones. Pyrite, clay, and silicified zones can be detected with IP-resistivity surveys. Deep circulating hydrothermal cells often leach materials from deep basement rocks and deposit it near the surface. In Nevada, sulfur isotope analyses often identify sulfur of Ordovician or Silurian age in Tertiary pyrite (Hofstra, 1997), an indication of a hydrothermal cell leaching sulfur from basement rocks.

6. Conclusions

Metal exploration probably has dozens of methodologies and tools that could be adapted to aid exploration for blind geothermal deposits. Geothermal cells are generally water in motion, in areas of high heat flow and active faulting. Seismic surveys should be most valuable for initial drill targeting. Then progressive use of the next more reliable methods can be employed to help refine the target for drilling. Direct temperature measurements by heat flux transducers had limited success in the distant past but could prove useful if adapted properly with modern technology. An acoustical survey may also be possible, listening for rhythmically flashing water at more shallow depths. These types of surveys would likely require burial of instruments in shallow (1-2 m deep) auger holes. Blind geothermal systems trapped at depth under pressure may only exhibit evidence of minor vapor phase alteration from vapor streaming into surface rocks far above the heat source. Vapor collection methods may need to be improved from industry standard sampling. It is possible that specialized vapor sampling programs along the major faults and lineaments could prove successful in discovering new geothermal systems. All new techniques should be tested and calibrated in an active geothermal field whenever possible. Areas with marginal indicators of a productive geothermal field should be re-examined for possible game changer geology, like heat flow focused on structural intersections or a diatreme. Low temperature geothermal cells should be re-evaluated for higher potential to make sure they are not just distal leakage or diluted appendages of a much larger but deeper productive geothermal system. Hydrothermal fluids rarely move straight upward in the earth and source areas are often more than 1 km laterally from the surface anomaly. By modelling and visualizing the dynamic hydrothermal system in 3D and knowing the size, depths, mineral zonation, structural controls, etc., you can optimize your chances of future success.

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