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Regional Tectonic Setting of Pilgrim Hot Springs, Seward Peninsula, Alaska

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ABSTRACT

The Central Alaska Hot Springs Belt (CAHSB), extending from eastern Alaska west to the Seward Peninsula, includes Pilgrim Hot Springs located 70 km north of Nome. The CAHSB continues west across Bering Strait to Chukotka, Russia, where over 30 more geothermal sites are known (Polyak et al., 2010; 2013). The faults and tectonic setting that control these geothermal resources are poorly known. We review the geologic and tectonic setting of geothermal sites nearest to the Bering Straits: the Pilgrim Hot Springs, Serpentine Hot Springs, those near the Kigluaik and Bendeleben Mountains, and the Lorino Hot Springs in Russia. Active faults close to these hot springs appear to re-activate older normal structures in today's N-S extensional stress field. Limited young displacement occurs on these faults, but at their time of formation in the Late Cretaceous to Eocene, larger displacements occurred, making them re-activated zones of weakness today.

Active faults on the Seward Peninsula include the E-W trending Kigluaik and Bendeleben normal faults that extend for 175 km with associated hot springs, including Pilgrim Springs. These faults uplift metamorphosed and intruded rocks and bound Cenozoic to Recent basins in their hanging wall. The parallel Bering Strait, Port Clarence and Norton Sound faults are active offshore. In Chukotka, the NW trending Kolyuchin-Mechigmen zone is likely a reactivated Cretaceous fault system that juxtaposed granitic and metamorphic rocks to the north with supracrustal rocks to the south (Bering Strait Geologic Field Party, 1997). First motions show normal and strike-slip and hot springs have variable isotopic evidence for mantle-derived He (Polyak et al., 2010; 2013).

The Bering Sea basalt province (BSBP) lavas range from 6 Ma to Recent and are similar in composition to those erupted in intraplate settings, oceanic islands, continental rifts and transtensional systems (Wirth et al., 2002; Akinin et al., 1997; Andronikov and Mukasa, 2007). Mantle sources are deep (>1.5 GPa, > 50 km) and lavas erupted with little or no residence time in shallower magma chambers (Wirth et al., 2002; Akinin et al., 1997). Although spatially associated with the westernmost CAHSB, only the Russian hot springs have evidence for mantle-derived helium. Seismic data and studies of crust and mantle xenoliths in basalts of the BSBP indicate highly extended 30-35 km thick crust beneath the Bering Shelf intruded by calc-alkaline magmas in the Cretaceous to Paleocene (Klemperer et al., 2002; Akinin et al., 2009; 2013). Faults bounding basins offshore Seward Peninsula were most active in the Paleocene-Eocene. Contemporary deformation and eruption of basalts in the Bering Strait region suggests renewed onset of extension in the last 6 Ma.

Alaska represents a complex tectonic setting in terms of its contemporary deformation, driven by high convergence rates and shallow subduction in southern Alaska that results in N-S shortening extending north to the Arctic margin. A review of deformation across Alaska compared to the Bering Strait region shows pronounced differences through time to the present-day. Eastern Alaska has undergone significant shortening that migrated north with time, while the Bering Shelf region underwent extensional deformation leading to quiescence after about 40-50 Ma. Today, western Alaska appears to be in the process of decoupling as it moves relatively S and W (e.g. Elliott and Freymueller, 2020) and has begun to extend again. Exploration for geothermal resources should focus on the Seward Peninsula-Chukotka region characterized by earthquakes that indicate N-S extension and eruption of mantle derived basalts. Blind geothermal systems should be considered in northern Seward Peninsula in the region of the Kotzebue Basin and Selawik Trough, which are pre-existing E-W trending structures that cut deep into the crust and are likely to be reactivated in the present-day stress field.

1. INTRODUCTION

Understanding the geologic history, contemporary tectonic setting and thermal state of the lithosphere beneath regions of known geothermal activity are critical in assessing exploration of these resources. Alaska has a geologic history and contemporary tectonic setting that is variable, complex, and in many places poorly understood (Fig. 1). The Central Alaska Hot Spring Belt (CAHSB) extends E-W across interior Alaska (Fig. 1). Chena Hot Springs, NE of Fairbanks, is near the eastern end of the CAHSB and hosts the one operational geothermal power plant in Alaska. Pilgrim Hot Springs, 70 km north of Nome (Fig. 2), is at its western extent (Fig. 1). The more than 30 additional geothermal sites known on the Chukotka Peninsula of northeast Russia (Polyak et al., 2010; 2013) (Fig. 1) define the western extension of the CAHSB (Fig. 1).

The geology and tectonic structures controlling the geothermal systems of the CAHSB are not well known and the reason for their presence in a nearly E-W belt remains speculative (Fig. 1). The thorough review paper on their geologic setting and chemical characteristics by Miller et al. (1975) followed by analysis by Kolker (2008) are the main references for the CAHSB hot springs. As most of the hot springs are close to granitic bodies or their contacts, but the plutons are old (Cretaceous and Paleocene), Miller et al. (1975) suggested that fractured and faulted plutons may allow deep circulation of meteoric water and its heating due to the geothermal gradient. Kolker (2008) explored the possibility that these older plutonic rocks were in part radiogenic heat sources for geothermal waters. A third explanation for the hot springs on the Seward Peninsula and Chukotka is that they lie in a modern rift zone defined as the northern extending boundary of a rigid Bering Sea Plate which is rotating clockwise (Fig. 1) (Mackay et al. (1997), an idea detailed by Polyak et al. (2010; 2013) for the hot springs in Chukotka. A fourth explanation is that of Batir et al. (2016) who suggest that interior Alaska hosting the CAHSB is an along strike continuation of the back-arc "Cordilleran Thermal Anomaly Zone" (CTAZ) of Blackwell (1969) and thus a zone of relatively higher heat flow (60-100 mW/m2). This paper describes the geothermal sites of the CAHSB closest to the Bering Strait in context of their local geology, earthquakes, and magmatic activity. We also consider the recent tectonic history of the Bering Strait region within the broader framework of Alaska's subduction-related tectonic history.

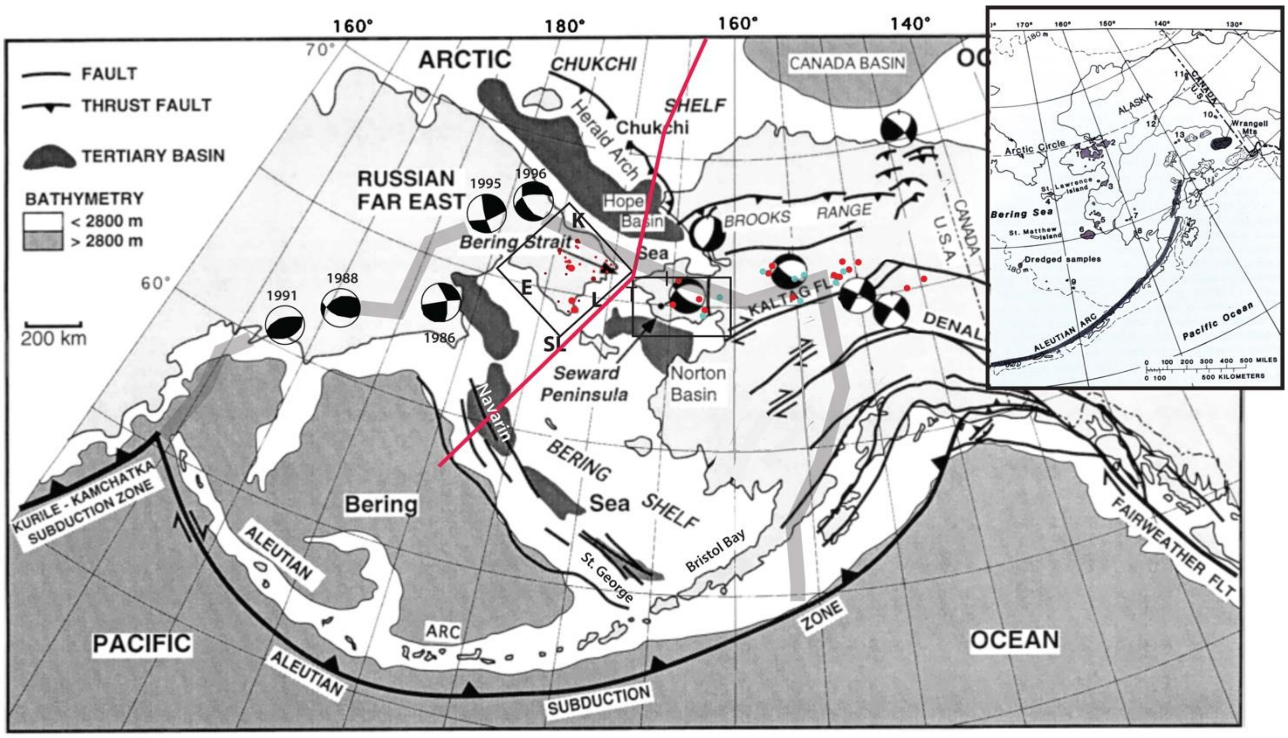


Figure 1. Index map of Alaska- Russia and Bering and Chukchi Shelves after Dumitru et al. (1995). Squares are maps in Fig. 2 (Seward Peninula) and Fig. 3 (Chukotka). Inset map shows basalts of the Bering Strait Basalt Province after Moll-Stalcup (1994). Red line is deep crustal seismic reflection profile of Klemperer et al. (2002), part shown in Fig. 5. Select focal mechanisms are lower hemisphere projections with compressional quadrants black from Page et al. (1991) and Mackay et al. (1997). Hot springs and wells of the Central Alaska Hot Springs Belt (CAHSB) are shown by red dots (>50°C) and green dots (20-50°C) from Batir et al. (2016). Hot springs in Chukotka from Polyak et al. (2010) where large red and medium dark red dots are > 80° C and small red dots less than 80 and more than 0 °C. E, Enmelen, K, Kolyuchin Bay, L, Lorino, SL, St. Lawrence Island. Light grey band is outline of the Bering Sea plate or block from Mackay et al. (1997).

2. GEOLOGIC SETTING OF BERING STRAIT GEOTHERMAL SITES

2.1 Introduction

There has been significant work on the igneous, metamorphic and structural history of the Bering Strait region, including the acquisition of deep crustal reflection data across the Bering Shelf (e.g. BSGFP, 1997; Akinin et al., 2002, 2009; Amato and Miller, 1998; 2004, Amato et al., 1994; Hannula et al., 1995; Klemperer et al., 2002; papers in Miller et al., 2002; Pease et al., 2018 and Till et al., 2011). The general takeaway from this work is that the magmatic history of the Bering Strait region is mostly Cretaceous to early Cenozoic in age. Stratified rock units that are Paleocene and younger are little disturbed by deformation. The studies of the geologic past of this region fail to explain the region's active seismicity, the eruption of basaltic lavas from 5-6 Ma to present, and today's hot springs.

Three regions with hot springs are discussed below that share similar geologic characteristics. Their commonalities include their close spatial association with active earthquake generating faults and with young to historic basalt fields whose composition and chemistry suggest a deep mantle origin (>50 km). The active faults are normal (and some strike-slip in Chukotka), have limited geologically young displacement, and appear to re-activate older structures (Late Cretaceous to Eocene) that once penetrated deep into the crust. These three regions include the Pilgrim Hot Springs north of the Kigluaik Mountains on the Seward Peninsula, hot springs in the Bendeleben and Darby Mountains of Seward Peninsula, Serpentine Hot Springs, and the Kukun Hot Springs in Russia near the native fishing community of Lorino (here called the Lorino Hot Springs) (Figs. 1, 2, 3). Overall, the reactivation of deep crustal structures in a primarily extensional environment may create avenues that tap deeper heat reservoirs and help keep fluid circulation pathways open.

2.2 Pilgrim Hot Springs, Seward Peninsula

Previous studies on geothermal resources in this region of Alaska focused almost entirely on the Pilgrim Hot Springs with the immediate benefit of helping ongoing exploration work aimed at meeting the energy needs of nearby Arctic communities, such as Nome, which spends a minimum of $8M per year on diesel-generated electricity. The latest studies from 2010-2014 (ACEP, 2015) included drilling 8 new wells to a maximum depth of 1294 ft (394 m)and only encountering a maximum temperature of 91°C. Temperature reversals suggested drilling was not directly over the main area of upwelling and no further development occurred.

Pilgrim Hot Springs lies 4-5 km north of the trace of the active Kigluaik normal fault (Fig. 2) and the saline alkali-chloride geothermal fluids are in Quaternary alluvium above granitic/gneissic rocks. Their detailed tectonic setting is discussed by Craig et al. (2024, this volume). Normal slip along the east–west-trending Kigluaik and Bendeleben faults forms a zone of active faulting about 175 km (109 mi) in length as described by Hudson and Plafker (1978) (Fig. 2). Faults occur on the north side of the Kigluaik Mountains and the south side of the Bendeleben Mountains. The two systems of faults do not connect; each dies out prior to where they might overlap (Fig. 2). The Kigluaik Mountains are an ~80 km long and 20 km wide glaciated mountain range (Fig. 2), formed as a sillimanite to granulite grade gneiss dome in the Cretaceous (e.g. Amato and Miller, 2004). Closely spaced metamorphic isograds are mapped along the southern, eastern and western flanks of the mountain and were collapsed during ductile deformation associated with rise of the gneiss dome through the crust (Miller et al., 1992) (Fig. 2). In the center of the dome lies an undeformed pluton dated at ca. 92 Ma (Amato and Miller, 2004). The isograd zone separates the high grade resistant metamorphic and igneous rocks of the gneiss dome from the surrounding lower grade (greenschist and locally blueschist) less resistant metamorphic rocks of the Nome Complex (Hannula et al., 1995; Amato and Miller, 2004; Till et al., 2011) (Fig. 2). Metamorphic foliation in the gneiss dome varies from shallow to moderately dipping and defines the overall structure of the dome (Amato and Miller, 2004). Although the gneiss dome originated in the Cretaceous and mostly cooled during the latest Cretaceous to early Cenozoic based on extensive argon and fission track thermochronology (Calvert et al., 1999; Dumitru et al., 1995) (Fig. 2), it is bound on its northern side by a normal fault system that cuts glacial moraine deposits. A parallel, south-dipping normal fault with much less offset has been mapped on the south flank of the range (Crater Creek Fault (CCF) of Koehler and Carver, 2018, Fig. 2) but geologic units show negligible offset (Miller et al., 1992; Amato and Miller, 2004). Rocks in the center of the dome and along the center of its northern edge yield the youngest apatite fission track cooling ages and date uplift of rocks to near surface conditions in the Eocene-Oligocene (Dumitru et al., 1995) (Fig. 2). These ages are interpreted as related to normal fault slip and associated uplift of footwall rocks during formation of the half-graben Imuruk Basin, which lies to the north (Fig. 2). The Kigluaik fault must have a minimum of ~2 km vertical motion as deduced by the 1.2 km maximum topographic relief of the range added to the 1 km minimum thickness of basin fill deposits (Turner and Swanson, 1981; Dumitru et al., 1995). Dumitru et al. (1995) concluded that most of the fault offset was Eocene-Oligocene and that recent offset remained poorly quantified.

An Eocene-Oligocene age for main fault motion of about 2 or more km is at odds with evidence for geologically more recent offset along the Kigluaik fault. The active fault system disrupts post-Wisconsin glacial landforms as evidenced by benches, notches, and scarps with vertical displacements between 4 and 10 m (13 and 33 ft) (Hudson and Plafker, 1978; Kaufman et al., 1989; Kaufman, 1986; Craig et al., this volume). The modern, northern range front of the Kigluaik Mountains suggests that at least several hundreds of meters of young dip slip motion must have occurred on this fault system to produce the faceted geomorphology of the range front. The new thermochronology data set for this mountain front (Craig et al., this volume) utilizes the U-Th/He method on apatite which is sensitive to the temperature range 40-80°C. These new ages are mostly indistinguishable to those acquired by the higher T (80-120°C) apatite fission track technique, thus the existing data support mostly older slip and limited post Eocene-Oligocene slip.

The above discussion suggests that contemporary motion on the Kigluaik fault system utilizes and re-activates pre-existing structures, specifically an older large-offset normal fault system developed at the tail end of extensional deformation across this region in the Eocene (Dumitru et al., 1995). There seems to have been a hiatus in slip along this fault system, with slip waning in the Eocene-Oligocene and then beginning again in recent geologic time, utilizing the same fault system.

2.3 Bendeleben-Darby Mountains, Seward Peninsula

The normal fault system in the Bendeleben Mountains juxtaposes Late Cretaceous intrusive rocks and their high-grade metamorphic country rocks in the mountains (Till and Dumoulin, 1994; McDannel et al., 2014) against an adjacent lowlands region, McCarthy's Marsh to the south (Fig. 2). The south-dipping Bendeleben fault extends from Mt. Bendeleben to the headwaters of the Tubutulik River, and is associated with clear scarps, observable on satellite imagery, along its south-facing range front. Geomorphic indicators of late Pleistocene and Holocene activity along the Bendeleben fault include slope breaks, saddles in colluvium, and scarps in glacial moraines and bedrock that range from 2 to 8 m high (6.6 to 26.2 ft high) (Hudson and Plafker, 1978; Kaufman, 1986; McDannell et al., 2014). The closest hot spring to this fault system is Lava Creek Hot Spring, in the footwall of the fault system, sited in plutonic and metamorphic rocks (Fig. 2). Measured surface temperatures are 53°C. Quaternary basalt flows occur in the creek bottom of Lava Creek (Miller et. al., 1975). Four other hot springs occur in the Bendeleben-Darby Mountains region, the Battleship Mountain (19°C), Kwiniuk (Elim) (41° C), Molly's (37°C) and Clear Creek (65°C) (Fig. 2). All of these are in granitic rocks close to contacts with metamorphic rocks (Miller et al., 1975; DGGS Geothermal Data Base). None are clearly associated with mapped faults.

South of the Bendeleben Mountains, beneath McCarthy's Marsh, lies a basin with sediment fill as deep as 3-4 km based on modelling of gravity data (Barnes and Hudson, 1977; McDannell et al., 2014). A fault nearly perpendicular to the Bendeleben range front fault occurs along the western side of the Darby Mountains and appears to form the eastern boundary of the triangular-shaped basin a described by Barnes and Hudson (1977) and McDannell et al., (2014) (Fig. 2). The deep, triangular-shaped basin suggests substantial, up to several kilometers of dip-slip motion along these range front fault systems. Apatite U-Th/He dates of footwall rocks, however, yield an Eocene weighted mean age of 41.3 ±4.8 Ma, suggesting little geologically recent slip on the fault system (McDannell et al., 2014). Modeling of this data together with higher temperature thermochronometers which detail the cooling of the granitic batholith in the footwall of this fault system suggest that, despite the presence of modern fault scarps, footwall rocks cooled rapidly in the Late Cretaceous to Eocene, slowing since the Oligocene. This conclusion is remarkably like the history of the Kigluaik Mountains and its bounding fault system (above; Dumitru et al., 1995; Craig et al., this volume). In both regions, geologically recent slip and earthquakes associated with normal fault slip utilize and re-activate pre-existing (normal sense) structures that may have previously penetrated deep into the crust but moved mostly in the Eocene.

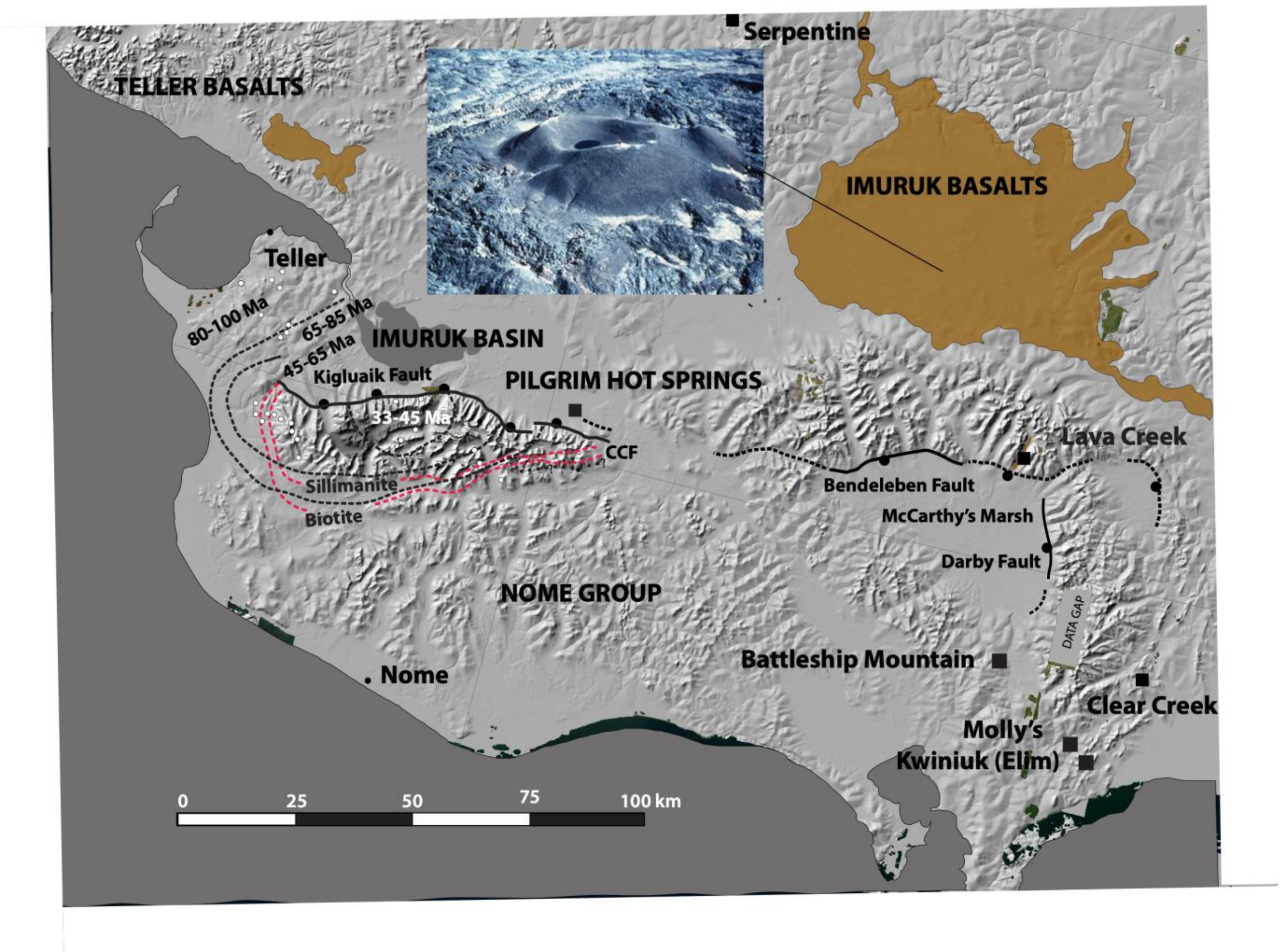


Figure 2. Index map showing the location of the areas discussed on the Seward Peninsula on Arctic DEM base. Mapped and suspected normal faults are shown, ball on downthrown side. Red dashed lines, biotite and sillimanite-in isograds from Amato and Miller (2004); Black dashed lines, generalized contours of apatite fission track ages; white dots are control points from Dumitru et al. (1995). Hot spring names and locations (black squares) are from Miller et al. (1975). Inset photo of Lost Jim basalt cone, photo credit to Travis Hudson.

2.4 Serpentine Hot Springs

Serpentine Hot Springs are the northernmost hot springs on the Seward Peninsula that form part of the CAHSB. The hot springs are sited in a Late Cretaceous granitic pluton about 1 km from its contact with metasedimentary rocks on Hot Springs Creek (Miller et al., 1975) in the Bering Land Bridge National Preserve. Increased use of the hot springs for bathing led to a more detailed investigation and report on this resource (Nordstrom et al., 2015). Application of various standard silica and cation geothermometers to the Serpentine Hot Springs waters yields subsurface temperature estimates of ~100-185°C (Nordstrom et al., 2015). Both discharge and geothermometer temperatures for Serpentine Hot Springs are the highest observed in central or western Alaska (Miller et al.,1975; Nordstrom et al., 2015). A $^{3}He/^{4}He$ of R/R_{Atm} = 0.343 suggest heating of waters in primarily a crustal setting. (Nordstrom et al., 2015).

2.5 Lorino Hot Springs, Chukotka Peninsula, Russia

The CAHSB continues across the Bering Strait to the Chukotka Peninsula, Russia, where over 30 additional geothermal sites are known (Polyak et al., 2010; 2013) (Fig. 1). Coal-fired central heating stations are used to heat buildings in the towns along the Chukotka coast. The coal is brought to these communities by ship during the summer months when the ports are not ice-bound. It would be a great benefit, both environmentally and economically to have access to geothermal resources for heating.

The Lorino Hot Springs lies 14 km NW of the native village of Lorino. During the Soviet era, the geothermal system was used for bathing and heating an array of greenhouses that produced vegetables for the local communities. Lorino Hot Springs discharge large quantities of thermal waters (45 L/sec) with temperatures up to 58°C (Arnason et al., 2005) with maximum temperatures of water obtained by drilling of 64°C. Chemical analyses indicate temperatures at depth in the range of 105-110°C with those waters mixing with cold groundwater (Arnason et al., 2005). Fractured bedrock at the site is granitic.

Most of the known hot springs in Chukotka occur in a broad NW trending belt from Mechigmen Bay near Lorino, to Kolyuchin Bay on the Arctic coast of Russia (Figs. 1, 3). Polyak et al. (2010, 2013) suggest, based on higher seismicity (normal and strike-slip first motions) and the presence of young basalt eruptive centers, that this trend may represent a rift zone (after Mackay et al., 1979). Geologic mapping and studies in Chukotka (BSGFP, 1997) identified an important normal fault contact between deep crustal metamorphic and igneous rocks that form a large gneiss dome complex that underlies the mountainous regions on either side of Lavrentya Bay (the Koolen gneiss dome) and supracrustal cover sequences to the southwest. This fundamental tectonic boundary represents the approximate northeastern margin of Polyak et al's (2010, 2013) rift zone (see map and cross-section of BSGFP, 1997, cross-section B-B' and trace of fault shown in red on Fig. 3a), which hosts the Lorino Hot Springs. A positive gravity anomaly that occurs in the lowlands (Polyak et al., 2010) (Fig. 3) reflects Mesozoic supracrustal sequences with abundant Permo-Triassic diabase and gabbro (e.g. Ledneva et al., 2011). Based on gravity, little or no sedimentary fill characterizes the Mechigmen-Kolyuchin "rift", but its seismicity, presence of young basalt centers and evidence for mantle-derived He in hot springs (Polyak, 2010, 2013) all suggest it is a region of incipient or minor extension today that re-activates Cretaceous crustal-penetrating normal faults. The isotopic values of He in all springs sampled range from 0.14 R_{Atm} to 1.23 R_{Atm}, corresponding to an addition of He_{morb} from 2.2% to 14% of total He content, the rest is crustal (Polyak, 2010).

(not at same scale)

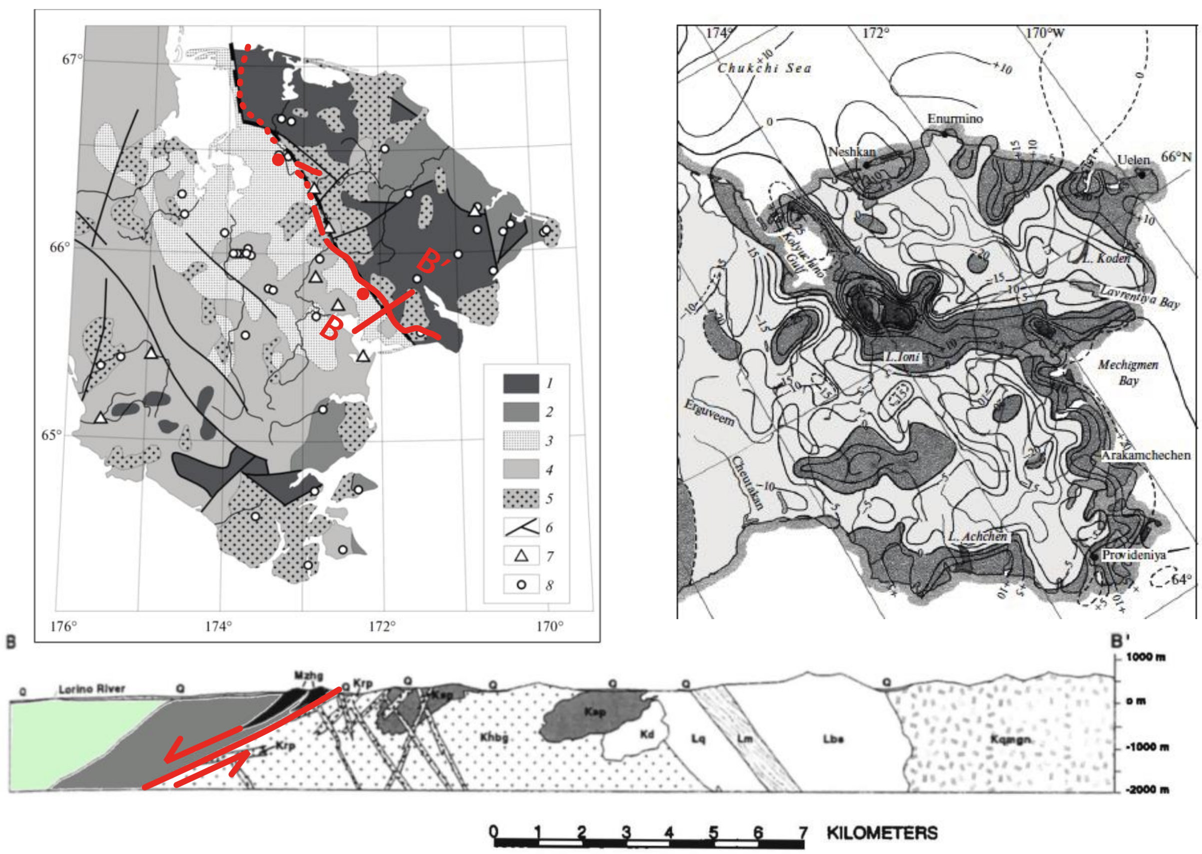


Figure 3. Upper left: Simplified geologic map of eastern Chukotka from Polyak et al. (2020) showing Neogene volcanic centers (triangles) and hot springs (circles). Heavy red line (dotted beneath alluvium) defines likely reactivated Late Cretaceous normal fault system that separates high grade metamorphic and plutonic rocks from supracrustal Paleozoic-Mesozoic sedimentary and overlying volcanic rocks of the Ohkotsk-Chukotsk volcanic belt as mapped by BSGFP (1997). B-B' shows line of cross section (not at same scale). See discussion in text and reference for metamorphic and igneous lithologies in footwall from BSGFP (1997). Upper right: Gravity anomaly map from Polyak et al. (2010) with gravity high along the Mechigmen-Kolyuchin Bay trend corresponding to sedimentary and volcanic rocks intruded by gabbroic bodies.

3. LITHOSPHERE EVOLUTION: CONTEMPORARY TECTONICS AND MAGMATISM

3.1 Earthquakes

Diffuse seismicity and displaced Quaternary landforms indicate that the Kigluaik and Bendeleben faults are active and can generate damaging earthquakes. In addition, several E-W to NW-SE trending active faults are present offshore including the Bering Strait, Port Clarence and Norton Sound fault zones (Fig. 4) (Plafker et al., 1994; Page et al., 1991; Koehler and Carver, 2018). Koehler et al. (2012a) assigned a slip rate of 0.2–1 mm/ yr (0.01–0.04 in/yr) to the Kigluaik and Bendeleben faults and numerous moderate earthquakes have occurred over the last 50 years in the general region of the Seward Peninsula including 62 M 4.0–5.0 and five M $\geq$ 5.0 earthquakes (Koehler and Carver, 2018; Mackey et al., 1997; Page et al., 1991) (Figs. 1, 4). This seismicity extends to Chukotka where both normal sense and strike-slip motion has been documented (Mackay et al., 1997; Polyak et al., 2010; 2013). The most recent earthquakes of note in westernmost Alaska occurred north of the Seward Peninsula and were associated with NW-SE striking normal faults and a vigorous aftershock sequence, the Noatak earthquake swarm (2014, M 5.6) (Koehler and Carver, 2018; Ruppert and Hotkamp, 2014) (Fig. 4)..The north-south extension implied by all of these fault systems is consistent with limited studies of their seismicity (Page et al., 1991; Biswas et al., 1986; Koehler and Carver, 2018), the inferred state of stress today across western Alaska (N-S extension, Lund-Snee and Zoback, 2020) and historical eruptions of basalt described in the next section (Mukasa et al., 2007).

The observed recent deformation seems driven by a similar deformation field or stresses that created very large and deep fault-bound basins offshore on the Bering and Chukchi Seas beginning in Paleogene time (Figs.1, 4). From north to south these include the Hope Basin (Elswick, 2003; Tolson, 1987), the Kotzebue Basin and its onshore continuation the Selawik Trough (Kirschner, 1988), and the Norton Sound Basin south of Nome (Fig. 4). The basins along the outer edge of the Bering Shelf (Navarin, St. George, and Bristol Bay) (Fig. 1) formed shortly thereafter, during and after the establishment of subduction beneath the present Aleutians by 45 Ma ago (Kirschner, 1988; Plafker and Berg, 1994; Worrall, 1991; Klemperer et al., 2002; Miller et al., 2017). The Bering Shelf basins continued to fill in the later Cenozoic and remain largely intact and undeformed today (Figs. 1, 4). Given the geologically extended time span between the Paleocene to Oligocene events that formed the offshore basins and today's recent seismicity and widespread eruption of basalt, deformation was most likely not continuous (in terms of strain rate) through time. It is likely that deformation today represents the beginning or renewed onset of extension across this region. As discussed for the onshore structures, these pre-existing offshore structures also represent zones of weakness in the crust that could be re-activated and move in the modern north-south extensional stress field.

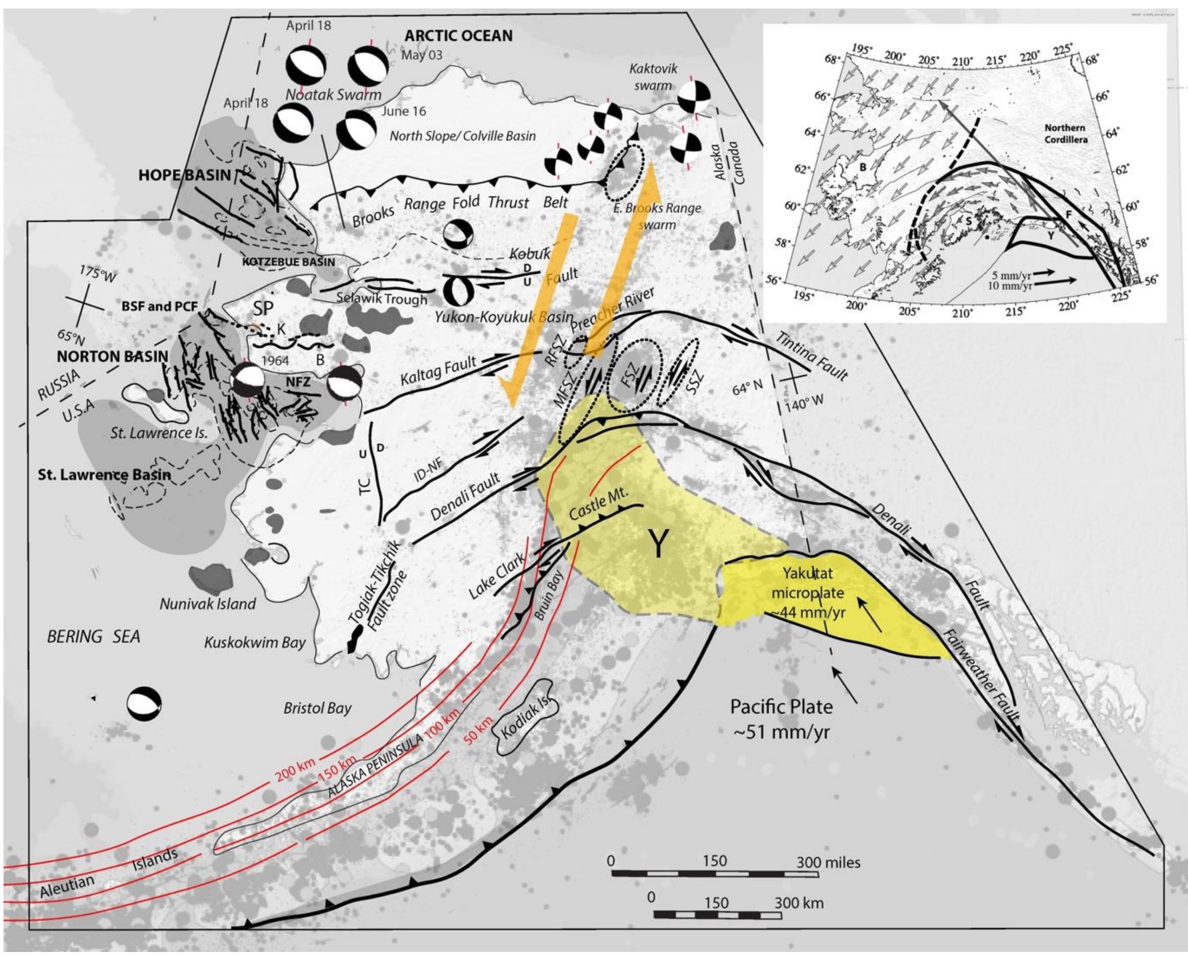


Figure 4. Summary map of faults, earthquakes and contemporary tectonic framework of Alaska with other features described in text. Faults and contoured depth to Benioff zone from Plafker et al. (1994). Earthquakes (grey dots and circles in

background) from 2020 from UAF Alaska Earthquake Center (http://earthquake.alaska.edu/earthquakes). Active faults offshore Seward Peninsula are BSF (Bering Strait Fault), PCF (Port Clarence Fault) and NFZ (Norton Fault Zone). Rampart (RFZ),Minton Flats (MFSZ), Fairbanks FSZ and Salsha (SSZ) Seismic Zones are near Fairbanks. First motions from the eastern Brooks Range and the Kaktovik earthquake swarms from Ruppert (2019). Orange arrows show regional sene of shear represented by these sesmic zones. Other first motions from compilation of Elliott and Freymuller (2020). Inset shows GPS-based block model for the motion of the Bering plate (B) and the adjacent Southern Alaska block (S) which is rotating. Subducting Yakutat microplate (Y represents subducted extent bound by dashed line on map) with modeled velocities with respect to N. America (Elliott and Freymuller, 2020; Cross et al., 2008; Freymuller et al., 2008). Eastern boundaries of Bering block shown as dashed lines in inset. Dark blobs, Cenozoic basalt fields. SP, Seward P., K, Kigluaik Mts., B, Bendeleben Mts., TC, Thompson Creek fault, ID-NF, Iditerod-Nixon Fork fault.

3.2 Magmatism

Late Cenozoic to Recent basalt fields, mainly north and east of Serpentine Hot Springs, cover about 10,000 km^2 (Till and Dumoulin, 1994). To the north of the Kigluaik and Bendeleben Mountains lie the broad Imuruk basalt fields capped by the historic Camille and Lost Jim lava flows (Fig. 2). Four Espenberg Maars occur 40 km north of Serpentine Hot Springs. These are broad craters formed by phreato-magmatic eruptions in the Late Pleistocene (17.5-200 ka) (Nordstrom et al., 2015). They are thought to be volcanic eruptions through thick permafrost (Beget et al., 1996). All four maars are larger than Kilauea caldera, Hawaii, and about an order of magnitude larger than any other known maars on Earth (Beget et al., 1966; Nordstrom et al., 2015).

These basalt fields form part of the Bering Sea basalt province (BSBP) that comprises a broad region of westernmost Alaska, the Bering Sea and NE Russia, extending to the northern Seward Peninsula and Chukotka Peninsula (Fig. 1). Defined by Moll-Stalcup et al. (1994), the BSBP is characterized by basaltic eruptive centers that lie far north of the Aleutian arc (Fig. 1). Over 95-97% of the lavas erupted are alkalic olivine basalt and tholeiites with basanite, tephrinite, hawaiite and nephelinite representing the remaining 3-5% (Moll-Stalcup, 1994). Alkalic and subalkalic basalts (SiO_2 = 38-45 wt%; $Na_2O + K_2O$ = 3-7.5 wt%) dominate over tholeiites. The lavas are similar in composition to those erupted in intraplate settings, oceanic islands, continental rifts and transtensional systems (Wirth et al., 2002; Akinin et al., 1997; Mukasa et al., 2007). The basalts were derived from mantle sources (from depths >1.5 GPa or > 50 km) and erupted at the surface with little or no residence time in shallower magma chambers (Wirth et al., 2002; Akinin et al., 1997).

Reliable ages on the BSBP volcanic fields show them to be all younger than 6 Ma (Mukasa et al., 2007). One of the largest fields, the Imuruk Field, is 5-6 Ma and its capping flows are historic (Mukasa et al., 2007). Those north of Teller on the Seward Peninsula are ca 3.5 Ma (Mukasa et al., 2007). This wide range of ages suggest low volumes of magma through time and that their eruptions repeatedly used the same pre-existing structural zones in the crust and upper mantle. Using age and area/volume constraints, eruption intensity is proposed to have increased with time and to the south in the BSBP (Mukasa et al., 2007). The inferred increasing volumes of magma with time suggest changing aspects in magma source regions in the mantle and/or tectonic regime (Mukasa et al., 2007).

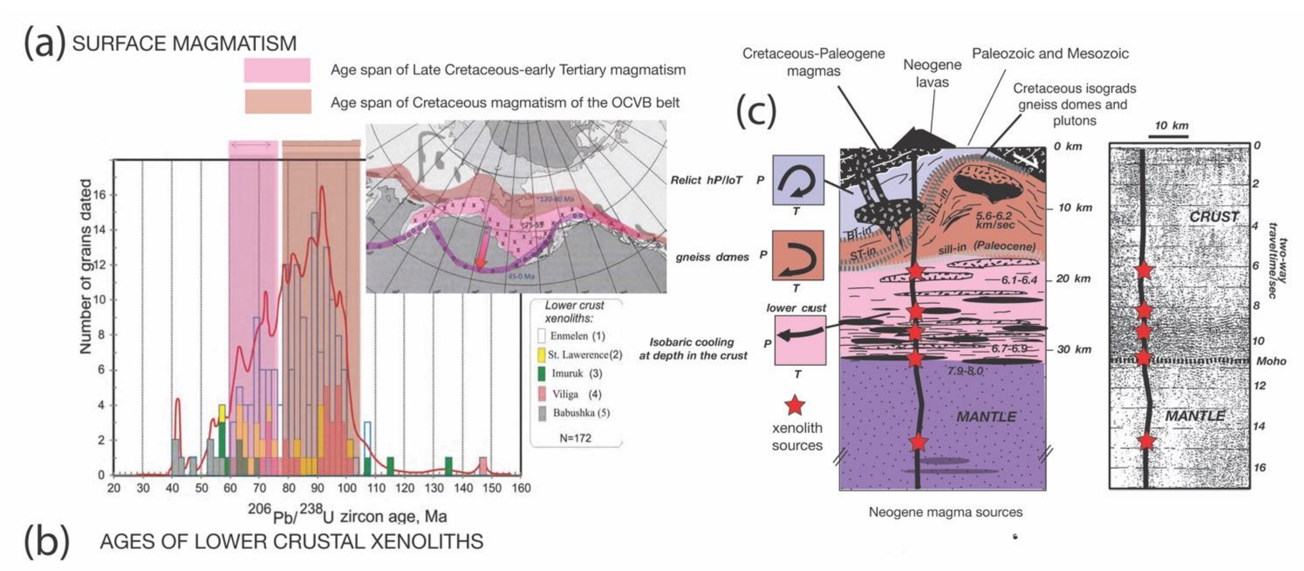


Figure 5. Lithospheric structure of the Bering Shelf based on seismic reflection and study of xenoliths from BSBP magmas. (a) Magmatism youngs southward with older mid-Late Cretaceous ages to north and younger but overlapping latest Cretaceous and Paleocene magmas to the south. Magmatism occurred prior to establishment of subduction beneath the present-day Aleutians, prior to 45 Ma. (b) Small histogram blocks represent U-Pb ages of zircon (both magmatic and metamorphic overgrowths) dated from crustal xenoliths entrained in Neogene basalt flows. The xenolith ages from the deep crust mirror the ages of magmatism at the surface. After Miller et al. (2017) from data in Akinin et al. (2009; 2013) and Akinin et al. (2020). (c) Schematic present-day lithospheric column for Bering Shelf and depth of origin of crust and

mantle xenoliths (Akinin et al., 2009; 2013) with portion of seismic reflection profile from Klemperer et al. (2002) (red line in Figure 1). Note break in scale above inferred source of melts in deeper mantle.

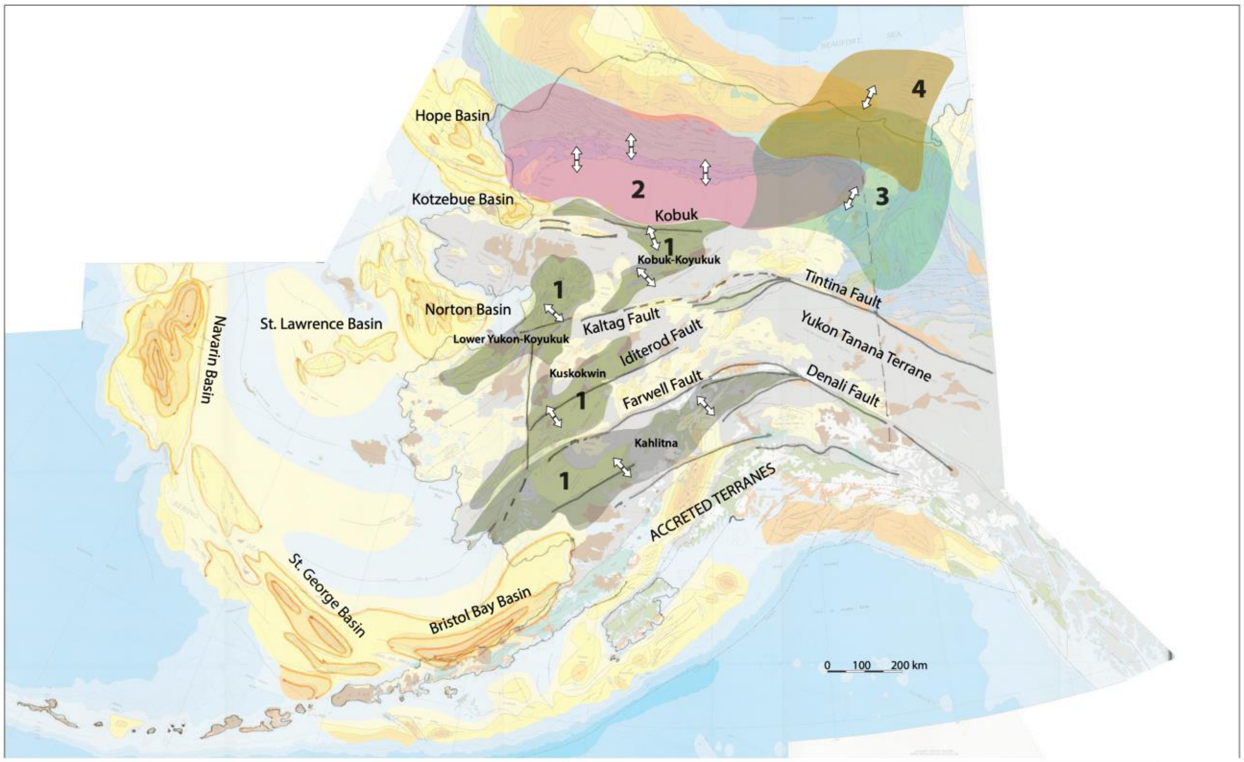
The study of these magmas is distinguished by the extensive study of their xenolith suites and what they reveal about the composition and thermal state of the crust and upper mantle beneath the Seward Peninsula and Bering Shelf (Fig. 5). Xenolith suites from St. Lawrence Island, south of the Seward Peninsula, the Imuruk field on Seward Peninsula, and the Enmelen field in Chukotka (Fig. 1) return remarkably consistent data and interpretations (Akinin et al., 2009; 2013) (Fig. 5). The xenolith suites are composed mostly of spinel lherzolites from the mantle, accounting for 80-90% of the xenolith population, with lesser pyroxenite, dunite and harzburgite (Akinin et al., 2013; 2009). Pyroxene-bearing granulites and gabbros comprise less than 2% of the population but provide direct evidence on the composition, nature, thermal state and age of the lower crust as they commonly contain zircon, the most reliable U-Pb geochronometer. The crustal xenoliths represent hand samples of the lower crust imaged with seismic reflection and refraction (Klemperer et al., 2002; Akinin et al., 2009; 2013) (Fig. 5c). They are in part orthogneisses and gabbros of calc-alkaline affinity intruded into the deep crust and subjected to granulite facies metamorphic conditions and deformation/flow (Akinin et al., 2009; 2013) (Fig. 5). The U-Pb ages of zircons from these xenoliths are equivalent to the intrusive and extrusive ages of mapped and dated supracrustal magmas (ranging from Late Cretaceous to the north and Paleocene to the south) emplaced during formation of Bering Shelf lower crust (Klemperer et al., 2002; Akinin et al., 2009; 2013) (Fig. 5c). In addition, they date the formation of the present-day imaged Moho which lies at ca. 30-35 km depth (Klemperer et al., 2002; Miller et al., 2002b) (Fig. 5). The closure temperature for the U-Pb geochronology system in zircon is about 900° C (Lee et al., 1987), and the reported ages, which range from as old as 135 to as young as ca. 55 Ma in the Imuruk, St. Lawrence and Enmelen fields, suggest conductive cooling of granulite facies lower crust beneath the Bering Straits and surrounding region shortly after its peak igneous and metamorphic history (Akinin et al., 2009; 2013). The cooling history of the crust and upper mantle beneath the Bering Shelf based on the zircon ages implies that the crust has not been mobile since, and that a strong rigid mafic lower crust and upper mantle, capable of transmitting stress, has existed beneath this region for about the last 40-50 Ma (Fig. 5).

The above data and considerations provide important context for the onset of renewed basaltic magmatism across the Bering Shelf. Analysis of seismic wave data provide evidence that the lithosphere-aesthenosphere boundary (LAB) (T ca 1300°C) may be rising beneath this region and now lies at 60-100 km depth beneath the Seward Peninsula (Gama et al., 2022). The deep mantle source regions of melting to produce the basalts and their mantle and crustal xenolith populations that freeze in a considerably older thermal history, together indicate that conductive heating and/or advective magmatic heating due to rise of aesthenosphere has not yet affected the upper mantle and lower crust. At its shallowest, the LAB beneath the Seward Peninsula (ca. 60 km based on seismic wave analyses (Gama et al., 2022)) is close to the estimated depths for melting based on the petrology of the Bering Sea Basalt Province. This overview of the magmatic and lithospheric history of the crust emphasizes that conditions are changing in the Bering Strait region and that the current earthquakes and eruption of basalt appear to herald these changes after a 40-50 Ma hiatus in magmatism and regional deformation.

4. REGIONAL PLATE TECTONIC SETTING

Alaska represents the tectonically most active region of the United States (https://www.usgs.gov/media/images/national-seismic-hazard-model-2023-chance-damaging-earthquake-shaking). It is an outstanding region for the study of tectonics, yet it is also a mostly inaccessible frontier region. In-depth studies have tended to focus on the analysis of convergent (subduction) and strike-slip structures in the eastern and southern parts of the state (e.g. papers in Freymuller et al., 2008) (Fig. 4). Here, subduction of the Pacific Plate operates together with large displacement right-lateral strike-slip fault systems such as the Fairweather, Denali and Tintina faults (Figs. 1, 4). Stresses responsible for intraplate north-south shortening are transmitted from the subducting plate boundary northwards to the Arctic continental margin, based on profuse seismicity, inferred diffuse deformation, and GPS based motions (e.g. Ruppert, 2008; Ruppert et al., 2008; Finzel et al., 2011; Koehler and Carver, 2018; Elliot and Freymuller, 2020) (Fig. 4). How this deformation extends across interior Alaska and its relationship to the Bering Strait region is not well understood. The large displacement right-lateral strike-slip faults that cut through the western Canadian Cordillera and then curve in interior Alaska (the Denali and Tintina-Kaltag faults) in part continue westward but with diminishing total displacement. The diffuse NNE-SSW oriented deformation boundary between the more seismically active eastern part of Alaska and the interior, northern and western parts Alaska appears to track the orientation of the subducting Pacific plate at depth and its passenger, the Yakutat terrane (Fig. 4; Elliot and Freymuller, 2020). Evidence for left-lateral motion and deep transtensional basins is well-documented within a series of parallel seismic zones near and west of Fairbanks (Dixit and Hanks, 2021; Page et al., 1995; Ratchkovski and Hansen, 2002; Ruppert et al., 2008) (Fig. 4). First motions in the eastern Brooks Range Kaktovik earthquake swarm show them to be a permissible parallel left lateral shear zone, however, no clearcut faults have been mapped (Ruppert et al., 2008; Ruppert, 2019) (Fig. 4) and the earthquake swarms are not continuous in map view with the left-lateral shear zones near Fairbanks (Fig. 4). This pattern of seismicity suggests possible changes in strain rate and/or nature of strain from east to west with partial decoupling between these two parts of the state in a left-lateral sense (Fig. 4, yellow arrows). This seismically active region also served to define the eastern boundary of the Bering Sea plate (Fig. 1) (Mackay et al., 1997). Deformation in the western part of the state has been modelled based on GPS data and seismicity and helps define this plate which is moving SW with respect to eastern Alaska (e.g. Elliot and Freymuller, 2020; Cross et al., 2008; Freymuller et al., 2008; Ruppert et al., 2008; Koehler and Carver, 2018) (Inset diagram, Fig. 4).

Earlier kinematic models to explain the geologic evolution of the Bering Strait region and Seward Peninsula depict its geology as the result of lateral (westward) escape of strike-slip bound crustal fragments as strain changes from N-S shortening in eastern Alaska to north-south extension in the Bering Strait (e.g. Scholl and Stevenson, 1991; Scholl et al., 1992; Dumitru et al., 1995). This "Aegean style" deformation was suggested to have begun as early as the Cretaceous based on geologic relationships, the presence of Paleocene/Eocene/Oligocene offshore basins (Fig. 1) and geochronology and thermochronology studies (e.g., Dumitru et al., 1995; MacDannell et al., 2014; Miller et al., 2017). Although this model may help explain Cretaceous to Cenozoic motions that led to the formation of offshore transtensional basins on the Bering Shelf, these basins seem to have persisted in their current positions, with little younger deformation, for a long time compared to a similarly long time-span of continuing crustal shortening in eastern Alaska (Fig. 4). Figs. 6a and b schematically show how these differences in tectonic histories in the eastern and western portions of Alaska have persisted through time, using the structural chronology of Moore and Box (2016) for northern and central Alaska:



TIME	BERING SHELF REGION	INTERIOR AND EASTERN ALASKA	TIME	MAP EVENT
15-0 Ma	·5-6 Ma to present: eruption of mantle derived basalt ·small motion on existing crust-penetrating structures ·Bering block begins to crack	·shallow slab subduction of Yakutat terrane ·Beaufort fold and thrust belt NE Brooks continues ·strike slip faulting continues	15-0 MA	4
34-15 Ma	·sedimentation continues in offshore basins Not much going on	·stresses transmitted to Brooks Range and beyond ·Beaufort fold belt begins ·strike slip faulting continues	35-15 Ma	3
66-34 Ma	Formation of offshore basins: Hope, Kotzebue, Norton ·syn-extensional Paleocene magmatism ·Subduction begins beneath Aleutians 55-45Ma ·Begin Bering Shelf edge basins form	·Shortening steps north to Brooks Range ·Map-scale thick skinned folds and thrust faults ·strike slip faulting continues	66-34 Ma	2
86-66 Ma	·Tail end of syn-extensional Cretaceous magmatism ·Magmatism migrates southward at ~ 70 Ma	·Deformation by folding and thrusting of marine basins: Kahlitna, Kuskokwim, Lower Yukon-Koyukuk, Kobuk-Koyukuk	86-66 Ma	1

Figure 6a and b. 6a. General regions of deformation in eastern and interior Alaska summarized from Moore and Box (2016) and color-coded to right-hand side of chart in 6b. White arrows, shortening direction. Base map of Kirschner (1988) shows location of Bering Shelf basins. For explanation, see text. 6b. Chart comparing timing of deformation and nature of deformation (purple is extensional, pink is shortening) on the Seward Peninsula, Bering Shelf and Chukotka versus interior and eastern Alaska. From Moore and Box (2016) and Bering Shelf from Akinin et al. (2020) and Miller et al. (2017).

1. In the Late Cretaceous to early Cenozoic (86 to 66 Ma) several broad regions of deep marine basins filled with clastic deposits underwent uplift by folding and thrust faulting during N-S to NW-SE shortening, resulting in the closure of the Kahlitna, Kuskokwim, Lower Yukon-Koyukuk Kobuk-Koyukuk basins (Moore and Box, 2016) (Fig. 6a and b). The Bering Shelf saw the waning intrusion of syn-extensional Cretaceous granites and the southward migration of magmatism in the Paleocene, during continued extension (Fig. 6a and b) (Akinin et al., 2009; Miller et al., 2017).

2. In the early Cenozoic (66-34 Ma ago), marine basins that had existed in central Alaska had closed; stress related to Pacific plate subduction was transmitted across this region to the Brooks Range to the north, and N-S shortening resulted in thick-skinned,

map scale, long wavelength and low amplitude folding and thrust faulting (Moore and Box, 2016) (Fig. 6a and b). The crust at depth on the Bering Shelf, intruded by Paleocene magmas (Fig. 5) was likely still mobile and transtension formed deep elongate sedimentary basins along the outer edge of the Bering Shelf: the Anadyr, Navarin, St. George, and Bristol Bay basins (Cooper et al. 1987; Worrall, 1991) (Figs. 1, 6a and b).

3. In the interval 34 to 15 Ma ago, stress transmission across Alaska caused deformation to extend further north, forming a fold and thrust belt with large scale antiforms and synforms on the North Slope of Alaska and into the Canada Basin (Moore and Box, 2016) (Fig. 6a and b). Not much occurred in the Bering Shelf region except for the continued filling of basins.

4. In the last 15 Ma, stress transmission across Alaska allowed continued deformation in the eastern Brooks Range and the Beaufort fold belt (Moore and Box, 2016) (Fig. 6a and b). In this time frame, subduction of the oceanic plateau portion of the Yakutat terrane began, underplating the overlying continental plate during shallowing of the subducting slab. This is thought to have begun less than 10 Ma ago and the terrane now underlies southern and central Alaska for about 250 km to the north of the margin (Fig. 4) (e.g. Elliott and Freymuller, 2020). Most of the uplift related to flat slab subduction took place 6 Ma and forward (Moore and Box, 2016). The left-lateral zones of seismicity developed in the upper plate north of the extent of the subducted shallow slab, and decoupling began between eastern and western Alaska Fig. 4). The thinner lithosphere and higher LAB beneath central and western Alaska may be due to mantle upwelling and westward flow of mantle in response to shallow slab subduction of the Pacific plate and Yakutat terrane. It might also be related to foundering of cold thickened mantle after the extensive shortening that caused the closure of the marine basins across interior Alaska in the latest Cretaceous. Viewed within this temporal framework (Fig. 6a and b), the eruption of the Bering Strait basalt province and extensional deformation in the Bering Strait region represents renewed but geologically young deformation leading to the onset of "cracking" of the Bering Strait block. Contemporary deformation and the eruption of basalts began by utilizing pre-existing zones of weakness in the crust and mantle across this region.

5. CONCLUSIONS

A review of the geology of the CAHSB on the Seward Peninsula and adjacent Chukotka shows that the region is actively deforming due to N-S extension mostly on E-W trending faults that are capable of generating earthquakes. However, although youthful, this deformation involves little total horizontal extension and appears to re-activate older (extensional) structures formed primarily during the Cretaceous to Eocene. Perhaps these re-activated structures cut deep into the crust and provide fluid pathways for geothermal circulation.

Magma chemistry and nature and age of mantle and crustal xenoliths found in 5-6 Ma to Recent basalt flows suggest that melt sources are deep (>1.5 GPa) and erupted at the surface with little or no residence time in shallower magma chambers (Wirth et al., 2002; Akinin et al., 1997). Young mafic intrusions are thus not likely heat sources in the crust in the western CAHSB. These data also support the eruption of basalts in an extensional tectonic setting, utilizing pre-existing deep zones of weaknesses in the crust and mantle.

Regional geology and tectonic considerations suggest that 80 Ma of northward-migrating crustal shortening affected Alaska while crustal extension and basin formation occurred in westernmost Alaska and across the Bering Shelf. This pattern of strain or deformation through time is like that observed today. Through time, north-south shortening was increasingly focused into a narrower zone in eastern Alaska especially during the shallow subduction of the Yakutat terrane in the last 10 Ma. Contemporary earthquakes define broad left-lateral shear zones that appear to decouple northward motion of eastern Alaska with respect to western Alaska which is moving relatively south and southwest. During this youngest time frame, western Alaska and the Bering Strait region began to deform by localized reactivation of older extensional structures during the rise of mantle asthenosphere (LAB) to 60-100 km depth beneath the Seward Peninsula in concert with the eruption of mantle-derived basalts.

Exploration for geothermal resources should focus on the Seward Peninsula-Chukotka region characterized by earthquakes that indicate N-S extension and where sites of eruption of mantle derived basalts exist. Blind geothermal systems should be considered in northernmost Seward Peninsula in the region of the Kotzebue Basin and Selawik Trough, which are pre-existing E-W trending structures that cut deep in the crust and could be reactivated in the present-day stress field.

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