Fluid sources and flow paths of non-magmatic convective geothermal resources in extensional and compressional terranes

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Abstract. The complete cycle of fluid, from origin to discharge, in non-magmatic convective geothermal resources is a significant but not fully understood feature of the dynamics of geothermal systems. It should be a key component in designing exploration strategies and for understanding constraints on projections of long-term sustained production of each resource. The tectonic settings of non-magmatic geothermal resources range from extensional terrane to compressional orogenic terrane. The sources of fluid can range from meteoric to mantle. One of the more common geothermal resource features of both these tectonic settings is the structural dilation conduits that host the near-surface upwelling geothermal fluid. These structural dilations are the primary exploration target for sustained geothermal production. This discussion is an abridged overview of a very broad topic.

1. Introduction
This paper discusses non-magmatic geothermal resources, their similarities and their differences, in two markedly different tectonic settings, the orogenic plate collision terrane and the extension terrane. The largest orogenic terrane is associated with the African, Arabian and Indian plates colliding with the Eurasian plate, extending from the Alps in Europe eastward through the Himalayas in southern and southeastern Asia with hydrothermal resources temperatures ranging from <100°C to >200°C. One of the largest contiguous extensional terranes is the Basin and Range province in the western United States, with hydrothermal resource temperatures ranging from <100°C to >275°C. The maximum potential fluid temperature of each geothermal resource site is limited by the crustal temperature gradient and the depth from which the geothermal water ascends.

The maximum temperature of any individual geothermal resource is defined by the temperature gradient of the crust, which is related to the thickness of the crust, and the depth at which the geothermal fluid collects and ascends to the surface. The crustal structure within a collision terrane is a complex combination of subducting continental crust, folding and thrusting, all part of crustal thickening. The crustal thickness of the Tibetan Plateau ranges from 60 to 85 km. [1][2]. The average crustal thickness in western Turkey is 38 km. [3], and between 34.5 and 40.5 km in central Anatolia [4]. The crustal thickness associated with the Arabian-Eurasian plates in Iran shows a very large range...
in crustal thickness (Figure 1) [5]. These variations in both regional and local tectonic structures suggest that the sources of and the deeper crustal hydrologic flow paths for geothermal fluids are likely quite complex. The crustal thickness within the extensional Basin and Range averages from 30 to 35 km (Figure 2) [6], thickening to greater than 40 km in the Sierra Nevada Range to the west and in the Colorado Plateau to the east.

The large-scale tectonic dynamics of these two terranes are different, and the variations in crustal thicknesses vary. There are both commonalities and differences in the possible fluid sources and hydraulic processes supporting the sustained economical production potential of geothermal resources.
in both terranes. The shallow crustal structures hosting upwelling geothermal fluids show significant similarities in both terranes, local stress-field changes that allow vertical dilated conduits to form. These shallow crustal structural conduits hosting the upflow of geothermal fluid in both terranes are the production targets for economic development of geothermal resources. Knowledge of the characteristics of these shallow structural upflow conduits is crucial for the effective design and expedient exploration and development strategy that conserves both time and cost. Understanding the fluid sources and flow paths supporting these geothermal discharge conduits provides perspective for more reliable constraints on projecting long-term sustained production estimates.

2. Orogenic Terrane
Orogenic terranes are formed as the process of two continental tectonic plates colliding, with one subducting beneath the other. The largest orogenic terrane extends from the Mediterranean area eastward through the Himalayan mountains, formed by the collision of the African, Arabian and Indian plates colliding with and subducting under the Eurasian plate. The geomorphology and tectonic structure of these collision zones are composed of thrust and fold belts with thickening crust.

The basic concept of plates colliding is compression along the boundary of collision and tension perpendicular to the direction of collision (Figure 3). The tectonic reality of plates colliding is far more complex than this simple conceptual image, due to variations in the plate boundary geometry, plate movement velocities, and direction of convergence, as observed in the eastern Mediterranean (Figure 4) or in the Himalayan Plateau (Figure 5). The basic dynamics, however, are observable, compression variably trending north-south and combinations of converse and normal faults accommodating extension in the opposite direction of compression. With regard to geothermal resource locations the transcurrent and normal faults hold the potential for geothermal cells to form.

Figure 3. Idealized concept of the structural dynamics in a plate convergence orogeny. Orogenic compression (blue) resulting in transcurrent faults (black) with extension (orange) normal to the direction of compression. Normal faults (red) associated with horst and graben block structures are structural artefacts of the extension.
3. Extensional Terrane

The Basin and Range geographical province is an expansive tectonic extensional terrane located in the interior of the western United States, bounded by the Sierra Nevada Range to the west and on the east by the Colorado Plateau (Figures 6 and 7). The name reflects the elongated horst and graben structures.
characteristic of the terrane, an artifact of episodic extensional tectonism with an initial east-west extension occurring between 17 and 12 million years ago [9]. The current extension, beginning subsequent to 10 million years ago in north-central Nevada, shows some clock-wise rotation with a west-northwest extension [10].

**Figure 6.** A general outline (red dashed line) of the Basin and Range province, western United States (map adapted from Wikipedia). The state of Nevada is centrally located within the Basin and Range, covering a large percentage of the geologic province.

**Figure 7.** Plate movement velocities from GPS measurements showing rate of movement from stations across the northern Basin and Range and adjacent terrane to the west [11]. The red arrows are data from earlier work. The blue arrows are from data collected for the 2005 report. The longer red and blue arrows depict greater northward-trending velocities in the block west of the Basin and Range Province.
4. Fluid Sources and Flow Paths
Geothermal resources are usually discussed in terms of the up-flow within the shallow crust, the depth at which a resource can economically be intersected and produced. This economic target is just the final up-flow and discharge end of a much larger hydrologic process. The total process of fluid sources and flow paths supporting geothermal resources has often been addressed in terms of numerical modeling rather than empirical data. This is unfortunate as the strategy for long-term sustained production of the resource is dependent on accurate projections of fluid source and flow rates. The potential sources of water supplying geothermal resources are diverse, and include surface-sourced meteoric and marine water, migration of connate water resulting from compaction, multiple stages of metamorphic dehydration events, and water migrating from the mantle, including magmatic fluid.

Published scientific data from the mining industry provides a significant view as to the sources of water supporting aqueous geothermal fluid flow and structural-related flow-paths. The relationship between geothermal systems and hydrothermal ore deposits has been recognized for well over a century (e.g. [13]). During the subsequent decades a great amount of information has been published regarding the structural and hydrological dynamics of the formation of hydrothermal ore bodies, four-dimensional reconstructions of the hydrothermal activity associated with the deposition of economic and sub-economic ore bodies. Lindgren [14] proposed a classification of hydrothermal ore deposits based on depth and temperature of formation: epithermal (shallow depth, up to 200°C), mesothermal (intermediate depth, 200-300°C) and hypothermal (great depths, 300-500°C). The terms now used by many are epizonal, mesozonal and hypozonal. This early classification has been refined over time with the better understanding of the dynamics of plate tectonics and hydrothermal ore body deposition in various tectonic settings (Figure 9).

Hydrothermal fluid flow in orogenic terrane is a most interesting area of study. The variety of potential fluid sources is greatest of all geothermal tectonic settings. Most of what is known about deep hydrothermal fluid movement in orogenic terranes comes from the metals mining industry's efforts to understand the formation of mesozonal and hypozonal ore deposits and fluid sources.
supporting ore deposition (e.g. [15] [16] [17]). Mesozonal ore bodies have been deposited in the lower brittle crust and hypozonal ore bodies have been deposited in the deeper ductile crust (Figure 9). Both of these types of ore bodies demonstrate upward aqueous fluid flow along fracture and shear zones deep within the crust. This fluid requires a discharge zone at some point in order to facilitate continuous flow at depth. These terminal discharge areas are what we observe as surface geothermal features. The maximum temperature of these geothermal resources depend on the depth at which the water begins its ascent and the conductive temperature gradient of the crust (e.g. [18]).

Both meteoric and metamorphic water is identified as sources for geothermal fluid (e.g. [15] [16] [20] [21]). Water sourced from physical and mineral phase changes with increased temperature and pressure within the crust can be a significant origin of geothermal fluid. Connate water within sedimentary rock is squeezed out with the mechanical compaction associated with increased pressure and burial depth. The generation of metamorphic water occurs in mineral dehydration stages with increased temperature and pressure, beginning with dewatering of smectite clay and continuing as changes in stable mineral phases occurs with increasing temperature and pressure (Figure 10). Deep crustal fluid collector structures in orogenic terrane most commonly take the form of shear zones within the ductile crust and fracture zones within the brittle crust (Figure 9). These structures allow metamorphic water and also possible fluids from the mantle to migrate toward the surface. Low-angle structures within the brittle portion of the crust are capable of acting as collector structures for meteoric water percolating downward from the surface.

Figure 9. A diagram depicting possible settings for hydrothermal fluid flow and site formation of hypozonal, mesozonal and epizonal ore bodies in orogenic terranes and ore bodies formed in extensional terrane [19].
Convergent terrane shows an interesting variation on the increased temperature with increased depth projection (Figure 11). A temperature reversal can occur in the zone of contact between the overriding and under-riding plates, where the top of the under-riding plate retains its cooler shallow crustal temperature. In this instance there is a repeat metamorphic grade sequence resulting in a duplicate metamorphic dewatering sequence, each with the potential of being source fluid for geothermal resources.

Figure 10. Metamorphic dehydration reactions related to increased temperature and pressure [22].

![Figure 10](image1)

![Figure 11](image2)

Figure 11. Temperature profile of overriding (gray) and subducting (green) plates during subduction. The top of the subducting plate (SS) is cooler than the base of the overriding plate (HW). This results in two metamorphic dehydration horizons, both potential sources of water for ascending geothermal fluid. Lower temperature metamorphic dehydration fluid from the subducted plate would actually increase in temperature as it ascends upward through the overriding plate [22].

Geothermal water within many Basin and Range systems has often been identified as meteoric water. Precipitation supports a broad dispersed regional downward percolation of the meteoric water. The downward velocity of this water varies with the range of physical lithologic properties of the underlying formations and the decreasing fracture permeability with depth. The downward flow is slow enough that it probably does not significantly suppress the regional crustal thermal gradient. This
downward flow continues through broad dispersed non-isotropic crustal fractures and reaches a point of extremely low flow rates. To facilitate water migration from broadly dispersed water-saturated fractures to a localized geothermal resource two structural components are needed. The first component would be some form of deep broad collector structure. This might be an anticlinal structure, or a horizontal to sub-horizontal boundary. The low-angle boundary could be a low-angle orogenic thrust detachment, low-angle thrust fault planes where the upper plate has undergone reverse extension movement. The second component would be a dilation structure that penetrates downward, intersecting a collector structure. The dilation structure then acts as host conduit allowing water along the collector structure to flow toward and up through the dilated conduit structure to the surface, forming a geothermal cell. The maximum temperature of ascending geothermal fluid is defined by the depth of the intersect of the two structures and the crustal conductive temperature gradient. The Basin and Range hosts an abundance of high-angle dilation structures. Most of them do not host geothermal cells. Only those structural dilation zones that intersect broad fluid collection structures are likely to host geothermal cells.

A not well understood type of geothermal systems within the Basin and Range are those associated with deep crustal trends with temperatures indicating fluid ascent from near or within the brittle-ductile boundary [23]. The actual physical process of meteoric water percolating downward 8 to 10 km in sustained volumes great enough to support observed and inferred discharge has yet to be explained. Though not yet substantiated, water from metamorphic dehydration and water from the mantle might contribute to the geothermal cell upflow observed in these high-temperature trends.

5. Shallow Crustal Up-Flow Structures
The geothermal up-flow structures in the upper 3 to 4 km of the crust are what is considered for exploration and development of geothermal resources. There are commonalities of these shallow crustal resource structures with both orogenic and extensional terranes. In both tectonic settings the up-flow cells are hosted by tensional vertical dilation structures that occur as the result of very localized changes in the stress field along normal and transcurrent faults. The up-flow and discharge processes of the geothermal cells are accommodated by the deep high-angle structural dilation conduits that act as flow paths for deep hot water to ascend to the surface. A simple block diagram presented by Aydin and Nur [24] shows how localized points of tension and compression are formed within differential strike-slip zones in extension terranes (Figure 12).

Potential geothermal cell host structures associated with strike-slip transcurrent and transform fault systems include jog dilation, step-over zones, ramp structures and rotation segments, similar to potential host structures in extension terranes.

Figure 12. A block diagram illustrating development of very localized points of tension and compression in a strike-slip stress field with minor normal stress [24].
Under differential strain two quadrants of tension and two quadrants of compression form (Figure 13). In geologic settings the tension dilation can form within fault splays, jogs, pull-apart grabens and ramp structures within the transcurrent fault zones and differential offset dilation structures in normal faults in areas of extension (Figures 14 and 15). Geothermal cells are able to develop when these high-angle dilation structures intersect a hydrologic collector structure at depth.

Figure 13. A diagram identifying quadrants of compression and tension resulting from strain between two boundaries of a right-lateral strike slip fault zone or along local offsets along normal faults [25].

Figure 14. A diagram depicting localized structural tension dilation at stepover offsets within a right lateral strike slip fault [26].

Grabens formed in pull-apart jogs along transcurrent faults are also capable of forming local high-angle dilation sites which can host geothermal cells. Detailed stress fields within larger pull-apart structures are often complex, with smaller-scale changes in tension and compression within the graben due to rotation and differential movement within the graben structure (Figure 15).
Areas of tension dilation opens fracture fluid flow in the brittle crust and shear-zone fluid flow in the deeper ductile crust (Figure 16). Metamorphic dewatering processes (Figures 10 and 11) are a major potential source for the deeper fluid flow from the ductile crust. These ductile fluid flow shear structures are associated with and hosts of hypozonal hydrothermal ore deposits (Figure 9).

Figure 15. A pull-apart section within the Sumatra transcurrent fault zone is approximately 30 km wide [27]. Note the location of micro-compressional and micro-tensional areas within the pull-apart structure and the fragmented micro-stress regimes within the pull-apart block. A volcano is located along the edge of the block (blue triangle) but much of the geothermal activity (red circles) are not in immediate proximity of the volcano.

Figure 16. Hydrothermal fluid flow within brittle and ductile crust within a compressional orogenic terrane [28]. Metamorphic and magmatic water migrate into deep crustal shear zones and into shallower brittle fracture zones allowing fluid to slow upward to geothermal surface discharge areas.
The multiple geothermal cells in Dixie Valley, located in the north-central portion of the state of Nevada (Figure 6), provide a well documented setting to view the dynamics of geothermal fluid flow within the shallow crust in an extension tectonic setting. The majority of the cells are located along the western boundary of Dixie Valley, along the eastern edge of the Stillwater Range (Figure 17). The dilation structures hosting the geothermal cells are located along offset intersects of the Pliocene north-striking normal faults (black lines in Figure 17) and the more recent Pleistocene-Holocene north-northeast-striking normal faults (green lines in figure 17). Rotating of regional tension from E-W to WNW-ESE resulted in a younger generation of NNE-striking normal faulting. Overlapping of this younger generation of normal faults resulted in minor strike-slip activation along the older north-striking faults. The strike-slip movement has resulted in the Stillwater Range-Dixie Valley boundary, which is composed of a number of high-angle faults (i.e. intra-range, range-front, piedmont), becoming segmented into individual range-front sections. Tectonic artifacts of the normal faulting truncated by a strike-slip component include rhombograbens, pull-apart zones, ramp structures, and areas of compression (Figure 18). Discrete dilation zones within these structures accommodate high-angle geothermal conduits (red in Figure 17) which host geothermal cells [29].

![Figure 17. The above map, overlain on a map by Speed [30], shows Miocene north-striking structures (black) crossing the Stillwater Range, and the current normal range front faults (green), the surface exposed traces of the bounding Dixie Valley/Stillwater Range fault zone. Red shows those areas with fumaroles, hot springs, shallow temperature anomalies and the power plant production area. The area boxed with black lines is location of Figure 18.](image-url)
6. Conclusion
Continental convergent and broad extension terranes are markedly different tectonic settings. Yet the economic geothermal development targets within the upper crust show remarkable similarities. Dilation conduits are the hosts of geothermal cells in both terranes. These host structures are associated with localized changes in stress directions in fault zones. The vertically dilated structures provide a tube network of fractures which support the up-flow of geothermal fluid. Production potential within these conduits or cells is determined by the sustained flow rate of fluid upward through the fracture network rather than from the static volume of the fractures. These terrains hold abundant sites of shallow structural dilation that do not host geothermal fluid up-flow. Only those structural dilation conduits that intersect more broad fluid collection structures at depth are likely to host geothermal cells. The depth of the collector structures and the conductive crustal gradient determine the temperature potential for each geothermal resource.

This discussion of geothermal resources in orogenic and extension terrane is a markedly abbreviated overview of a topic that deserved more detailed in-depth research before a true
understanding of the dynamics of the complete geothermal cycle is understood. It is the hope of the author that this brief overview may stimulate both curiosity and more detailed research into the fluid source and migration processes supplying geothermal resources in both terranes.

A humble reminder to us all: Stober and Bucher [33] point out that it is easy to construct a numerical model, but very difficult to generate anything that is geologically meaningful.

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