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Geophysical investigations of the Geologic and Hydrothermal Framework of the Pilgrim Springs Geothermal Area, Alaska

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ABSTRACT

Pilgrim Hot Springs, located on the Seward Peninsula in west-central Alaska, is characterized by hot springs, surrounding thawed regions, and elevated lake temperatures. The area is of interest because of its potential for providing renewable energy for Nome and nearby rural communities. We performed ground and airborne geophysical investigations of the Pilgrim Springs geothermal area to identify areas indicative of high heat flow and saline geothermal fluids, and to map key structures controlling hydrothermal fluid flow. Studies included ground gravity and magnetic measurements, as well as an airborne magnetic and frequency-domain electromagnetic (EM) survey. The structural and conceptual framework developed from this study provides critical information for future development of this resource and is relevant more generally to our understanding of geothermal systems in active extensional basins.

Potential field data reveal the Pilgrim area displays a complex geophysical fabric reflecting a network of intersecting fault and fracture sets ranging from inherited basement structures to Tertiary faults. Resistivity models derived from the airborne EM data reveal resistivity anomalies in the upper 100 m of the subsurface that suggest elevated temperatures and the presence of saline fluids. A northwest trending fabric across the northeastern portion of the survey area parallels structures to the east that may be related to accommodation between the two major mountain ranges south (Kigluaik) and east (Bendeleben) of Pilgrim Springs. The area from the springs southward to the range front, however, is characterized by east-west trending, range-front-parallel anomalies likely caused by late Cenozoic structures associated with north-south extension that formed the basin. The area around the springs (~10 km^2) is coincident with a circular magnetic high punctuated by several east-west trending magnetic lows, the most prominent occurring directly over the springs. These features possibly result from hydrothermal alteration imposed by fluids migrating along intra-basin faults related to recent north-south extension.

The Pilgrim River valley is characterized by a NE-elongate gravity low that reveals a basin extending to depths of ~300 m beneath Pilgrim Springs and deepening to ~800 m to the southwest. The margins of the gravity low are sharply defined by northeast-trending gradients that probably reflect the edges of fault-bounded structural blocks. The southeastern edge of the low, which lies very close to the springs, also corresponds with prominent NE-striking anomalies seen in magnetic and resistivity models. Together, these features define a structure we refer to as the Northeast Fault. The location of the hot springs appears to be related to the intersection of the Northeast Fault with a N-oriented structure marked by the abrupt western edge of a resistivity low surrounding the hot springs. While the hot springs represent the primary outflow of geothermal fluids, additional outflow extends from the springs northeast along the Northeast fault to another thaw zone that we interpret to be a secondary region of concentrated upflow of geothermal fluids.

The Northeast Fault apparently controls shallow geothermal fluid flow, and may also provide an important pathway conveying deep fluids to the shallow subsurface. We suggest that geothermal fluids may derive from a reservoir residing beneath the sediment basin southwest of the springs. If so, the shape of the basin, which narrows and shallows towards the springs, may funnel fluids beneath the springs where they intersect the Northeast Fault allowing them to reach the surface.

An alternative pathway for reservoir fluids to reach intermediate to shallow depths may be afforded by the main Kigluaik range front fault that coincides with a resistivity anomaly possibly resulting from fluid flow and associated hydrothermal mineralization occurring within the fault zone.

1. INTRODUCTION

Pilgrim Springs is located on the Seward Peninsula roughly 60 miles north of Nome Alaska (Figure 1). It sits in the Imuruk Basin along the Pilgrim River Valley that forms an extensional graben (or half-graben) bound by a major active normal fault to the south along the range front of the Kigluaik Mountains (Turner and Forbes, 1980). To the North the valley is bound by Marys, and Hen and Chickens Mountains. The basement comprising most of the Seward Peninsula is composed of Precambrian metamorphic rocks and overlying Paleozoic carbonates. The nearest outcrops to Pilgrim Springs consist of Cretaceous plutonic (granites and metagranites) and Paleozoic and Proterozoic high-grade (amphibolite to granulite facies) meta-sedimentary and meta-igneous rocks that occur 2.5 mi to the south in the Kigluaik Mountains, and low-grade metamorphic rocks that outcrop 2.5 mi to the north at Hen-and-Chickens Mountain (Figures 1; Amato et al., 2004; Till et al., 2011). The sedimentary fill in the Pilgrim River Valley at Pilgrim Springs comprises a ~ 300 m section of unconsolidated to poorly consolidated Quaternary alluvial fill consisting of interbedded fluvial, glacio-lacustrine and brackish lagoon sediments ranging from clay to gravel derived from the surrounding mountains (Miller et al., 2013).

The Pilgrim hot springs is a low temperature geothermal system characterized by hot springs, surrounding thawed regions, and elevated lake temperatures indicative of elevated heat flow. The area has been historically used for direct use applications of the hot springs since at least the early 1900s. More recently, the system has been studied as a possible resource for providing reliable, baseload power for Nome and several nearby rural communities and reducing their reliance on petroleum-based power generation. Interest in this potential resource has grown due to the high cost of diesel that has to be transported by sea or air, and by recent fuel shortages caused by extreme weather conditions that have isolated the area and delayed fuel deliveries (see e.g., http://www.washingtontimes.com/news/2012/jan/14/harsh-winter-causing-fuel-shortages-alaska/?page=all).

Geologic and geophysical reconnaissance studies were performed in the late-70's through early 80's to assess the origin, character and potential of geothermal resources of the Pilgrim Springs area (Dean et al., 1981,1982; Economides, 1982; Economides et al., 1982; Forbes et al, 1975, 1979; Kline 1981; Kline et al., 1980; Kirkwood, 1979; Kunze and Lofgren, 1983; Lockhart and Kienle, 1981; Lofgren 1983; Stefano 1974; Swanson et al., 1980; Turner and Forbes, 1980 Turner and Swanson, 1981;). These studies recorded well temperatures up to 90°C (to depths of 50m) and estimated deep reservoir temperatures of 150°C based on springwater geochemistry (Lofgren, 1983; Liss and Motyka, 1994). It was suggested that the location of the hot springs was controlled by the intersection of basement faults (Lockhart, 1981; Kienle and Lockhart, 1980) but, due to the limited extent of these investigations and the lack of adequately identified structures, this was not confirmed. Furthermore, the heat source responsible for elevated temperatures at Pilgrim Springs was not determined, though several of these early investigations attributed the heat to a magmatic source associated with active rifting and related Quaternary volcanism (Westcott and Turner, 1981). Motyka et al. (1980) argue that highly saline alkali-chloride springs are consistent with a magmatic source, and point to the Quaternary Imuruk Lake basalt field, located 60 km away from Pilgrim Springs, as evidence that young volcanism could be a potential source of heat for the Pilgrim geothermal system. An alternative source may be radiogenic heat, derived from the Precambrian basement and Cretaceous intrusive rocks that outcrop in the surrounding uplands and floor the Pilgrim Valley. This is consistent with the conclusion of Miller (1994) who notes that Pilgrim, like all other thermal springs across interior Alaska, lies in close proximity to outcrops of granitic plutons. Kolker (2008) also concludes that anomalously radioactive plutons are associated with nearly every hot spring within central Alaska.

More recent investigations at Pilgrim Springs (Daanen et al., 2012; Dilley, 2007; Haselwimmer et al., 2013; Miller et al., 2013) involving borehole, stratigraphic, temperature and geophysical studies, all indicate a shallow (~ 50m) outflow aquifer overlying a deeper (~200m) reservoir and an upflow of 90°C geothermal fluids. Exploration wells encountered crystalline metamorphic basement beneath the springs at depths of ~320 m. Borehole temperatures in these wells reach as high as 91°C between depths 25-50 m, indicating the outflow of geothermal fluids. Following this spike, temperatures reverse between depths of 30-100m due to mixing with cold meteoric waters, then gradually climb to bottom-hole temperatures approaching 80-90°C in the deepest holes (>300 m). The high geothermal gradient below 100 m suggests the presence of a deeper geothermal reservoir, however it is still unclear from existing research whether the ultimate source of heat is magmatic or radiogenic, where the main reservoir resides, how fluids migrate from the source to the springs, and what structures are responsible for conveying fluids to the surface.

In the context of the surface thermal features at Pilgrim Springs and the regional geology, we examine new ground and airborne geophysical datasets to identify potential structures that may control hydrothermal fluid flow. The region-wide geologic and geophysical framework presented here also addresses potential reservoirs and heat sources at Pilgrim Springs.

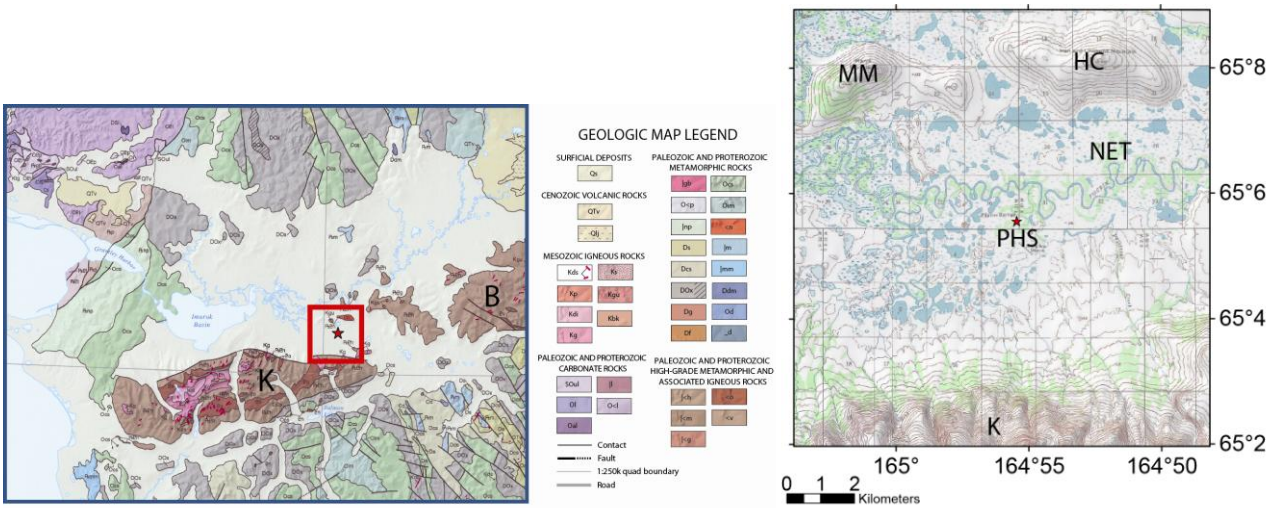

Figure 1: (a) Geologic map (after Till et al., 2011) of the southwestern Seward Peninsula. Pilgrim Springs is shown by the red star. The red box outlines our study area shown in (b). (b) Topographic map of the study area. B – Bendeleben Mountains; HC – Hen and Chickens Mountain; K – Kigluaik Mountains; MM – Marys Mountain; NET – Northeast Thermal Anomaly; PHS-Pilgrim Hot Springs (referred to in text).

2. DATA COLLECTION AND INTERPRETATION

2.1 Gravity and Airborne Magnetics

Helicopter magnetic data were acquired by Fugro using a system equipped with a high sensitivity cesium magnetometer at an altitude of ~40 m above ground along flight lines spaced 0.2-0.4 km apart (Figure 2b). In addition, we collected 295 gravity stations in the early spring of 2010 using two Scintrex CG-5 gravimeters. The gravity data were collected at 100 to 300m spacing along several profiles in the vicinity of the springs, in addition to regionally throughout the project area (Figure 2a). Observed gravity values were reduced to isostatic anomalies using standard formulas (Blakely, 1995). Existing gravity stations (Saltus et al., 2006), including data collected in 1979 and 1980 (Lockhart, 1981; Kienle and Lockhart, 1980) as part of early investigations of the Pilgrim geothermal system; these data were re-processed and combined with the newly-collected data to provide broader coverage in the greater vicinity around the study area.

Gravity highs coincide with crystalline rocks over the Kigluaiks and Mary's Mountains, and, to a lesser extent, Hen and Chickens Mountain (Figure 2a). A NE-elongate gravity low extends from Pilgrim Springs, where it is ~4.5 mGal, southwestward where the lowest values (~10 mGal) in the valley occur ~4km southwest of the springs. The gravity map (Figure 2a) suggests that Pilgrim Springs is located on the edge of a shallow tongue of a basin that deepens to the southwest over the gravity low. The margins of the low are characterized by NE-trending gradients that probably reflect the edges of fault-bounded structural blocks. The southeastern edge of the low, in particular, lies very close to the springs and may be related to an important pathway conveying deep fluids to the surface.

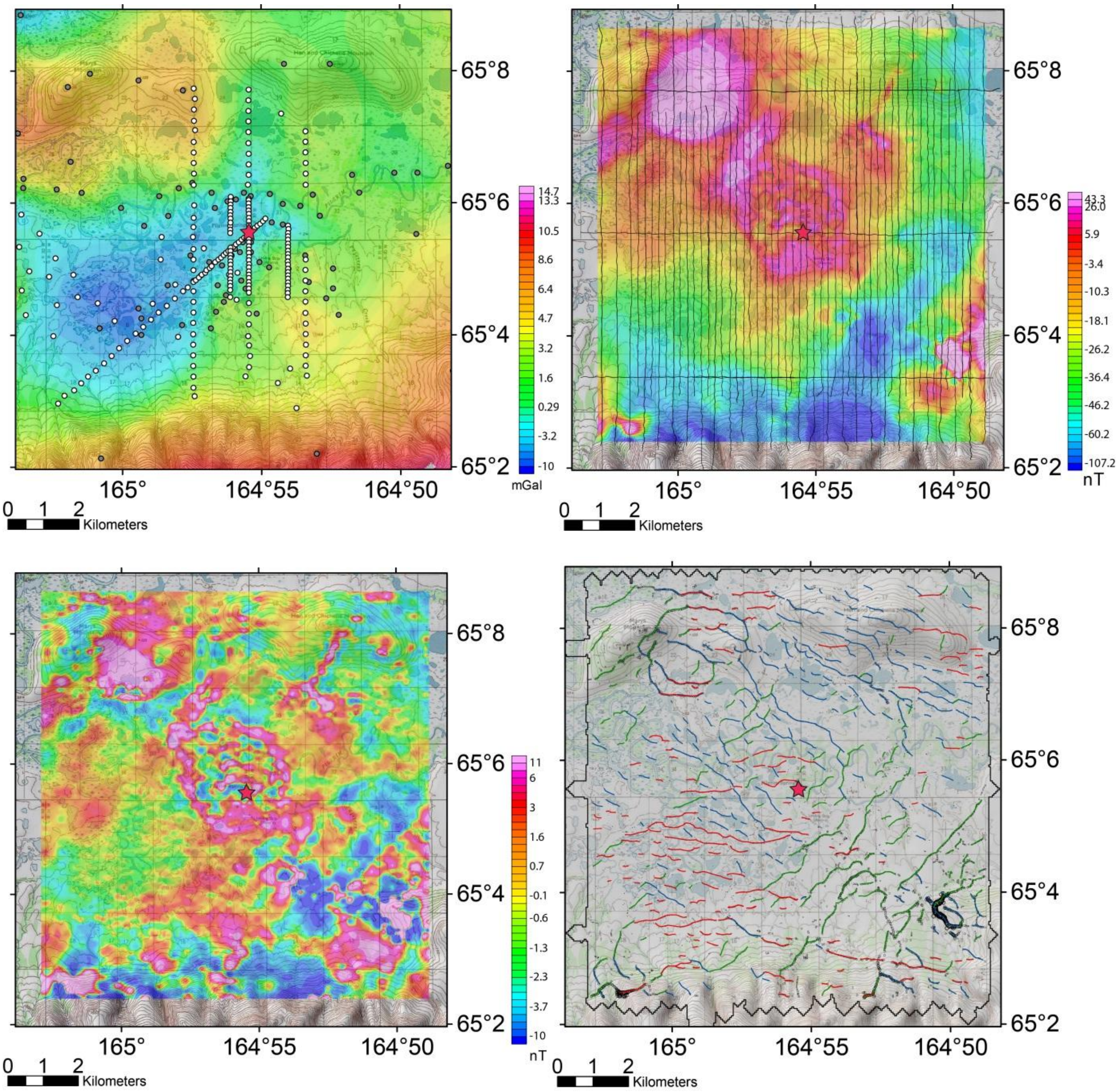

Figure 2: A (top left) Isostatic gravity map showing existing (grey symbols) and new (white symbols) gravity stations; B (top right) Reduced to pole magnetic field showing flight lines (black lines); C (bottom left) Residual reduced to pole magnetic field highlighting shallow-sourced anomalies; D (bottom right) magnetic lineations based on maximum horizontal gradients of pseudogravity (red: EW-trending, blue: NW-trending, green: NE-trending). Black outline shows the extent of the airborne survey. Geophysical grids are superimposed on a topographic base map; Pilgrim Springs is shown by red star.

The most pronounced magnetic high in the study area is located northwest of Pilgrim Springs (Figure 2b). This feature is offset to the southeast of Mary's Mountain and likely indicates magnetic basement rocks buried beneath the basin fill. It is likely that this, and a similar circular high around the springs, are related to Cretaceous plutons similar to those outcropping in the Kigluaik and Marys Mountains. The most extensive magnetic lows occur close to the range front of the Kigluaik Mountains and along a NE-trending corridor southeast of the hot springs.

The maximum horizontal gradients (MHG) of the pseudogravity transformation of the magnetic data is used to highlight the edges of magnetic bodies and to define structural trends. A map of the pseudogravity MHG (Figure 2d) shows a dominant northwest trending anomaly pattern characterizing the northeastern portion of the survey area between Pilgrim Springs and Hen and Chickens Mountain which may reflect structures that cut basement to the east. These may represent accommodation structures with a transition zone between the two major mountain ranges south (Kigluaik) and east (Bendeleben) of Pilgrim Springs (Figures 1, 2b,c). Cutting across this NW-trending fabric is a prominent NE-trending narrow linear magnetic high (Figure 2b, 2c) in the NE part of the survey area, which is indicative of a dike, as its trend is in the same direction as mapped dikes in the Kigluaik Mountains (see geologic maps of the Kigluaik Mountains: Amato and Miller, 2004; Till, et al., 2011).

The southern part of the study area, including the region around the springs, is dominantly characterized by east-west trending, range-front-parallel anomalies likely caused by late Cenozoic structures associated with north-south extension that formed the basin. This trend closely parallels the strike of bedding planes measured within the Kiguaik Mountains (Turner and Forbes, 1980). These east-west-trending anomalies, however, are less pronounced immediately east of Pilgrim Springs, where northeast-trending magnetic fabric becomes dominant and extends throughout the southeast portion of our study area. This change in structural fabric at Pilgrim Springs may be a significant factor in controlling the location of the thermal anomalies observed in the area.

The region immediately around the hot springs is characterized by a regional magnetic high that is punctuated by several east-west trending magnetic lows, the most prominent occurring directly over the springs (Figure 2c). The lows may result from hydrothermal alteration imposed by fluids flowing along range-front parallel features that dissect the basin. Hydrothermal fluids interacting with the host rock typically result in changes of rock chemistry and mineralogy. In a study of hydrothermal areas in Yellowstone National Park, Finn and Morgan (2002) showed that hydrothermal areas are often characterized by pronounced magnetic lows. This occurs because hydrothermal alteration tends to destroy magnetic minerals such as magnetite by transforming them into weakly magnetic minerals such as hematite, goethite, montmorillonite, and pyrite.

2.2 Airborne Electromagnetics

Helicopter EM data were acquired at the same time as the magnetic-field data using a Fugro RESOLVE system. This multi-coil, multi-frequency EM system acquires data at 6 discrete frequencies ranging from 400-140,000 Hz; navigational data include GPS positioning and a laser altimeter. We inverted in-phase and quadrature EM data along each profile using the laterally-constrained inversion of Auken et al. (2005) (Figure 3). Data were inverted for 25-layer models starting from a 1000 ohm-m half-space and with no prior model. The depth extent of the model domain is 125 m, although typical depth-of-investigation (DOI), as defined using the method of Christiansen and Auken (2012) is less than 100 m. In Figure 3, regions below the DOI have been blanked out.

A region of very low resistivity (1-3 ohm-m) surrounds Pilgrim Springs, starting at a depth of 5-7 m and extending to at or beyond the local DOI at ~30 m (Figure 3a). These low resistivities are confined within a ~1.5 km^2 rhomb-shape area co-located with a thaw zone delineated by recent permafrost mapping. An additional more discontinuous region of similar resistivity is located beneath the Northeast thermal anomaly (NET, Figure 1) near the south end of Hen and Chickens Mountain. We attribute the low resistivity to saline geothermal fluids associated with the hot springs and within a region of generally high heat flow (Figure 3a). The hot spring waters are characterized by Cl^- ion concentrations between 3000 and 4500 ppm (Liss and Motyka, 1994; Turner and Forbes, 1980). Together with temperature estimates of 60° to 80°C for the upper 50 m, we estimate a fluid resistivity of between 0.5 and 1 ohm.m. These fluids, coupled with porosities of 20 to 40%, are sufficient to explain the low resistivity beneath PHS and NET. A more widespread conductive region, with resistivity between 3 and 10 ohm.m connects PHS and NET but is terminated abruptly by a NE-trending boundary (Figure 3a). This broader conductive region is attributed to thermal waters migrating laterally away from PHS and NET and mixing with cold meteoric waters.

More resistive regions to the west, south, and east of the PHS thaw zone reflect discontinuous permafrost, and zones of high resistivity (> 1000 ohm-m) agree with, and are more comprehensive than, permafrost mapping immediately surrounding Pilgrim Springs. More moderate resistivities (50-500 ohm-m) characterize surrounding rivers and streams and are associated with thermokarst lakes as well as variations in sediment clay content. The broad, high resistivity (>3000 ohm-m) zone that extends across the southern portion of our study area reflects more resistive glacial outwash sediments. Similar high resistivities are associated with the mountain ranges, and reflect Precambrian metamorphic basement and overlying Paleozoic carbonates. Two high conductivity zones in the southeast corner of the survey area (Figure 3b) fall within the Precambrian basement, and are coincident with mapped graphitic metaquartzite (Turner and Forbes, 1980). An east-west trending break in the otherwise high resistivity Kigluaik range (100-1000 ohm-m) follows the base of the Kigluaik Mountains (Figure3b,c) and may indicate fractured rocks within the range-front fault that hosted fluid flow and subsequent mineralization. Retrograde metamorphism has been locally identified along this fault (Turner and Forbes 1980), and is consistent with this interpretation.

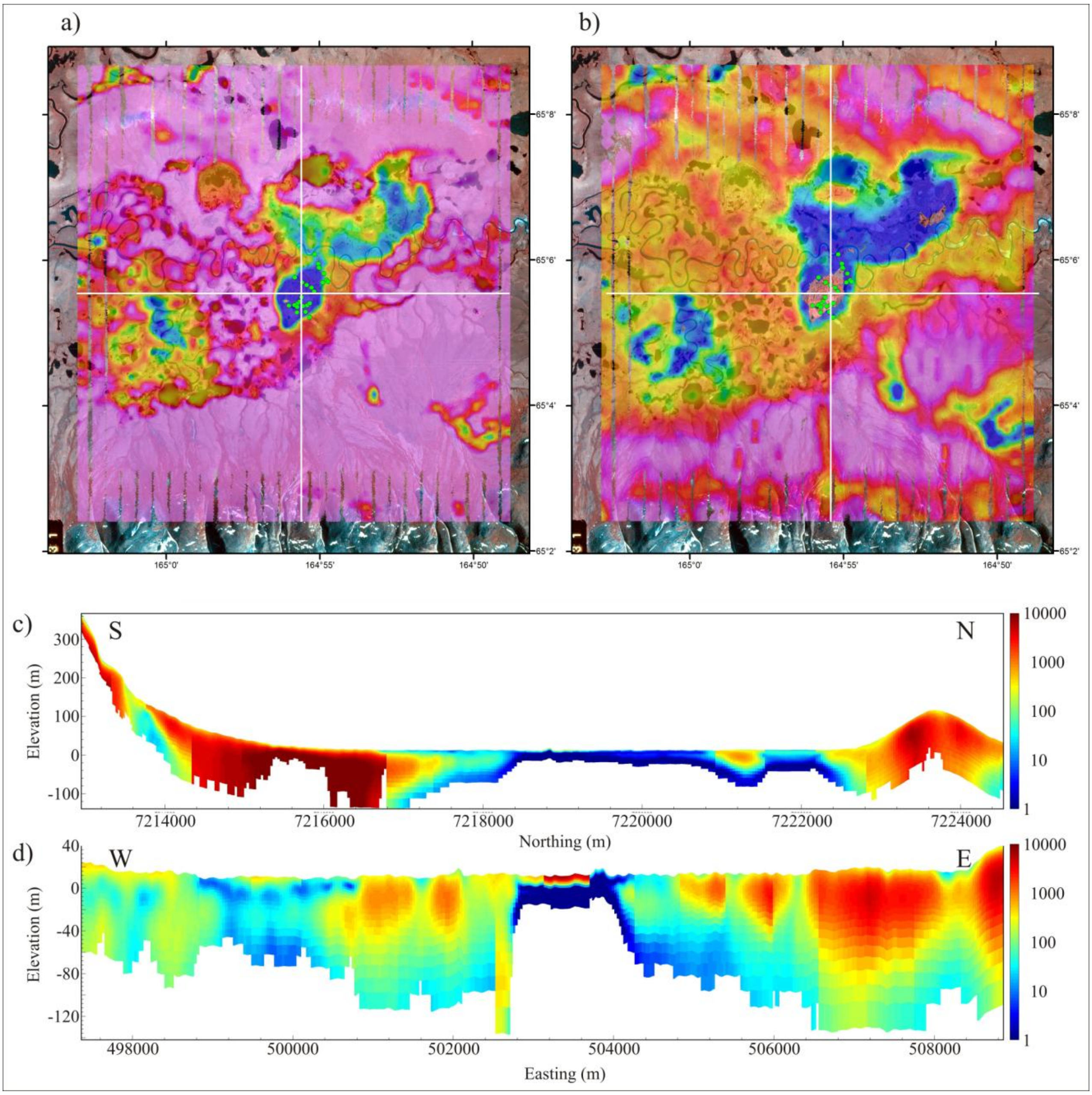

Figure 3: Airborne EM resistivity depth slice at (a) 15 m and (b) 35 m. Resistivity cross-sections along the (c) North-South and (d) West-East profiles indicated in Figure 1b. Models have been blanked out where below the depth-of-investigation.

3. STRUCTURES RELEVANT TO HYDROTHERMAL FLOW

The combined geophysical datasets identify faults, basement geometry, and relationships between the observed thermal features at Pilgrim Springs. The geophysics reveal EW-trending structures reflecting the N-extensional regime of the Pilgrim River Valley. Most pronounced is the EW-trending, Kigluaik range-front fault, previously mapped in part, that extends across the southern part of our study area. The clear signature of the Kigluaik fault in the EM data suggests a history of fluid flow along this fault. Based on the EM model, this fault is dipping 25-45° to the north, contrary to the observation that high-angle faults are common in the Kigluaik Mountains (Turner and Forbes, 1980) yet consistent with the dip of bedding planes within this portion of the Kigluaik Mountains. Given this range of fault dips, the Kigluaik fault would intersect Pilgrim Springs at depths of 2.5 to 5 km. Fault offset cannot be estimated from the resistivity sections due to their limited depth extent, however the prominent break in slope and the thick section of glacial outwash in the hanging wall of the fault suggest there may be significant offset along the Kigluaik Fault. A minimum offset of 300 m can be estimated based on the known depth of valley fill.

The geophysics also point to the existence of a previously unmapped fault trending approximately 50-55° east of north that extends close to, if not through, Pilgrim Springs. Close to the springs, the southeast edge of the gravity low is roughly collocated with the linear southeast edge of the low resistivity rhombus and aligned with NE-trending magnetic lineations. This sharp edge in the resistivity extends further to the northeast and intersects another thermal anomaly located to the northeast of Pilgrim Springs. This second thaw zone has corresponding low-resistivities, and we interpret it to be a secondary region of upflow of geothermal fluids. Although northeast-trending structure can be seen clearly in our data, this is similar to the NE-trend of thermal anomalies noted by Turner and Forbes, 1980 that led them to suggest a possible fault in this location. This northeast trending structure, here named the Northeast Fault, is located at the transition between east-west-trending and northeast-trending structure, as defined by the magnetic data (Figure 2c,d). The northeast-trend in structural fabric is truncated near the base of Hen and Chickens Mountain, where northwest trending features, sub-parallel to the Hen and Chickens range-front fault predominate. The geophysics suggest that the Northeast Fault is a through-going structure connecting the hydrothermal areas with the range-front fault to the northeast at the base of Hen and Chickens Mountain, and, at depth, with the Kigluaik fault which extends out into the basin beneath the springs. The Northeast fault has a trend similar to regional basement fabric mapped in the Kigluak and Hen and Chickens Mountains, suggesting that it reflects an inherited or reactivated basement structure that propagates into the overlying basin sediments.

Turner and Forbes (1980) suggest that north-south-trending faults may extend through the Pilgrim River Valley, possibly intersecting crystalline basement at depth and providing a deep conduit for upward migration of thermal waters. One such fault extends just west of Pilgrim Spring (Turner et al., 1979). It is likely that a north-south-trending fault bounds the western edge of the low-resistivity rhombus. This roughly corresponds with the eastern edge of the deep gravity low (Figure 2a) and may reflect a major fault or warp in basement along which fluids from a deep geothermal reservoir beneath the deep basin migrate to the NE beneath the springs. Magnetic data do not reveal any obvious N-trending structure (either in the magnetic map or MHG, Figures 2c,d), however, the flight lines for the aeromagnetic survey were flown north-south and would not be able to easily image a N-oriented structure. As a result, in the MHG analysis we excluded interpretations of N-oriented gradients to avoid gridding artefacts related to flightline orientation. If such a N-trending feature exists, Pilgrim Springs is located at the intersection of the Northeast Fault with the North-South fault, both of which likely intersect range-front faults at depth.

4. DISCUSSION

4.1 Heat Source

Early investigations attributed the Pilgrim geothermal system to a magmatic source associated with active rifting and related Quaternary volcanism (Westcott and Turner, 1981). The regional magnetic map of the Seward Peninsula (Cady and Hummel, 1976) reveals that Quaternary volcanic fields located on the Peninsula (including Quaternary Imuruk Lake basalt field, located 60 km away from Pilgrim Springs) are characterized by high amplitude, high frequency magnetic fabric similar to a region immediately north of the Pilgrim River valley that is covered by Quaternary alluvial fill (Figure 4). It is possible that this area, lying within 10 km of PHS, may represent a potential magmatic heat source that could be feeding the Pilgrim system. Alternatively, a more likely heat source feeding the Pilgrim geothermal system is radiogenic heat, derived from the Precambrian basement and Cretaceous intrusive rocks that outcrop in the surrounding uplands and floor the Pilgrim Valley.

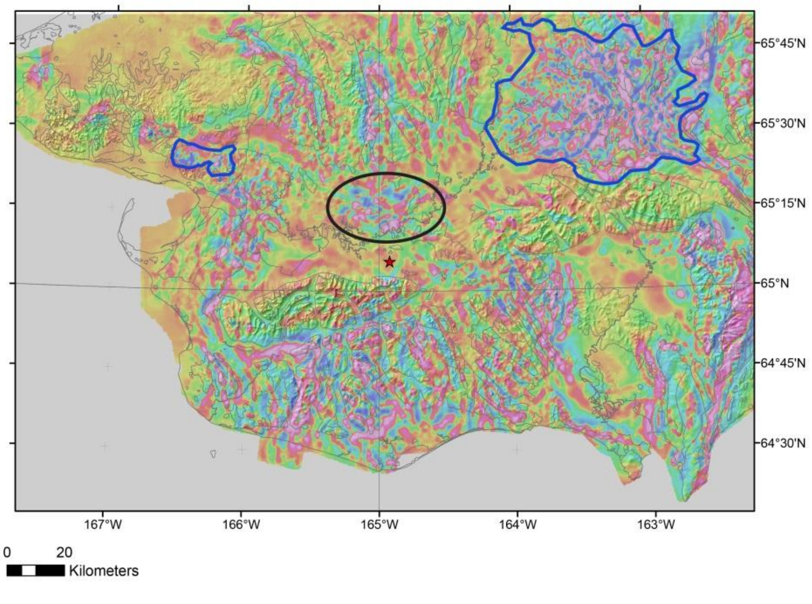

Figure 4: Regional magnetic map (data from Cady and Hummel, 1976) showing magnetic highs in reds and low in blues. Blue outlined areas show approximate mapped extents of mapped Quaternary volcanics NE and NW of Pilgrim Springs (shown by the red star). The black ellipse outlines a region immediately north of Pilgrim Springs that is covered by Quaternary alluvial fill but has a very similar magnetic anomaly pattern (characterized by high amplitude, high frequency magnetic fabric that lacks a consistent trend).

4.2 Geothermal Reservoir and Regional Fluid Flow

The gravity data reveal a NE-elongate basin that extends from the springs and deepens to nearly a kilometer at a location 4 km southwest of the springs. The shape of the basin, shallowing and narrowing towards the springs, could direct fluids towards the surface. In this scenario geothermal fluids migrate from a reservoir (residing in the crystalline basement and insulated by the thicker sediments filling this part of the basin) up-slope along the basement contact to the springs where they intersect vertical structures that provide a pathway to the surface. This conceptual model is outlined in Figure 5. A geothermal reservoir residing in fractured crystalline basement migrates upwards and along N and NE-trending intra-basin structures identified by geophysical mapping. One possible source for the reservoir is within the deepest part of the Pilgrim River basin identified by a local prominent gravity low. In this scenario, geothermal fluids migrate to the NE along a basement-related structure and are conveyed to the surface along vertical structures. An alternative scenario is that geothermal fluids migrate upwards along the main Kigluaik range front fault and then migrate basinward towards the springs where they again intersect vertical structures which convey them to the surface. Both scenarios predict focused upflow through the basin sediments (and possibly the basement) along vertical structures such as the N and NE faults in close proximity to the hot springs. This is consistent with borehole temperature logs, which suggest a narrow zone of upflow directly beneath the hot springs (Miller et al, 2013).

An alternative model is suggested by the EM data that reveal an EW-trending linear low resistivity (100-1000 ohm-m) anomaly following the base of the Kigluaik Mountains. This anomaly is interpreted as the main range front fault, and may result from fluid flow and associated hydrothermal mineralization occurring within the fault zone. If so, this may provide a primary pathway for deep geothermal fluids to reach mid- to shallow-crustal levels. In this case, the deeply rooted and laterally extensive Kigluaik fault could reach a much larger reservoir within the crystalline basement than is represented by the crustal block encompassed by the gravity low.

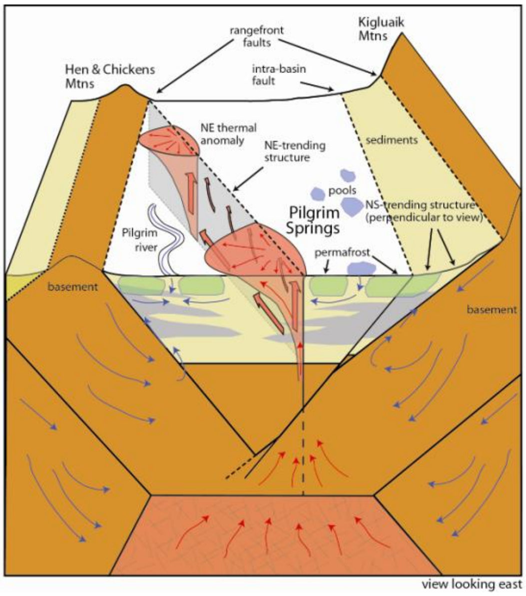

Figure 5: Cartoon illustrating our conceptual model of the Pilgrim Springs geothermal system.

5. CONCLUSIONS

Ground and airborne geophysical investigations of the Pilgrim Springs geothermal system were used to identify areas indicative of high heat flow and saline geothermal fluids, and to map key structures controlling hydrothermal fluid flow. These data reveal several previously unidentified hydrothermal and structural features that lead to a new conceptual model for the geothermal reservoir and pathways for fluid flow.

- Derivative and filtering methods applied to magnetic data, used to locate faults, contacts, and to define structural domains, reveal the Pilgrim area is characterized by a complex geophysical fabric reflecting a network of intersecting fault and fracture sets ranging from inherited basement structures to Tertiary faults. A dominant NW-trending fabric in the northeastern part of the basin may be related to structural accommodation associated with the transition between the two major range fronts of the Kigluaik and Bendeleben Mountains to the south and east of Pilgrim Springs.
- A dominant EW-trending fabric in the southern part of the study area, including the hot springs, most likely reflects NS-extensional Cenozoic structures related to basin development. Several of these features in the immediate vicinity of the springs may result from alteration caused by hydrothermal fluids in the upflow zone.
- A NE-trending structure seen in resistivity models and gravity and magnetic data appears to connect thermal features at Pilgrim Hot Springs with thaw zones to the northeast at the base of the Hen and Chickens Mountain. We interpret this to be a major structure controlling shallow geothermal fluid flow. This structure, referred to here as the Northeast Fault, is subparallel to regional basement fabric mapped throughout the Kigluaik Mountains and probably reflects inherited/reactivated structures in the basement that floors the Pilgrim basin.
- The location of Pilgrim Hot Springs appears to be related to the intersection of the Northeast Fault with a N-oriented structure that marks both the western edge of a rhombus-shaped resistivity low surrounding the hot springs, and the eastern edge of the deep basin identified in the gravity data.
- A prominent gravity low southwest of Pilgrim Hot Springs, reflects a deep (~800m) basin that may represent the primary geothermal reservoir for fluids that feed the Pilgrim Hot Springs. Fluids, controlled by the shape of the

basement/sediment interface, may flow from the deep basin northeast towards the springs where they intersect N and NE-trending structures that transmit fluids to the surface.

- EM data show a linear resistivity low associated with the basin-bounding Kigluaik range front fault that may provide an alternative pathway for reservoir fluids to reach intermediate to shallow depths before flowing downslope to the springs. If this is the primary flow path then the main range front fault could tap a much larger reservoir within fractured crystalline basement.

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