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Regional crustal-scale structures as conduits for deep geothermal upflow

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ABSTRACT

Geothermal fluids produced from two of the largest production geothermal fields in the Great Basin have helium isotope ratios that are anomalously high relative to basin-wide trends. These data indicate that the geothermal systems, Dixie Valley, Nevada and McGinness Hills, Nevada have an anomalously high fraction of mantle derived fluid. These connections to deeply derived fluid and heat may supplement crustal heat production and be responsible, in part, for the anomalously high production capacity, relative to other Great Basin geothermal fields, that Dixie Valley and McGinness Hills support. Deep-seated crustal structures across the Great Basin and around the world are known to be associated with structural reactivation, can have relatively high permeability, and can act as fluid flow conduits. These deep seated structures across the Great Basin control upflow of deeply derived heat and fluids into the shallow geothermal systems at Dixie Valley and McGinness Hills, contributing to their productivity.

1. Introduction

The deeply derived component of geothermal fluids can be interpreted from the helium isotope ratio of the fluids. The light isotope, ^{3}He, is primarily present in the Earth's mantle, originating during planetary accretion. ^{4}He is present in abundance in the Earth's crust, continually produced through radioactive decay of uranium and thorium (Craig et al., 1978; Kennedy et al., 1997, 1985; Oxburgh and O'Nions, 1987). The ratio of ^{3}He to ^{4}He in geothermal fluids is therefore indicative of the relative abundances of mantle and crustal derived volatiles in those fluids. Geothermal fluids produced at Dixie Valley, Nevada and McGinness, Nevada have $^{3}He/^{4}He$ that is anomalously high relative to regional trends (Fig. 1), indicative of an anomalously high fraction of mantle derived fluids (Kennedy and van Soest, 2007, 2006). This signal also indicates relatively rapid upwelling, in order for mantle derived fluids to reach the near-surface before dilution by crustal ^{4}He (Kennedy and van Soest, 2007, 2006; Kennedy et al., 1997). The relatively rapid upflow of deeply derived mantle fluids through the crust and into shallow geothermal systems is probably associated with discrete, through-going crustal permeability pathways. Similar rapid upflow of mantle derived fluids and anomalously high $^{3}He/^{4}He$ has been demonstrated to occur along other crustal-scale structures, for example the San Andreas fault system (Kennedy et al., 1997), in the Morongo Basin, California (Kulongoski et al., 2005), and along the Newport-Inglewood fault zone (Boles et al., 2015).

Dixie Valley and McGinness Hills also each support a total gross generation capacity of 72 MWe. The mean gross installed capacity of the other twenty, non-magmatic geothermal fields within the Great Basin is 16 MWe, and no single field supports capacity higher than 50 MWe (capacity data from Geothermal Energy Association, http://geo-energy.org/). The anomalously high productivity of Dixie Valley and McGinness Hills, relative to other Great Basin systems may be related to this connection to deeply derived fluids and the associated heat advection occurring with fluid upflow (e.g., Kennedy and van Soest, 2006). We hypothesize that ancient, structural zones serve as deeply extending permeability conduits and rapidly transmit mantle derived fluids and heat to the surface at Dixie Valley and McGinness Hill. To test this, we evaluate the crustal-scale structures local to Dixie Valley and McGinness Hills as well as across the Great Basin for evidence for modern fluid upflow.

2. Helium anomalies

Crustal fluids have $^{3}He/^{4}He$ isotopic ratios of ~0.02 Ra (Ra is $^{3}He/^{4}He$ in air), while mantle derived helium has a $^{3}He/^{4}He$ of ~8.0 Ra or higher (Craig et al., 1978; Kennedy et al., 1997, 1985; Kulongoski et al., 2005). From east-to-west across the Great Basin,

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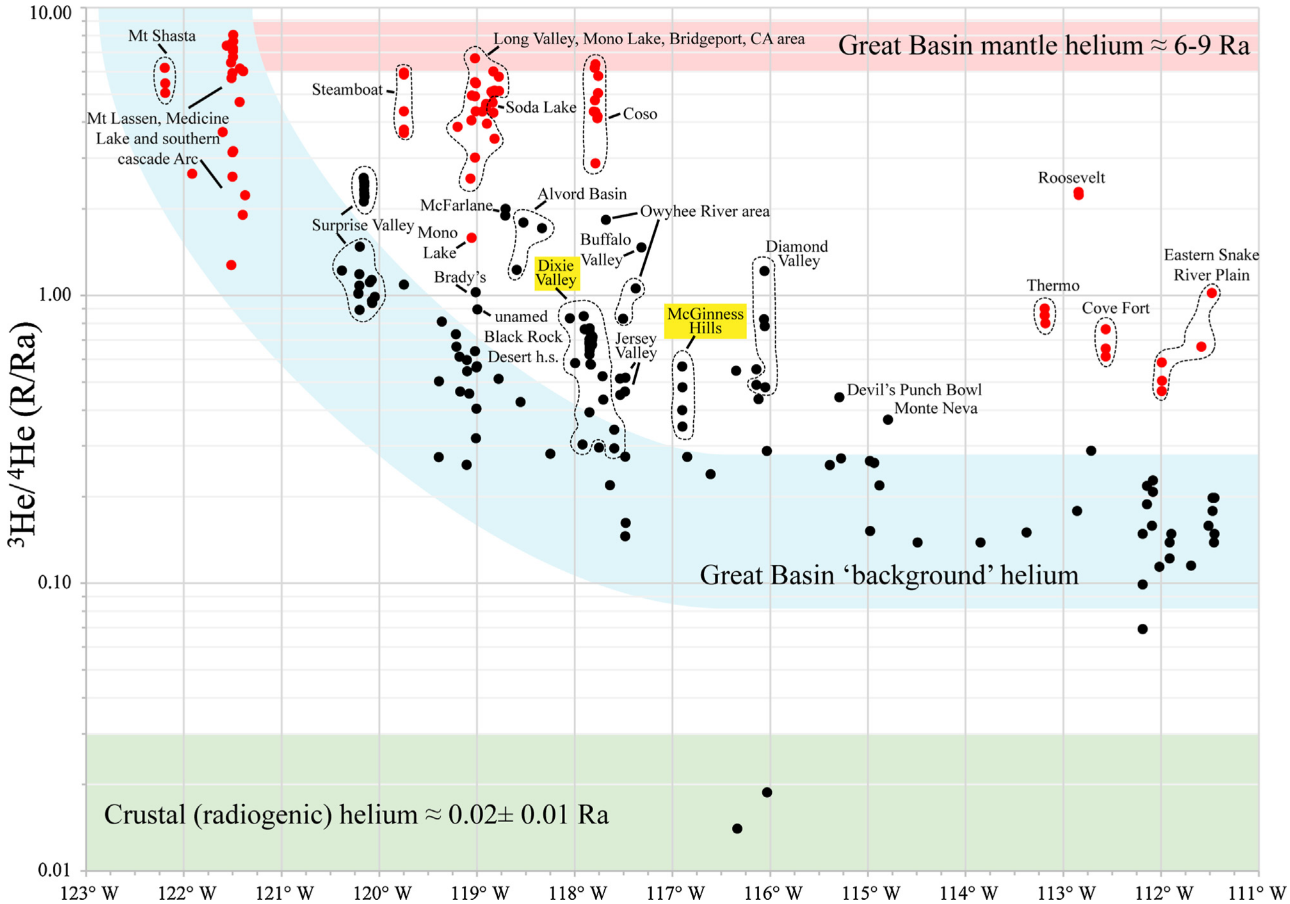

Fig. 1. $^3He/^4He$ vs. longitude across the Great Basin. Magmatic systems in red are interpreted based on the presence of known local Pleistocene and younger magmatic activity. $^3He/^4He$ data from (Craig et al., 1978; Hunt et al., 2005; Kennedy and van Soest, 2007, 2006; Kennedy et al., 2000; Newell et al., 2005; Tonani et al., 1998; Torgersen and Jenkins, 1982; B.M. Kennedy unpublished data, personnal comm.). Background, crustal and mantle $^3He/^4He$ fields from (Craig et al., 1978; Kennedy et al., 1997, 1985; Kulongoski et al., 2005).

the 'background' $^3He/^4He$ in geothermal fluids increases from ~0.2 Ra along the eastern boundary of the Great Basin to ~2.0 Ra along the western margin (Fig. 1; data from Craig et al., 1978; Hunt et al., 2005; Kennedy and van Soest, 2007, 2006; Kennedy et al., 2000; Newell et al., 2005; Tonani et al., 1998; Torgersen and Jenkins, 1982; B.M. Kennedy unpublished data). $^3He/^4He$ values of 0.2 corresponds to a mantle helium fraction of a few percent (Kennedy et al., 1997), and are ~10× higher than the average crustal $^3He/^4He$ values. The east-to-west increase of ~0.2–2.0 Ra in Great Basin geothermal fluids corresponds to an exponential increase in the fraction of mantle helium from a few percent to as much as ~25% across the Great Basin (based on calculations by Kennedy and van Soest, 2007; Kennedy et al., 1997).

The presence of an elevated (realtive to crustal values) $^3He/^4He$ signature in shallow geothermal fluids can arise through direct mixing with mantle derived fluids or by the interaction of geothermal fluids with young, mantle derived magmatic rocks (Kennedy and van Soest, 2007, 2006; Kennedy et al., 1997; Kulongoski et al., 2005; Torgersen and Jenkins, 1982). Magmatic geothermal systems occur along the periphery of the Great Basin, throughout the western United States and around the world (e.g., Moeck, 2014). Within the interior of the Great Basin however, there is little evidence for active magmatism. In the absence of active magmatism, the background ~0.2–2.0 Ra $^3He/^4He$ trend in geothermal systems within the Great Basin is a function of mixing with deeply derived mantle fluids and an east to west increase in the fraction of those mantle derived fluids (Kennedy and van Soest, 2007, 2006). This signal also indicates relatively rapid upwelling from the mantle and an east to west increase in the rate of upwelling, in order for mantle derived fluids to reach the near-surface before dilution by crustal ^4He (Kennedy and van Soest, 2007, 2006; Kennedy et al., 1997).

2.1. Magmatic helium in geothermal systems around the periphery of the Great Basin

Magmas are extensively degassed during emplacement and eruption, so fluids must circulate through an active or very young magmatic system in order to obtain a ^3He signature associated with that magmatism (Kennedy and van Soest, 2006). Torgersen and Jenkins (1982) suggest that magmatic systems ~1.1–1.5 Ma may be sufficiently young to impart magmatic helium signatures to geothermal fluids, while Kennedy and van Soest (2007) suggest that magmatism older than ~8.0 Ma is too old impart anomalous $^3He/^4He$ on geothermal fluids. Within those constraints, the $^3He/^4He$ values in geothermal systems around the magmatically active periphery of the Great Basin including the southern Cascade volcanic arc (1.2–8.1 Ra), Roosevelt hot springs (0.22–0.23 Ra), Cove Fort (0.62–0.77), and Thermo (0.80–0.91 Ra), in Utah, at Steamboat (1.1–6.0 Ra) and Soda Lake (4.3–4.2 Ra) in Nevada, at Coso (2.9–6.4 Ra), Mono Lake (1.6–5.5 Ra), and the Long Valley (2.5–6.7 Ra) area, in California and in the eastern Snake River Plain (0.47–1.0 Ra), in Idaho (Figs. 1 and 2) are probably associated with interaction of geothermal fluids with local Pleistocene and younger magmatic systems (e.g., Bacon et al., 1980; Bailey et al., 1976; Hunt et al., 2005; Koenig and McNitt, 1983; McCurry et al., 2011; Ross and

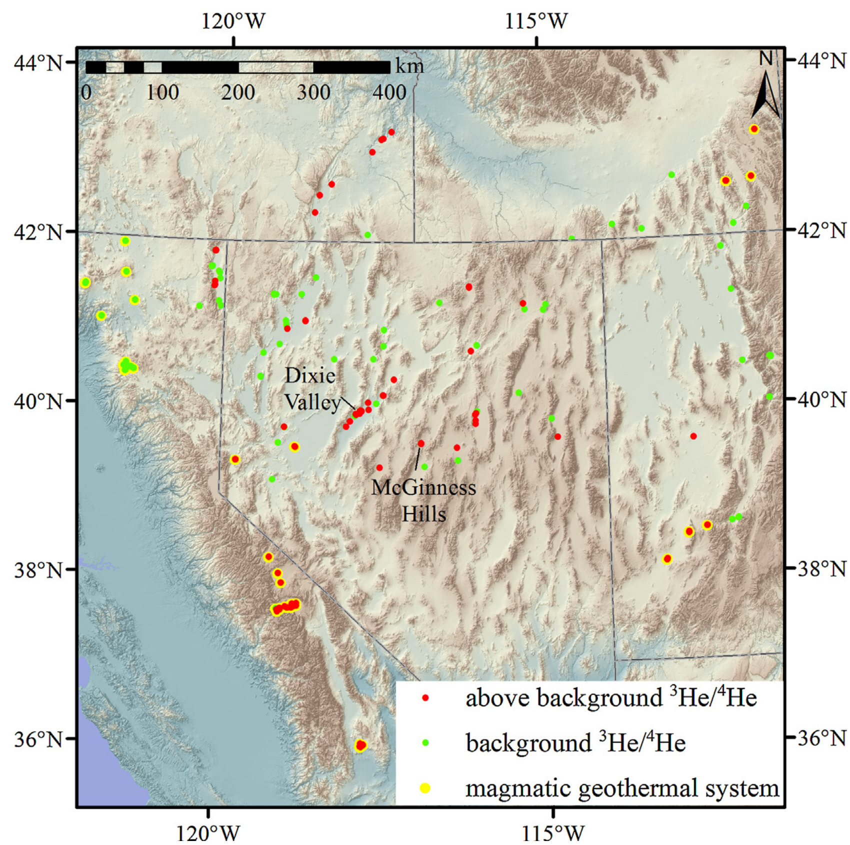

Fig. 2. Map of $^3He/^4He$ in geothermal fluids across the Great Basin. Above background vs. background based on Fig. 1. Magmatic systems (halo) are interpreted based on the presence of known local Pleistocene and younger magmatic activity. $^3He/^4He$ data from (Craig et al., 1978; Hunt et al., 2005; Kennedy and van Soest, 2007, 2006; Kennedy et al., 2000; Newell et al., 2005; Tonani et al., 1998; Torgersen and Jenkins, 1982; B.M. Kennedy unpublished data, personnal comm.).

Moore, 1985; Torgersen and Jenkins, 1982; Zhang and Lin, 2014) rather than mixing with upwelling of mantle derived fluids.

2.2. Amagmatic helium in geothermal systems within the Great Basin

The background $^3He/^4He$ trend in geothermal fluids across the Great Basin is ~0.2–2.0 Ra and increases exponentially from east to west (Fig. 1). With no evidence for active magmatism throughout the interior of the Great Basin this $^3He/^4He$ signal is related to upwelling of mantle derived fluids. The increase from east to west in $^3He/^4He$ values is a function of an east to west increase in strain rates causing a similar east to west increase in mean crustal permeability and fluid upflow rates (Kennedy and van Soest, 2007). Increasingly rapid upwelling results in higher $^3He/^4He$ values because mantle derived fluids spend less time in the crust where they are subject to dilution by crustal ^4He (Kennedy and van Soest, 2007, 2006; Kennedy et al., 1997). Superimposed upon this background trend are local spikes, $^3He/^4He$ values that are anomalously high relative to the background trend. Notable Great Basin geothermal systems of this type include McGinness Hills (0.35–0.57 R/Ra) and Dixie Valley (0.31–0.84 Ra) as well as Brady's hot spring (0.41–1.0 Ra), Devil's Punch Bowl (0.44 Ra), Monte Neva (0.37 Ra), and several systems in Diamond Valley (0.48–1.2 Ra), Jersey Valley (0.45–0.52 Ra), Buffalo Valley (1.5 Ra), and the Black Rock Desert area (0.90–2.0 Ra), all in Nevada, several systems in Surprise Valley (2.1–2.6 Ra), California and several systems in the Alvord Basin and along the Owyhee River (1.2–1.8 Ra) area in Oregon (Figs. 1 and 2). These anomalous $^3He/^4He$ values are several times higher than the Great Basin background $^3He/^4He$ values at corresponding longitudes and $\sim 30x \geq 100x$ higher than crustal $^3He/^4He$ values. Again, with no known, sufficiently young local magmatism, anomalous $^3He/^4He$ in these systems are associated with local mantle fluid upwelling that is more rapid than the 'background' mantle fluid upwelling occurring throughout the interior of the Great Basin. Kennedy et al., (1997) suggest anomalous $^3He/^4He$ along the San Andreas fault system is associated with rapid upwelling of mantle derived fluids along the fault system. Similarly, the rapid apparent rapid upwelling of mantle derived fluids across the Great Basin is probably associated with similar zones of relatively high permeability that extend from the near surface to the base of the crust (Kennedy and van Soest, 2007, 2006; Kennedy et al., 1997). We hypothesize that these deep permeability conduits occur along ancient, deeply extending crustal structures that have been tectonically reactivated many times throughout the evolution of the Great Basin, continually generating and maintaining their permeability. These structures are again reactivated for crustal-scale fluid upflow into modern geothermal systems.

3. Crustal structures

Major structural discontinuities are relatively abundant in the Earth's continental crust and lithosphere. These structural zones are generated by plate-scale tectonic activity and tend to be reactivated by subsequent tectonic events throughout geologic time (e.g., Butler et al., 1997; Crafford and Grauch, 2002; Daly et al., 1989; Dewey et al., 1986; Grauch et al., 2003; Sykes, 1978). Tectonic reactivation of these structures occurs as a result of their weakness relative to the surrounding intact crustal or lithospheric materials caused by the generation of mechanically weak alteration materials, deformation related materials or deformation fabrics, and/or by high pore fluid pressures (Butler et al., 1997; White et al., 1986).

Very high fluid pressure in particular is necessary for reactivation of structures that are miss-aligned relative to the tectonic stress regime, for example reactivation of highly oblique structures or reactivation of shallowly dipping thrust structures for extension (Sibson, 1985). Coupled with the fact that reactivated structural zones have been shown to control fluid flow associated with ore deposition in the Great Basin and around the world (Breach, 1976; Glen and Ponce, 2002; Grauch et al., 2003; Muntean et al., 2007; Pili et al., 1997; Ponce and Glen, 2002; Rasmussen et al., 2007; Tosdal et al., 2000), this suggests that structural reactivation can be associated with significant permeability enhancement. Permeability enhancement and fluid flow along structures are probably episodic and structures may alternate between open to fluid flow and being effectively sealed to fluid flow in both space and throughout time (Sibson, 1995). In addition to fluid flow, crustal structures also focus intraplate (distal from modern tectonic plate boundaries) seismicity and magmatism (Daly et al., 1989; Sykes, 1978).

The western Cordillera of North America underwent continental-scale rifting in the late-Proterozoic and has undergone nearly continuous, collisional, extensional and strike-slip deformation since the Devonian (Dalziel, 1997; Dickinson, 2006; Lund, 2008 and references therein). These deformational events have generated a series of crustal- and lithospheric-scale structures of varying character and age throughout the Great Basin. These structures are generally not manifest as single, map-able features, but have been interpreted based on regional-scale geologic structural and terrane mapping, regional isotopic studies and regional-scale geophysical studies and probably represent broad (hundreds of meters or more wide) crustal zones with variable lithologic character.

3.1. Wasatch Front

The eastern margin of the Basin and Range province lies along the Wasatch Mountains in central Utah and marks the eastern extent of Cenozoic-to-modern Basin and Range extensional deformation across the Great Basin (Fig. 3). This area has also been the locus of several plate-scale tectonic events dating back to the Late Proterozoic. We will refer to this structural zone as the Wasatch Front. The Wasatch Front may have developed as a major tectonic boundary as early as the late Proterozoic, associated with rift structures during rifting and the formation of the passive continental margin of Laurentia (Allmendinger et al., 1987; Bissell, 1974; Burchfiel et al., 1992; Dalziel, 1997; Karlstrom et al., 1999; Stewart, 1972), although isotopic studies have shown that the terminal edge of the craton lies farther to the east (Crafford and Grauch, 2002; Grauch et al., 2003; Wooden et al., 1998). The Wasatch Front was also active as the fulcrum for subsidence of the Laurentian passive margin to the west during late Proterozoic though the Triassic (Bissell, 1974; Stewart, 1980) and was subsequently reactivated in the Jurassic-Cretaceous as an axis of thrusting during the Sevier orogeny (DeCelles and Coogan, 2006). The Sevier belt may have been connected to the contemporaneous Luning-Fencemaker thrust system in central Nevada (Fig. 3) through a common mid- to lower-crustal shear zone (Oldow, 1984).

The Wasatch Front has remained active through Miocene-to-recent times as the eastern extent of normal faulting during Basin and Range extension (Cluff et al., 1975; Wernicke, 1992) and a locus of strain (Hammond, 2004; Hammond et al., 2014; Kreemer et al., 2012). Voluminous 2.5 Ma-to-Holocene mafic volcanism in the Grand Canyon-Black Rock Belt that occurs along the Wasatch Front is a result of focused lithospheric extension along the Wasatch Front (Nelson and Tingey, 1997 and references therein). Pre-existing structures may have been reactivated as conduits for rising magmatic material (Koenig and McNitt, 1983). The Wasatch Front is also characterized by a significant increase from west-to-east in crustal thickness and in the depth of the lithosphere-asthenosphere boundary (Allmendinger et al., 1987; Levander and Miller, 2012), though the relative magnitude and precise locations of these thickness transitions vary in the literature (Nelson and Tingey, 1997 and references therein).

3.2. Eastern extent of Mesozoic magmatism and metamorphism

To the west of the Wasatch Front, the eastern extent of Mesozoic metamorphism and magmatism (Fig. 3) is another crustal-scale structural zone that may have an impact on modern crustal fluid flow. This feature is the eastern extent of plutonic rocks and related metamorphic rocks associated with subduction and terrane accretion during the Mesozoic Nevadan and Sevier orogenies (Schweickert and Cowan, 1975) and was reactivated as a zone of focused extension and exhumation of mid-crustal rocks on abnormally weak normal fault zones in the Eocene-Oligocene (Allmendinger et al., 1987; Wernicke, 1992; Wernicke et al., 1987). The eastern extent of Mesozoic plutonic and intrusive rocks is also the eastern extent of the pronounced, relatively shallow (~30 km) Moho (the geophysical boundary interpreted as the base of the crust) in the central Great Basin (Allmendinger et al., 1987).

3.3. Edge of the Proterozoic craton

Further to the west, the western edge of the Proterozoic Laurentian craton is a structural boundary that has been reactivated during numerous tectonic and hydrothermal fluid flow events. The western edge of the Laurentian craton was originally defined by the Sr = 0.706 line (Kistler, 1990; Oldow, 1992), but more recent lead and strontium isotopic studies (Crafford and Grauch, 2002; Grauch et al., 2003; Wooden et al., 1998) and sedimentary facies studies (Lund, 2008) have delineated the edge of the craton with a higher degree of detail (Fig. 3). In the Great Basin, these studies delineate a northwest striking continental margin, and have defined boundaries, from east-to-west, between undeformed continental crust, thinned and extended continental crust and crust of oceanic affinity (Fig. 3). Though the north–northwest striking late Proterozoic rift segments are orthogonal to pre-existing structures, transform/transfer zones may reactivate even older inferred northeast-striking Paleo- to Mesoproterozoic basement structures (Lund, 2008).

Structures associated with the western margin of the Laurentian craton are known to be important controls on shallow magmatism and fluid flow associated with the prolific Eocene–Oligocene sediment-hosted disseminated (Carlin-type) gold deposits in central and northern Nevada (Crafford and Grauch, 2002; Grauch, 1998, 1995; Grauch et al., 2003, 1998; Henry and Boden, 1998; Wooden et al., 1998; Fig. 2). Concurrent hydrothermal fluid flow and ore deposition along the Getchell, Crescent Valley-Independence and Alligator Ridge mineral trends (Fig. 3) is also interpreted to have been controlled by preexisting, possibly Proterozoic, crustal structures, though the age and nature of the structures remain more ambiguous (Cline et al., 2005; John et al., 2003; Lund, 2008).

The Roberts Mountain thrust system associated with the Devonian–Mississippian Antler orogeny, the Golconda thrust system associated with the Permian–Triassic Sonoma orogeny (Miller et al., 1992; Oldow, 1984; Speed and Sleep, 1982; Speed, 1977) and the Jurassic–Cretaceous Luning-Fencemaker thrust system (Hardyman and Oldow, 1991; Oldow, 1984; Wyld, 2002) are coincident with and may have reactivated structures associated late Proterozoic rifting as well (Grauch et al., 2003).

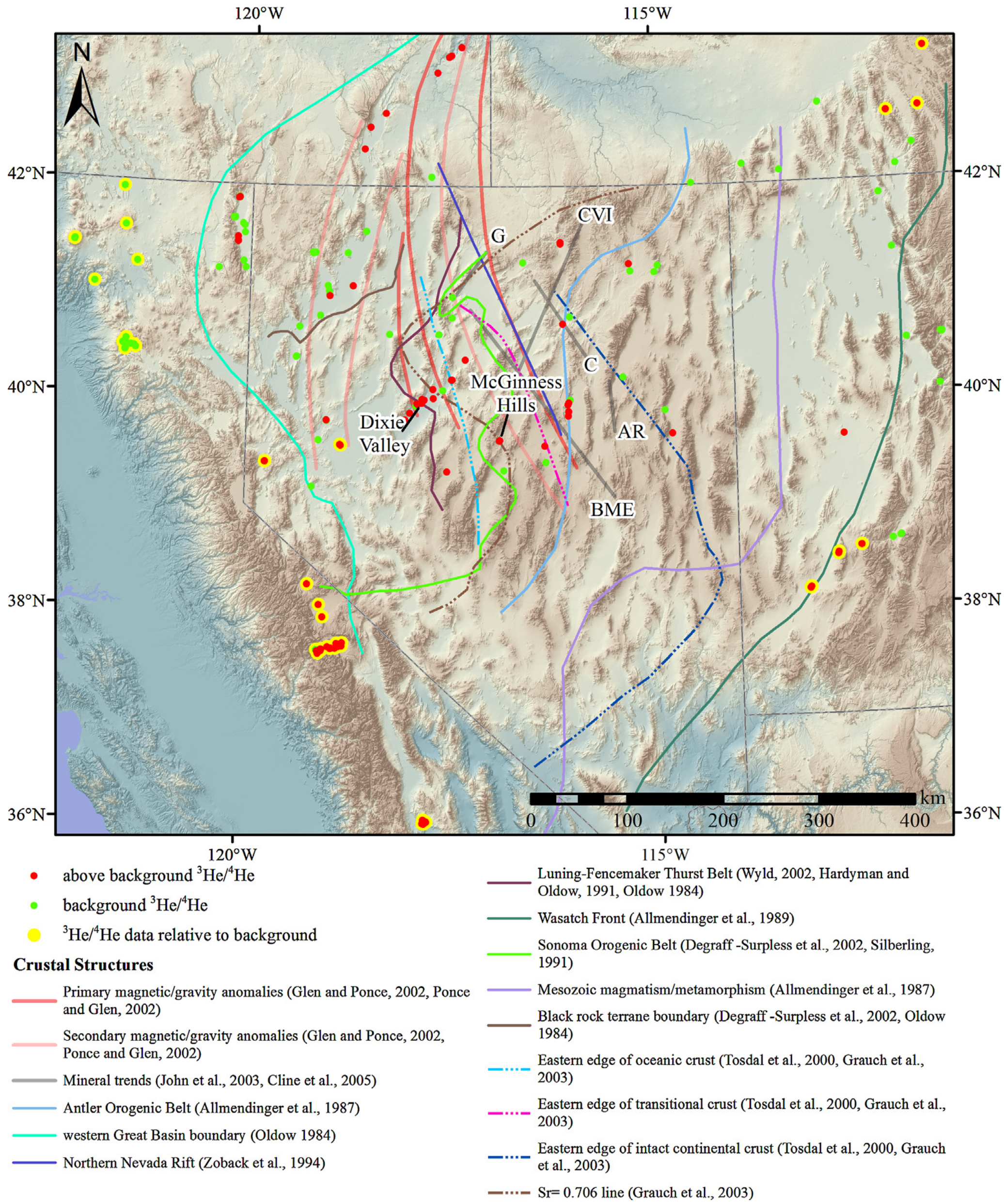

Fig. 3. Map of Great Basin crustal-scale structures and $^3He/^4He$ data. Above background vs. background based on Fig. 1. $^3He/^4He$ data from (Craig et al., 1978; Hunt et al., 2005; Kennedy and van Soest, 2007, 2006; Kennedy et al., 2000; Newell et al., 2005; Tonani et al., 1998; Torgersen and Jenkins, 1982; B.M. Kennedy unpublished data, personnal comm.). Crustal structures from (Allmendinger et al., 1987; Degraaff-Surpless et al., 2002; Dilek and Moores, 1995; Glen and Ponce, 2002; Grauch et al., 2003; Hardyman and Oldow, 1991; Oldow, 1984; Ponce and Glen, 2002; Silberling, 1991; Tosdal et al., 2000; Wyld, 2002; Zoback et al., 1994). Mineral trends; BME = Battle Mountain-Eureka, C = Carlin, AR = Alligator Ridge, G = Getchell, CVI = Crescent Valley-Independence (Cline et al., 2005; John et al., 2003).

3.4. Northern Nevada rift

Magmatism and faulting associated with the mid-Miocene northern Nevada rift (Fig. 3) may also have reactivated crustal structures associated with late Proterozoic rifting (Ponce and Glen, 2002), though the near surface geometry of rift related faults and intrusions was probably controlled the prevailing stress conditions at the time (Zoback et al., 1994). Rift related structures likely channeled both concomitant magmatic material and hydrothermal fluids during rifting as well as during a second phase of younger epithermal mineralization (Ponce and Glen, 2002; Wallace and John, 1998). Several arcuate magnetic and gravity anomalies lie coincident with and to the west of the northern Nevada rift (Fig. 3). These have been interpreted as deep crustal structures related to the northern Nevada rift and to the contemporaneous impingement of the Yellowstone hot spot on the crust. These structures have statistical proximity to the mid-Miocene and younger epithermal mineral deposits associated with the northern Nevada rift, indicating that they exerted control on the localization of fluid flow (Glen and Ponce, 2002; Ponce and Glen, 2002).

3.5. Black Rock terrane boundary

Lying to the west of structures associated with the late Proterozoic cratonic boundary is the Black Rock terrane (Fig. 3), an accreted Paleozoic–Mesozoic magmatic arc (Oldow, 1984; Wyld, 2002). The Black Rock terrane was probably accreted to North America on a west-dipping thrust system along its eastern boundary during the earliest stages of development of the Jurassic Luning-Fencemaker thrust system. The location and geometry of this structural bound-

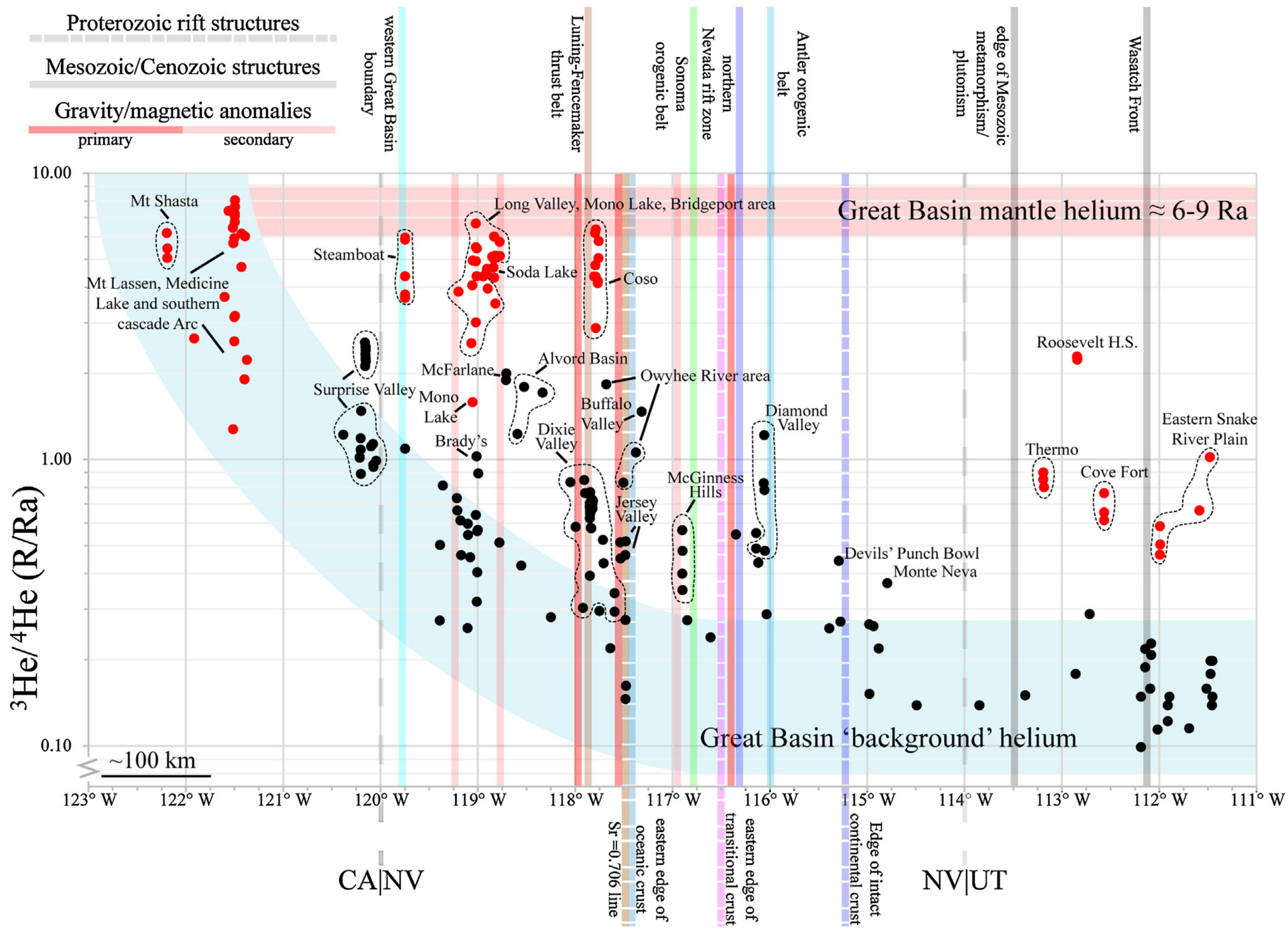

Fig. 4. $^3He/^4He$ vs. longitude and deep seated crustal-scale structures across the Great Basin. Magmatic systems in red are interpreted based on the presence of known local Pleistocene and younger magmatic activity. $^3He/^4He$ data from (Craig et al., 1978; Hunt et al., 2005; Kennedy and van Soest, 2007, 2006; Kennedy et al., 2000; Newell et al., 2005; Tonani et al., 1998; Torgersen and Jenkins, 1982; B.M. Kennedy unpublished data, personnal comm.). Background and mantle $^3He/^4He$ fields from (Craig et al., 1978; Kennedy et al., 1997, 1985; Kulongoski et al., 2005). Structures plotted at their longitude at 40° N latitude, the latitude of the Dixie Valley geothermal system. Crustal structures are the same as Fig. 3.

ary, however, are obscured in many locations by Cenozoic basin fill, and thus are not particularly well constrained (Wyld, 2002).

3.6. *Western Great Basin boundary*

The western boundary of the Great Basin is coincident with the Pine Nut fault (Fig. 3), an inferred Jurassic–Cretaceous sinestral strike-slip system which bounded the eastern side of the Sierran magmatic arc (Oldow, 1984). This boundary along the eastern side of the modern Sierra Nevada mountains has been reactivated by subsequent Miocene-to-recent Basin and Range extension and by dextral strike-slip deformation in the Walker Lane and eastern California shear zone (Faulds and Henry, 2008; Faulds et al., 2005; Stewart, 1988) and is associated with young magmatism modern crustal strain-rates that are high relative to rest of the Great Basin (Hammond, 2004; Hammond et al., 2014; Kreemer et al., 2012).

4. Crustal temperatures

Crustal scale structural zones acting as conduits for rapid upflow of mantle derived fluid may have a significant effect on local crustal temperatures. Fluid advection through the crust is a much more efficient means of heat transport than conduction. Anomalously high temperatures at shallow depths are generally related to shallow geothermal circulation (e.g., Blackwell, 1983), accordingly, anomalously high temperatures at deeper levels may be indicative of crustal-scale fluid upflow along discrete conduits. Kennedy and van Soest (2006), for instance, suggest that as much as ~3–30 mWm^{-2} of the ~90 mWm^{-2} total heat flux at Dixie Valley, Nevada may be associated with heat flux provided by upwelling mantle derived fluids. Heat flow data (Williams and DeAngelo, 2011) and bottom hole temperature databases from more than 36,000 wells as deep as ~6600 m from across the Great Basin (NGDS, http://geothermaldata.org/) show that heat flow is relatively high along the western boundary of the Great Basin, through central and northern Nevada and western Utah and along the Wasatch Front. Relatively high heat flow along the western and eastern margin of the Great Basin is probably associated with young magmatism, while relatively high heat flow in central and western Nevada occurs collocated with a high density of many recognized deep crustal structures (Fig. 5) and with anomalous $^3He/^4He$ in Dixie Valley, Jersey Valley and Buffalo Valley, Nevada (Fig. 4). Bottom hole temperatures in all wells and in wells deeper than 2000 m are also higher proximal to the crustal structures that we analyzed (Fig. 5 inset).

5. Crustal conductivity data

Zones of relatively high electrical conductivity in the crust can be related to magmatism, increased fluid content and/or to the

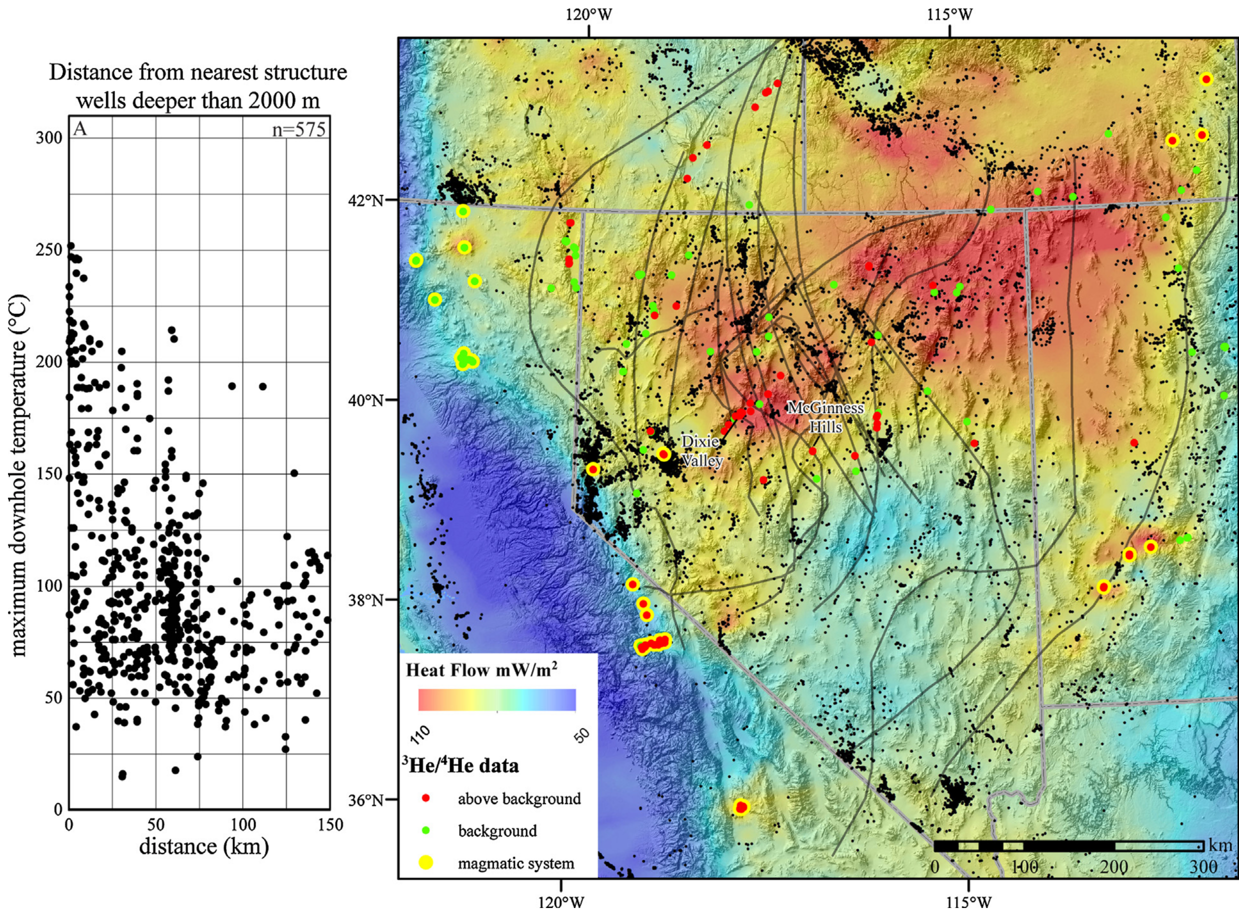

Fig. 5. Left side: Bottom hole temperature for wells deeper than 2000 m vs. distance to crustal structure. Bottom hole temperature databases from Arizona, California, Idaho, Nevada, Oregon and Utah from the National Geothermal Data System (http://geothermaldata.org/) Right side: Heat flow and crustal-scale structures across the Great Basin. Bottom hole temperature measurements in black dots. Heat flow data from (Williams and DeAngelo, 2011). Crustal structures are the same as Fig. 3.

development of conductive minerals. All of these can be indicative of modern or past geothermal fluid circulation (Newman et al., 2008; Spichak and Manzella, 2009; Wannamaker et al., 2007, 2006). Magnetotelluric methods in particular are commonly used at the geothermal field-scale in order to identify conductive zones and locate and characterize geothermal fluid flow conduits and conductive clay caps (e.g., Bertrand et al., 2012; Cumming and Mackie, 2007; Uchida and Sasaki, 2006; Wannamaker et al., 2013a, 2011, 2008, 2007, 2006). At the crustal- and lithospheric-scale, conductivity anomalies identified by magnetotelluric methods indicate both active and ancient tectonic and magmatic features as a result of modern or past fluid circulation within these structures (e.g., Meqbel et al., 2014). Beneath Dixie Valley, Nevada for instance a zone of relatively high electrical conductivity at ~20 km depth extends all the way to the near-surface. This feature has been interpreted to represent basaltic underplating at the base of the crust, associated fluid release and fluid upwelling towards the surface (Wannamaker et al., 2013b, 2007).

6. Discussion

Anomalously high $^3He/^4He$ in geothermal fluids at Dixie Valley, Nevada and McGinness Hills, Nevada, as well as in many other geothermal systems (Fig. 2) indicate that these geothermal systems are associated with more rapid upwelling of mantle derived fluids realtive to the geothermal systems with background $^3He/^4He$ values Fig. 6 (Kennedy and van Soest, 2007, 2006). At Dixie Valley, $^3He/^4He$ values are ~3–4× higher than the regional Great Basin background values and ~30–40× higher than typical crustal values (Fig. 1). Conservatively, this corresponds to ~7.5% of total helium as mantle derived helium, and a mantle heat flux of ~3 m Wm^{-2} (Kennedy and van Soest, 2006). However, of the total ~90 m Wm^{-2} heat flow at Dixie Valley, as much as 20–30 m Wm^{-2} is not explained by crustal heat production, so the mantle heat flux may be as high as the 20–30 m Wm^{-2} residual (Kennedy and van Soest, 2006). The relatively high geothermal productivity supported by Dixie Valley (72 MWe total capacity) is suggestive that Dixie Valley is associated with higher recoverable geothermal potential than typical, amagmatic Great Basin geothermal systems, where the mean installed capacity is ~16 MWe (Fig. 1). Though installed capacity is not equivalent to the total thermal power output of a system, in lieu of data to the contrary, we consider installed capacity as a first-order proxy for the power production potential of a system. The supply of mantle derived heat and fluid contribute to this anomalously high geothermal production at Dixie Valley, relative to other geothermal systems in the interior of the Great Basin. The same may be true at McGinness Hills (also 72 MWe total capacity) and other geothermal systems with anomalously high $^3He/^4He$ in geothermal fluids.

The rapid upflow of mantle derived fluids that imparts anomalous $^3He/^4He$ in Great Basin geothermal systems is probably associate discrete zones of relatively high permeability (Fig. 6). Fluid upflow rates of ~1–10 mm/year and a permeability of ~10^{-18}–10^{-21} m^2 associated with similar anomalous $^3He/^4He$ and crustal-scale fluid upflow occur along the San Andreas fault system and in the Los Angeles Basin (Boles et al., 2015; Kennedy et al.,

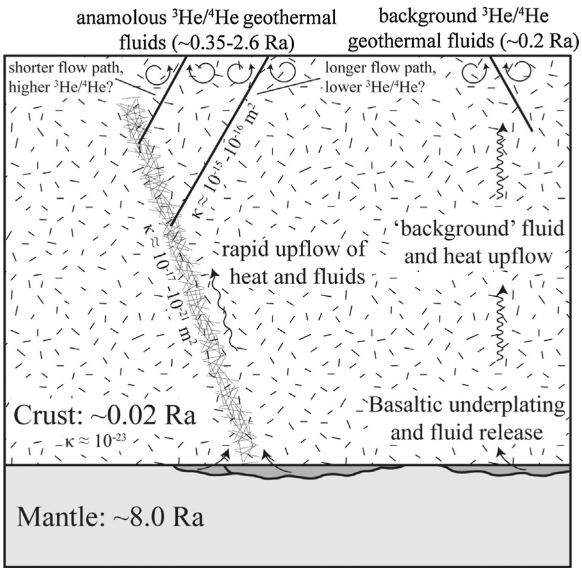

Fig. 6. Conceptual model of the upflow of mantle derived fluids into shallow geothermal systems (modified after Kennedy and van Soest, 2006). Not to scale. Basaltic underplating at the base of the crust releases fluids (e.g., Wannamaker et al., 2013b, 2007) with $^3He/^4He$ ~8.0 Ra. Background flow of these fluids through relatively impermeable intact crust ($\kappa = 10^{-23}$) is relatively slow, allowing for dilation by crustal ^4He. Tapping of these fluids by shallow geothermal systems results in background, ~0.2 Ra geothermal fluids. Relatively rapid (1–10 mm/year) upflow of fluids occurs in permeable ($\kappa = 10^{-17}–10^{-21}$) conduits controlled by crustal-scale structural zones allowing for less dilution by crustal ^4He (Boles et al., 2015; Kennedy et al., 1997). Tapping of these fluids by shallow geothermal systems results in anomalously high $^3He/^4He$ in these geothermal fluids.

1997). Boles et al. (2015) calculate a permeability of ~10^{-17} m^2 associated with deep upflow of mantle helium along a paleo-subduction zone in the Los Angeles Basin. Both of these are several orders of magnitude higher than bulk permeability of intact crystalline rock (~10^{-23} m^2; Ingebritsen et al., 2001). Wisian and Blackwell (2004) estimate permeability in shallow geothermal systems must reach ~$10^{-15}–10^{-16}$ m^2 for natural fluid circulation to occur. Thus, the crustal-scale permeability conduits related to deeply upflow of He^3 bearing fluids are probably not the same structures as those that conduct fluid circulation in shallow geothermal systems (Fig. 6). Still, the anomalous $^3He/^4He$ signal implies the existence of discrete conduits in the crust with permeability that is several orders of magnitude higher than the intact crustal materials. Deeply derived fluids, possibly associated with basaltic underplating at the base of the crust (e.g., Wannamaker et al., 2013b, 2007), upwell along these permeability conduits, are tapped by shallow structures and mix with shallowly derived geothermal fluids in the deep roots of geothermal systems (Fig. 6).

Ancient structures in the crust likely serve as these discrete fluid flow conduits. It is clear that many ancient structures across the Great Basin have been reactivated for subsequent tectonism and fluid flow (e.g., Butler et al., 1997; Crafford and Grauch, 2002; Daly et al., 1989; Dewey et al., 1986; Grauch et al., 2003; Ponce and Glen, 2002; Sykes, 1978; Tosdal et al., 2000). Reactivation of these structures occurs as a result of favorable orientation relative to the tectonic conditions of the time (Butler et al., 1997; Cline et al., 2005; White et al., 1986; Zoback et al., 1994), but also is associated with structural weakness relative to adjacent intact crustal materials, brought on by intense deformation and/or high fluid pressures, both of which indicate permeability enhancement and the presence of fluids. Reactivation of deep structures that are miss-oriented up to ~25° is mechanically possible in the middle crust with sufficiently high fluid pressures (Ranalli, 2000). Assuming modern east–west extension across the Great Basin, nearly the full strike length of all the crustal structures considered here are within this range and thus are satisfactorily oriented for modern reactivation. In the upper crust, strain on faults can lead to grain size and permeability reduction, especially in fault cores. Still, permeability can be elevated by several orders of magnitude in fractured wall rock proximal to fault cores (e.g., Sibson, 1996, 1994, 1986). It remains unclear how structural permeability is generated and maintained in the middle crust and below the brittle ductile transition. Still, $^3He/^4He$ data indicate that mantle derived fluids do indeed flow to the surface along zones of relatively high permeability, so fluid flow pathways must extend though the middle crust and ductile zone (Kennedy et al., 1997). If the original $^3He/^4He$ composition of the mantle is assumed to be constant, some of the variation in anomalous $^3He/^4He$ across the Great Basin and perhaps even within a discrete systems (Fig. 1) may be associated with realtive variations in permeability between the various crustal conduits and/or variations in the length of the upwelling flow path (Fig. 6).

Across the Great Basin neither the spatial density of the $^3He/^4He$ data nor the spatial precision of the locations of the crustal structures permit association of a particular anomalous $^3He/^4He$ geothermal system with a particular structure. Indeed, the $^3He/^4He$ signal associated with mantle derived fluid upflow along the San Andreas fault spans a ~50 km width around the fault system, with the signal decreasing with distance from the fault (Kennedy et al., 1997). If the same is true of upflow along ancient structures in the Great Basin, much of breath of the Great Basin would be within range of tapping a mantle derived fluids conduit.

Even so, several regional scale trends in $^3He/^4He$ data, crustal heat flow data and structure are evident. Anomalous $^3He/^4He$ is most prevalent in the western Great Basin, where many of the known ancient crustal structures are located (Figs. 3 and 4). Bottom hole temperatures in deep wells are also higher and occur in higher density close to the crustal structures analyzed here (Fig. 5 inset). Central Nevada in particular contains the highest density of ancient structures and is also an area of relatively high crustal heat flow (Fig. 5). The relative density of deeply extending crustal structures in this area may generate high mean permeability relative to the surrounding crust, allowing for relatively higher rates of mantle derived fluid upflow. Anomalous $^3He/^4He$ occurs at Dixie Valley, Buffalo Valley, and Jersey Valley in central Nevada as well. This same area of the central Great Basin has a relatively high spatial density of ancient crustal-scale structures, many young and active faults, has anomalous seismic activity (Bell et al., 2004; Caskey et al., 2004; Rowan and Wetlaufer, 1981), and has relatively high modern strain-rates (Hammond, 2004; Hammond et al., 2014; Kreemer et al., 2012). This combination of relatively high modern strain-rates and a density of pre-existing structures appears favorable for rapid upwelling of mantle derived fluid.

Relatively high strain-rates and young and active faults also occur along the Wasatch Front and along the western margin of the Great Basin (Hammond, 2004; Hammond et al., 2014; Kreemer et al., 2012). Both areas are associated with magmatic geothermal systems. High strain along the western margin of the Great Basin and Wasatch Front is focused in a relatively narrow area, <100 km wide, while relatively high strain in central Nevada is relatively diffusely distributed over a region many 100s of km wide (Hammond, 2004; Hammond et al., 2014; Kreemer et al., 2012). Perhaps the discretely focused strain along the western margin of the Great Basin and Wasatch Front allows for production and upwelling of magmas into the upper crust (e.g., Koenig and McNitt, 1983; Nelson and Tingey, 1997), while diffusely distributed strain allows for fluid upwelling from depth without allowing for production ascent of magmatic material.

7. Conclusions

Anomalously high $^3He/^4He$ in amagmatic geothermal systems within the Great Basin indicates that these geothermal systems are associated with more rapid supply of deeply derived mantle fluids than Great Basin geothermal systems associated background $^3He/^4He$ values. These relatively rapidly upwelling fluids carry heat from depth, which supplements crustal heat production. The transportation of this heat occurs through rapid upflow of mantle derived fluids along discrete crustal-scale structural conduits that have a high permeability relative to adjacent intact crust. Modern reactivation of these structures is dependent on the magnitude and orientation of modern tectonic strain and on high fluid pressures. Though some crustal structures across the Great Basin, do appear to be spatially coincident with anomalous $^3He/^4He$ geothermal systems and with high heat flow and crustal temperatures, distinct relationships between $^3He/^4He$ and crustal structural data remain elusive. The limited spatial distribution of $^3He/^4He$ and crustal temperature data, and the uncertainties on the location and permeability character of crustal-scale structures with increasing depth limit our ability to define clear cut links between the $^3He/^4He$ signature of near-surface geothermal fluids, crustal-scale structures and the upflow mantle derived fluids through the crust.

Great Basin geothermal systems with anomalous $^3He/^4He$ must have some fraction of mantle derived fluid, and may be associated with as much as 10s of mWm^{-2} of deeply derived heat. Dixie Valley, Nevada and McGinness Hills Nevada, have anomalous $^3He/^4He$ and each have a total capacity 72 MWe, much higher than the mean capacity of ~16 MWe supported by the other 20 amagmatic geothermal systems across the Great Basin. It follows that other geothermal systems with anomalously high $^3He/^4He$ may be more prospective for large (many 10s MWe) geothermal systems, rather than the ~10–20 MWe capacity that is typical of amagmatic geothermal systems within the Great Basin. Understanding the specific details related to the supply of mantle derived fluids to shallow geothermal systems will be important to future discovery of large, Dixie Valley-like or McGinness Hills-like geothermal systems in the Great Basin.

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