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Analysis of Step-Overs (or Relay Ramps) in Normal Fault Systems in the Great Basin Region, Western USA: Implications for Geothermal Exploration and Development

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ABSTRACT

The Great Basin region (GBR) in the western U.S. hosts vast amounts of undiscovered conventional geothermal resources. However, as much as 75% of the geothermal resources in the GBR may be blind or hidden. Nearly all geothermal systems in the GBR reside in six types of favorable structural settings, including normal fault terminations, step-overs (i.e., relay ramps) in normal faults, fault intersections, accommodation zones, displacement transfer zones whereby strike-slip faults end in arrays of normal faults, and pull-aparts in strike-slip faults. Although the affinity between geothermal systems and these structural settings is widely known, little research has been conducted to distinguish which geometries of a particular structural setting are more conducive for geothermal activity. Distinguishing the most favorable geometries is crucial to improving exploration strategies for hidden systems, selecting optimal drilling targets, and increasing the efficiency of existing power plants. Step-overs in Quaternary normal fault zones are the most common favorable structural setting for known geothermal activity in the GBR. Complex fault geometries in the step-overs, including multiple minor faults connecting the major overlapping fault strands, enhance permeability and generate efficient pathways for hydrothermal fluid flow. Step-overs are common in normal fault zones, and more than 450 were identified across the region in this study, with only a fraction associated with known geothermal activity. It is difficult to distinguish which step-overs might host a hidden geothermal system. However, step-overs come in a variety of geometries depending on relative overlap, underlap, and spacing between major fault strands. In addition, the geometry of minor faults that breach the step-over can vary from oblique-slip faults that connect the major fault strands to en échelon faults that parallel the major fault strands. Step-overs were therefore further classified based on orientation, sense of stepping (right vs. left), amount of overlap and spacing between main fault strands, and linkage style (hard vs. soft). Of identified step-overs in the GBR, ~54% are right stepping, ~51% hard linked, and ~50% underlapping. Relay ramp widths ranged from 0.1-14.6 km, with an average of 2.8 km. Step-overs associated with higher-temperature (>120°C) geothermal systems are ~56% right stepping, ~70% hard-linked, and ~56% overlapping; about ~74% lie between fault strands oriented north to north-northeast. Average relay ramp width for the higher-temperature step-overs is 3.3 km. Producing systems (i.e., containing operating power plants) in step-overs preferentially step left (~64%), are hard-linked (~73%), overlap (~55%), and have an average relay ramp width of 3.4 km. These data suggest that higher-temperature systems favor overlapping, hard-linked geometries, which have relatively high densities of fractures, faults, and fault intersections, all of which enhance permeability. Additional structural complexity provides subvertical conduits of enhanced permeability that facilitates transport of hot fluids from greater depths. These attributes combined with faults optimally oriented to accommodate dilation in the current stress field provide long-lived permeable pathways that can host higher-temperature geothermal systems. This information may facilitate more efficient exploration of hidden geothermal systems across the GBR.

1. INTRODUCTION

Presently, the United States leads the world in geothermal energy production, with a total of 3.6 GWe reported in 2019 (Robins et al., 2021). Traditional exploration methods involve drilling near surface features (fumaroles, hot springs, or steam vents). However, many geothermal systems are hidden and do not breach the surface (Richards and Blackwell, 2002; Coolbaugh et al., 2007). The identification and development of these hidden (also referred to as "blind") geothermal systems presents a challenge for exploration. One such area that hosts abundant geothermal systems, many hidden, is the Great Basin region in the western United States. Most of the systems in this region are amagmatic, meaning that the heat is not produced from volcanic input but rather stems from a high geothermal gradient resulting from crustal extension and thinning (McKenzie, 1978; Curewitz and Karson, 1997; Faulds et al., 2021b).

The Great Basin region is a distinct physiographic province of North America encompassing over 600,000 km^2 of the Basin and Range province and characterized by Cenozoic crustal extension and transtension. This region is bounded by the Sierra Nevada to the west, the Wasatch Mountains to the east, the Snake River Plain to the northeast, less extended terrain to the northwest, and the Mojave Desert region to the south (Grayson, 2011). For this project, the study area incorporates much of the Great Basin region and includes most of Nevada, western Utah, southern Idaho, southeastern Oregon, and eastern California (Figure 1). The study area is not constrained to the hydrographic definition of the Great Basin initially defined by Fenneman (1928) but rather to a broader region of active extensional to transtensional tectonism spanning ~499,178 km^2 (Figure 1).

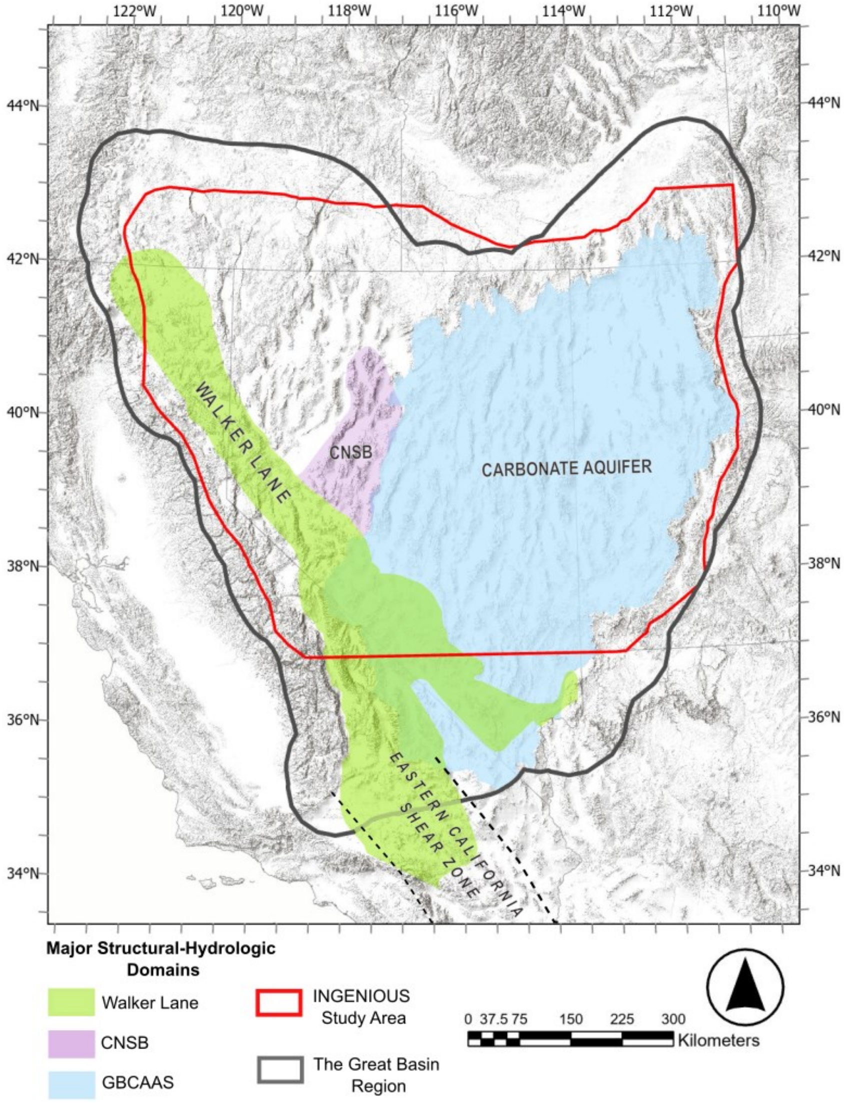


Figure 1: Structural and hydrographic domains in the INGENIOUS study area including the Walker Lane, central Nevada seismic belt, and Great Basin carbonate and alluvial aquifer system.

In the Great Basin region, most geothermal systems are structurally controlled (e.g., Curewitz and Karson, 1997; Blackwell et al., 1999; Faulds et al., 2004). Quaternary normal faults provide permeability at depth and act as conduits that channel hydrothermal fluids to the surface (or near surface in the case for hidden systems). Understanding the geometries associated with known hydrothermal systems is therefore essential for refining exploration techniques in the region.

Previous studies have catalogued the favorable structural settings of known geothermal systems across the Great Basin region (Faulds et al., 2011, 2021a; Faulds and Hinz, 2015). This work has shown that major normal faults host relatively few geothermal systems. Instead, most geothermal activity occupies fault interaction zones (cf., Curewitz and Karson, 1997), including 1) fault terminations, 2) step-overs or relay ramps in normal fault zones, 3) fault intersections, 4) accommodation zones involving intermeshing oppositely dipping normal faults (cf., Faulds and Varga, 1998), 5) displacement transfer zones whereby strike-slip faults terminate in arrays of normal faults, and 6) transtensional pull-aparts (Faulds et al., 2011, 2021a; Faulds and Hinz, 2015; Figure 2).

Permeability is increased in regions of interacting faults due to structural complexity, greater density of faults, more abundant fault breccia versus fault gouge, and stress concentrations (e.g., Curewitz and Karson, 1997; Faulds and Hinz, 2015; Siler et al., 2018). Accommodation zones and displacement transfer zones are two of the more complex favorable structural settings. Accordingly, the two largest producing systems in Nevada, McGinness Hills and Steamboat, occupy complex accommodation zones, where two oppositely dipping normal fault systems overlap, terminate, and intersect at depth. However, accommodation zones only account for ~5% of all Nevada geothermal systems. Displacement transfer zones account for ~16% of producing systems yet amount to only 4.1% of structural settings identified for known geothermal systems in Nevada (Faulds et al., 2021a).

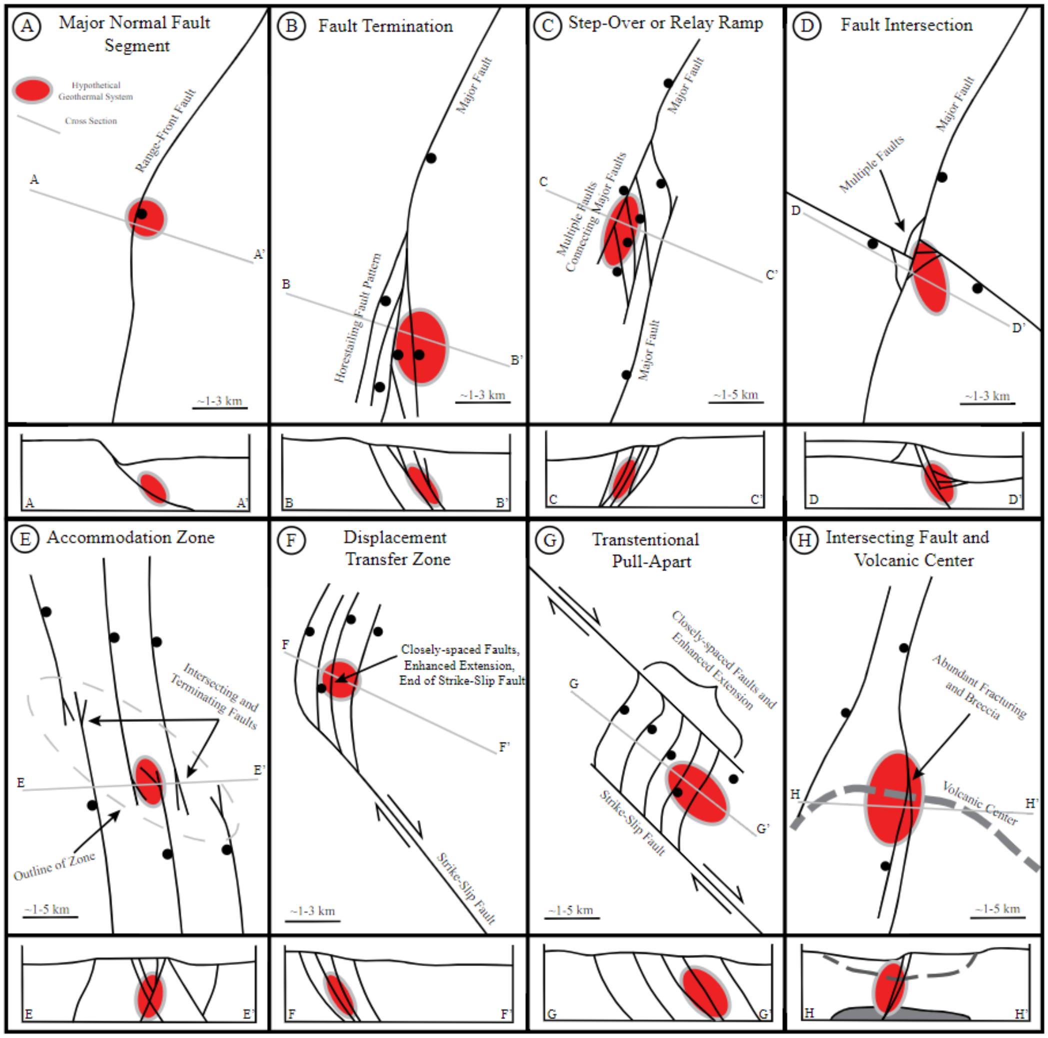


Figure 2: The most common structural settings hosting known geothermal systems in the Great Basin region (from Faulds et al., 2021a). Major normal faults (A) rarely host geothermal activity. Settings B through G host most geothermal systems in the Great Basin region.

The most common structural setting for known geothermal systems in the Great Basin region is the step-over or relay ramp, which accounts for ~47% of all producing systems in Nevada and ~39% of all known Nevada geothermal systems (Faulds et al., 2021a). This structural setting is common throughout the Great Basin region and manifests in many different configurations depending on how the main fault segments interact. It is important to analyze these step-overs to determine which geometries are most conducive to geothermal activity. Step-overs can be classified based on orientation, dip direction of major faults, step direction, amount of overlap, linkage style (hard vs. soft-linked), and distance between main fault strands (i.e., relay ramp width).

The purpose of this paper is to assess the varying geometries of step-overs relative to known geothermal activity in order to evaluate which geometries are more likely to host a hidden geothermal system. Through the analysis of existing geological maps, available LiDAR, the USGS Quaternary fault and fold database (U.S. Geological Survey, 2020), and regional gravity and magnetic datasets, a comprehensive database of step-overs and their attributes was produced (Giddens, 2024). This database provides an important resource to guide further exploration in the Great Basin region. This analysis was part of the broader INGENIOUS project funded by the Geothermal Technologies Office of the Department of Energy (Ayling et al., 2022; Faulds and Richards, 2023). INGENIOUS stands for INnovative Geothermal Exploration through Novel Investigations Of Undiscovered Systems.

The primary goal of the INGENIOUS project is to accelerate discoveries of new, commercially viable hidden geothermal systems in the Great Basin region of the Basin and Range province in the western USA, while significantly reducing the exploration and development risks for all geothermal resources. Major objectives of the INGENIOUS project include: 1) compiling regional geological and geophysical datasets for the Great Basin region; 2) enhancing regional- and local-scale play fairway exploration workflows, and using these to produce new geothermal potential maps for the region; 3) quantifying resource potential, uncertainty, and degree of exploration at a few promising hidden geothermal prospects in the region; 4) releasing multiple geoscience data products for public, academic, and industry use; and 5) ultimately generating a geothermal developers playbook that consolidates current conceptual understanding and best practices for geothermal exploration in the region. This paper provides crucial analysis of favorable structural settings, which is one of the more important regional datasets and also one of the most relevant at the scale of individual geothermal prospects.

2. REGIONAL GEOLGOICAL SETTING

The Great Basin region of the western U.S. has been shaped by multiple tectonic events spanning Archean through Cenozoic time. The most relevant events for present-day geothermal activity are of those in the Cenozoic, which have generated the contemporary tectonic domains. For the purposes of this study, the Great Basin region is divided into four major tectonic domains: 1) the Walker Lane-eastern California shear zone, 2) central Nevada seismic belt, 3) western Great Basin, and 4) Great Basin carbonate and alluvial aquifer system (Figure 1).

The transition of western North America from a convergent to a transform plate boundary since ~30 Ma (e.g., Atwater and Stock, 1998) induced periods of mid to late Cenozoic crustal extension in the Great Basin region that produced the characteristic basin-and-range landscape (e.g., Wernicke, 1992; Dickinson, 2006). As the transform boundary (i.e., San Andreas fault system) lengthened through the Miocene, some of the plate boundary motion was transferred inland. This resulted in belts of primarily dextral faults in the Walker Lane and eastern California shear zone in the western part of the Great Basin (e.g., Stewart, 1988; Faulds and Henry, 2008). The Walker Lane currently accommodates as much as ~25% of the dextral motion between the Pacific and North American plates (e.g., Hammond et al., 2007; Kreemer et al., 2009). The Walker Lane terminates northwestward within the northwestern part of the Great Basin in concert with the offshore termination of the San Andreas fault at the Mendocino triple junction (Faulds and Henry, 2008). As the Walker Lane terminates, dextral shear is transferred to extension within the northern Great Basin. This generates a broad region of transtension, which helps to accentuate extensional strain rates and geothermal activity (e.g., Faulds et al., 2004). The central Nevada seismic belt is a 300-km-long zone of increased historical earthquake activity and enhanced Quaternary extension that extends northward from the Walker Lane (Figure 1). It is characterized by a series of linear, relatively continuous faults that strike north to north-northeast and have been active since the Miocene (Bell et al., 2004). The western Great Basin domain includes remaining parts of the Great Basin to the east of the carbonate aquifer and outside the Walker Lane and central Nevada seismic belt; this area has also experienced regional extension generally from Miocene to Quaternary time.

The Great Basin carbonate and alluvial aquifer system includes 177,000 km^2 of laterally extensive, highly permeable layers of Paleozoic miogeoclinal carbonates that underlie the eastern Great Basin (Figure 1; Masbruch et al., 2012; Allis et al., 2012). The Paleozoic carbonates (mainly limestone and dolomite) were deposited primarily from the Cambrian to Devonian along the western passive margin of North America and can exceed 5 km in thickness (Masbruch et al., 2012). The lithologies vary from fine crystalline lime mud to more porous lithotypes composed of bioclastic carbonate. This relatively cool aquifer can potentially mask thermal anomalies. However, the carbonate units can also serve as geothermal reservoirs, particularly where they are augmented by fractures and dissolution features and insulated by sediments in Neogene basins (Allis et al., 2012). Permeability of carbonate reservoirs can increase from dissolution and karst features, ultimately allowing for and enhancing fluid circulation.

3. OVERVIEW OF STEP-OVERS

Step-overs are a common geometry of faulting in extensional settings, whereby the main normal fault ‘steps’ and transfers strain to an adjacent parallel fault, with the same direction of dip (Larsen 1988; Peacock and Sanderson, 1994). There are two ways these structures can develop. The first results from the propagation of two kinematically independent parallel normal faults. The second is the propagation of a singular independent fault strand that steps laterally (Childs et al., 1995; Fossen and Rotevatn, 2016). The zone between the two parallel normal faults is referred to as a relay ramp or step-over (Figure 3).

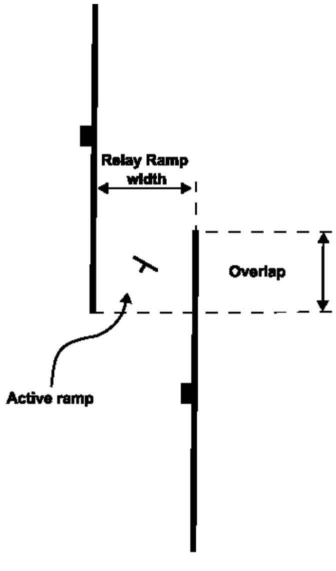


Figure 3. Map view of a left-stepping, soft-linked, overlapping relay ramp. Modified from Crider and Pollard (1998).

Relay structures exhibit geometric properties that are consistent across different scales, including their elongated shape (typically 3 to 3.5 times longer than the width) and variations in displacement along the overlapping fault tips, which influence the geometry of the ramp. These structures are more complex than single, isolated faults, because they involve a larger number of faults and fractures with a wider range of orientations (Peacock and Sanderson, 1991). The interaction between the main fault strands can manifest in many ways such as overlapping, underlapping, or ultimately linking.

Four distinct groups encompass the degree of interaction and linkage of overstepping fault segments throughout the evolution of the system (Figure 4). In the first stage, fault segments are underlapping and are not interacting. As both faults continue to propagate and interact, a relay ramp is formed (stage 2). Stage 3 is classified by the breaching or linking of the relay ramp, commonly the upper ramp. Ultimately as a normal fault system continues to propagate, there can be complete destruction of the relay ramp (stage 4), as both faults overlap and connect (Peacock and Sanderson, 1994; Fossen and Rotevatn, 2016; Oliveira et al., 2019). The formation and destruction (breaching) of relay ramps occurs continuously throughout the development of a normal fault system (Fossen et al., 2009).

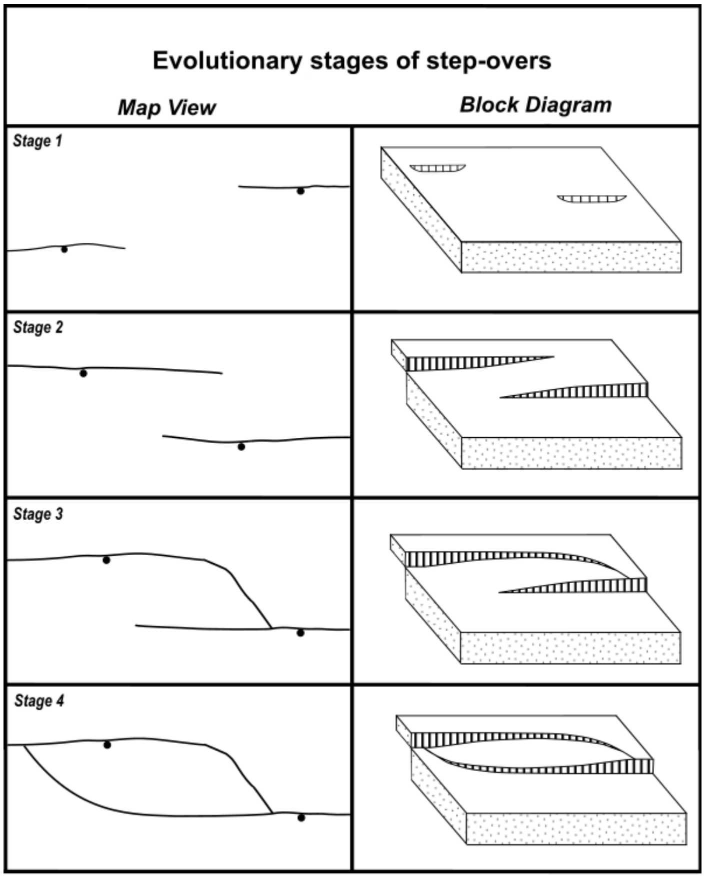


Figure 4: Evolutionary stages of step-overs and an overstepping fault (from Peacock and Sanderson, 1994). Stage 1: Fault segments are underlapping and not interacting. Stage 2: Fault tips propagate and begin to overlap forming the intervening ramp. Stage 3: The upper ramp is breached and becomes hard-linked. Stage 4: Full detachment of the relay ramp from the two parallel overlapping normal faults.

These ramp geometries can be further divided into two main categories: ‘soft-linked’ and ‘hard linked’. Ramp geometries that are not completely detached or breached by a connecting fault are referred to as ‘soft linked’ (Çiftçi and Bozkurt, 2007; Oliveira et al., 2019). Larsen (1988) observed that soft-linked relay structures are common in extensional settings at relatively low strain rates. Areas with higher strain rates will produce greater displacement along the individual parallel faults, potentially leading to complete detachment, or breaching, of the relay ramp by linking of the main faults (‘hard-linked’). Soft-linked ramps may become hard-linked throughout the evolution of the fault system due to fault tip propagation (Peacock and Sanderson, 1994).

The style, age, and orientation of fault interaction can directly affect the subsurface fluid flow. Relay ramps inherently provide vertical channels for fluid migration due to their closely spaced faults and associated damage zones (Faulds and Hinz, 2015; Fossen and Rotevatn, 2016; Oliveira et al., 2019). These ramps can also serve as pathways for fluid flow from footwall to hanging wall between two otherwise sealed fault segments (Crider and Pollard, 1998). They are characterized by a complex structure that consists of numerous faults and fractures, and these structures can have a wide range of orientations (Oliveira et al., 2019). The relationship between the two fault strands can influence the permeability within the step-over or relay ramp.

In normal fault zones, permeability is maintained by stress concentration (Anderson and Fairley, 2008). Stresses are concentrated at structural discontinuities, such as step-overs, and are relieved when a fault plane slips. This stress is subsequently transferred to the surrounding crust or faults and fractures distal to the main segment, causing micro and macro fractures that increase permeability by an order of a magnitude (Anders and Wiltschko, 1994; Curewitz and Karson, 1997; Crider and Pollard, 1998; Siler et al., 2018). Highly stressed faults allow for hydraulic conductivity, as the fault plane becomes brecciated or dilated. This zone of structural discontinuity can ultimately generate conditions for hydrocarbon or fluid migration (Anderson and Fairley, 2008; Fossen et al., 2009).

In summary, step-overs are complex structures with multiple attributes that can influence fluid flow. The density, orientation, and connectivity of faults and fracture networks play crucial roles in determining permeability within the step-overs. Fault interaction zones can perturb the principal stress direction (e.g., Çiftçi and Bozkurt, 2006), causing variations in permeable pathways. Stress concentration at structural discontinuities, such as fault tips in overlapping step-overs, can generate new fracture networks, thereby enhancing permeability in the relay ramp. However, stress is less likely to be relieved in step-overs due to the presence of minor faults and lack of major fault strands that can accommodate slip of large seismic events. Consequently, the dynamic interplay between regional tectonic stresses, stress perturbations, and the resulting fracture networks create a complex environment that will affect the subsurface fluid flow of geothermal systems. This begs the question as to which step-over geometries are more commonly associated with geothermal activity, especially higher temperature geothermal systems.

4. METHODS

The primary objective of this study was to integrate multiple geological and geophysical datasets to define the locations and geometries of Quaternary faults such that step-overs could be identified, characterized, and compiled into a comprehensive database. Geological datasets that were examined included: 1) published geological maps, 2) the USGS Quaternary fault and fold database (U.S. Geological Survey, 2020), 3) LiDAR, 4) NAIP (National Agriculture Imagery Program) imagery of the Earth's surface, and 5) the known geothermal systems database. Regional geophysical datasets included: 1) gravity surveys, 2) magnetic surveys, and 3) magnetotelluric (MT) data.

Multiple geological datasets were employed to identify the locations and general geometries of Quaternary faults such that favorable structural settings could be defined and the geometries of the many step-overs or relay ramps could be characterized. If of sufficient detail and quality, published geological maps were used to define the step-overs. However, with only ~25% of the study area mapped in sufficient detail (e.g., 1:24,000), the USGS Quaternary fault and fold database, Lidar, and NAIP imagery provided the most relevant information in most areas. LiDAR and hill shades were utilized to identify the extent and location of Quaternary faults in combination with other datasets. Available one-meter LiDAR from the GeoDAWN (Geoscience Dara Acquisition for Western Nevada) project was provided by the USGS. The GeoDAWN footprint primarily encompasses the Walker Lane in western Nevada and an east-trending arm extending from the Walker Lane into north-central Nevada (U.S. Geological Survey, 2023). For the remainder of the study area, 10-meter digital elevation models were utilized through the USGS National Map as part of the USGS 3D Elevation Program (3DEP). NAIP imagery was also used to identify topography indicative of step-overs and other structural settings, as well as fault scarps suggesting late Pleistocene to Holocene ruptures, especially in the absence of high-resolution lidar and detailed geological maps.

The initial database for known geothermal systems in the Great Basin region was created by Coolbaugh (2003). This dataset established over 400 geothermal systems in the Great Basin as outlined by Fenneman (1928) with a 70 km buffer, which facilitated the inclusion of systems along the margin of the region (Coolbaugh et al., 2005; Faulds et al., 2021b). Further classification and refinement of the Great Basin region was carried out between ~2010 and 2013 and was incorporated into multiple subsequent publications (e.g., Faulds et al., 2011; Faulds and Hinz, 2015). This included more accurately locating many of the known systems based on analysis of NAIP imagery. Age, recency, location, orientation, and dip of Quaternary faults were integrated into the final database. The general trend of each step-over was measured in ArcPro to obtain the general strike of the main fault segments.

In addition to the geological datasets, gravity, magnetic, and MT datasets were employed to help identify the locations and general geometries of Quaternary faults such that the geometries of the main step-overs could be characterized. Gravity surveys were the most useful geophysical dataset in defining the extent and geometries of the major Quaternary faults and were instrumental in characterizing many of the geometries. The geophysical datasets were crucial for constraining the step-overs in the INGENIOUS study area, where basin fill conceals many faults and geothermal upwellings may have altered rocks and generated low magnetic and low resistivity anomalies (e.g., Witter et al., 2016; Craig et al., 2021).

Within ArcPro, attributes of each step-over were documented including direction of stepping, width of relay ramp, orientation and relationship (overlap vs. underlap) of main fault strands, and linkage style (hard vs soft-linked). The relay ramp width was measured as the spacing between fault segments, perpendicular to strike. Fault age, recency, direction of dip, and slip sense of each step-over was derived primarily from the Quaternary Fault and Fold Database (U.S. Geological Survey, 2020).

5. RESULTS

Results from the overall compilation of step-overs across the entire INGENIOUS study area are initially addressed below. This is followed by brief descriptions of the step-overs in each of the tectonic and hydrographic domains.

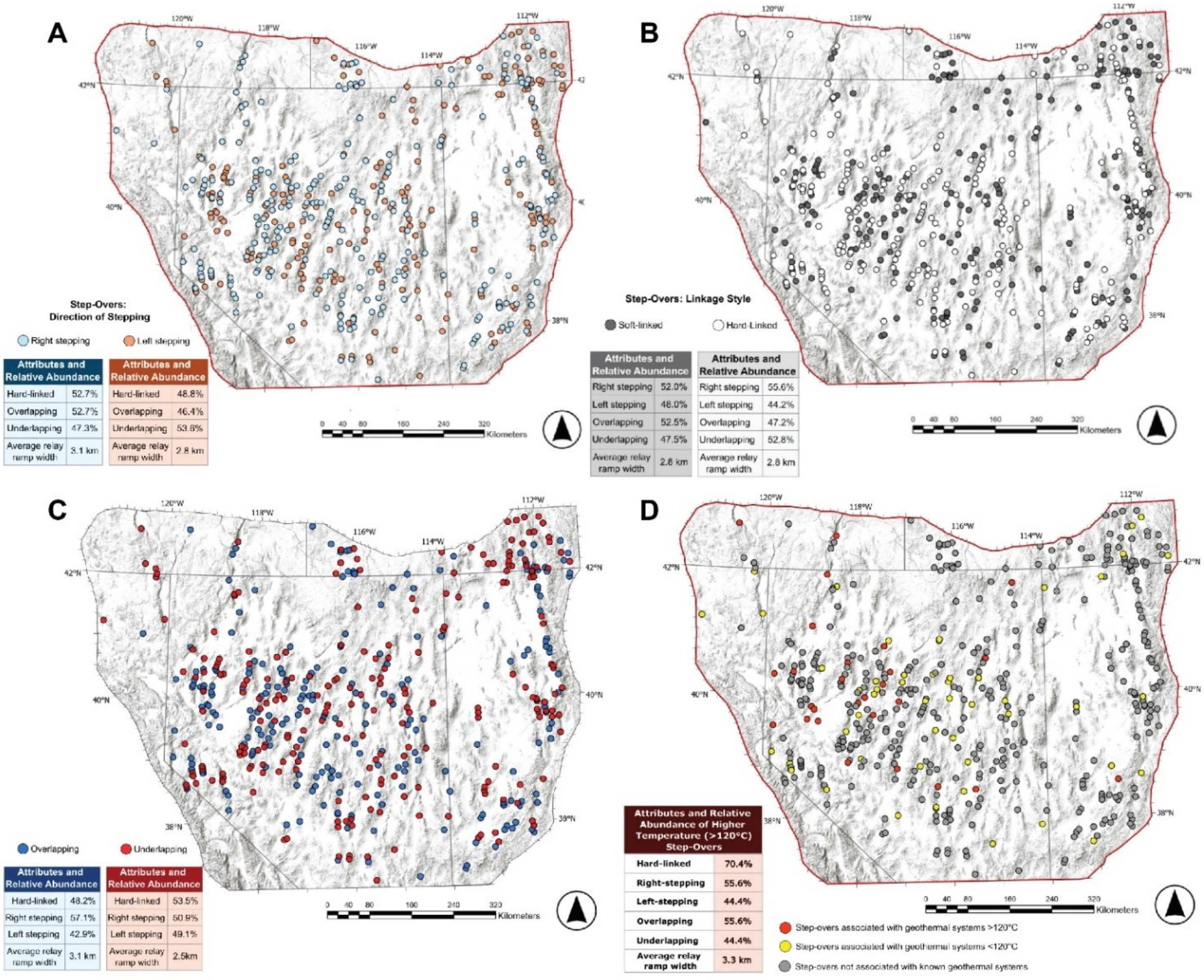
5.1 Entire INGENIOUS Study Area (Great Basin Region)

Step-overs are the most common structural setting observed in the region. Approximately ~63% of identified step-overs are in the state of Nevada, followed by ~21% in Utah, ~13% in Idaho, ~1.8% in Oregon, and ~1.5% in California. Of the observed step-overs across the study area, 50.9% are hard-linked, ~54% are right-stepping, and ~50.2% are underlapping (50.2%). The average relay ramp width is 2.8 km. Within the right-stepping subset, step-overs are more commonly hard linked, overlap, and have an average relay ramp width of 3.1 km (Figure 5A). Over 73% of right-stepping step-overs reside on fault strands that strike north to north-northeast. Over ~58% occur along westerly dipping faults. Left-stepping step-overs are more commonly soft linked, underlap, and have an average relay ramp width of 2.8 km (Figure 5A). Approximately ~75% lie along faults that strike north to north-northeast, and over 61% occur on westerly dipping faults.

Within the hard-linked subset, step-overs more commonly are right-stepping (55.6%), underlapping (52.8%), and have an average relay ramp width of 2.8 km (Figure 5B). These hard-linked step-overs more commonly occupy fault strands that strike north to north-northeast (78.4%) and faults that dip west (59%). Soft-linked relay ramps make up approximately ~49% of all step-overs. These preferentially step right (52%), overlap (52.5%), and have an average relay ramp width of 2.8 km (Figure 5B). Soft-linked step-overs more commonly occupy fault strands oriented north to north-northeast (69.5%) and dipping west (59.6%).

Step-overs with overlapping main fault strands make up 49.8% of all those identified. These step-overs preferentially step right (57.1%), are soft-linked (51.8%), and have an average relay ramp width of 3.1 km (Figure 5C). Over 75% of overlapping step-overs have main fault strands oriented north to north-northeast, and 56.6% occupy west-dipping faults. Underlapping step-overs are very slightly more common in the Great Basin region (50.2%). Within this underlapping subset, step-overs preferentially step right (50.9%), are hard-linked (53.5%), and have an average relay ramp width of 2.5 km (Figure 5C). Approximately 73% of underlapping step-overs have main fault segments oriented north to north-northeast, and ~63% reside on west-dipping faults.

Approximately 17% of all the step-overs in the Great Basin region are associated with known geothermal systems. Within this subset, ~35% are considered higher temperature (>120°C) and are preferentially right-stepping, hard-linked, and overlap. The average relay ramp width of the higher-temperature step-overs is 3.3 km (Figure 5D). These higher-temperature step-overs more commonly lie between fault strands oriented north to north-northeast (~74%) and dipping east (~56%).



Attributes and Relative Abundance	
Hard-linked	52.7%
Overlapping	52.7%
Underlapping	47.3%
Average relay ramp width	3.1 km

Attributes and Relative Abundance	
Hard-linked	48.8%
Overlapping	46.4%
Underlapping	53.6%
Average relay ramp width	2.8 km

Attributes and Relative Abundance	
Right stepping	52.0%
Left stepping	48.0%
Overlapping	52.5%
Underlapping	47.5%
Average relay ramp width	2.8 km

Attributes and Relative Abundance	
Right stepping	55.6%
Left stepping	44.2%
Overlapping	47.2%
Underlapping	52.8%
Average relay ramp width	2.8 km

Attributes and Relative Abundance	
Hard-linked	48.2%
Right stepping	57.1%
Left stepping	42.9%
Average relay ramp width	3.1 km

Attributes and Relative Abundance	
Hard-linked	53.5%
Right stepping	50.9%
Left stepping	49.1%
Average relay ramp width	2.5km

Attributes and Relative Abundance of Higher Temperature (>120°C) Step-Overs	
Hard-linked	70.4%
Right-stepping	55.6%
Left-stepping	44.4%
Overlapping	55.6%
Underlapping	44.4%
Average relay ramp width	3.3 km

Figure 5. A. Step-overs (454 total) identified in the INGENIOUS study area categorized by direction of stepping and relative abundance of other attributes. B. Step-overs identified in the INGENIOUS study area categorized by linkage style with relative abundance of other attributes. C. Step-overs identified in the INGENIOUS study area characterized by the overlapping versus underlapping geometry of the main fault strands and associated relative abundance of other attributes. D. Step-overs and associated temperatures in the INGENIOUS study area.

5.2 Walker Lane

Step-overs in the Walker Lane are more commonly hard-linked (59.3%), step right (74.1%), underlap (51.9%), and have an average relay ramp width of 2.0 km (Figure 6A). Over 66% of the Walker Lane step-overs lie along faults oriented north to north-northeast. Approximately 67% of step-overs are within east-dipping fault zones. All fault zones hosting step-overs in the Walker Lane have been active within the past 1.6 Ma (e.g., U.S. Geological Survey, 2020), with 11.1% less than 130 ka and 18.5% less than 15 ka. Step-overs are more commonly hard-linked in the Walker Lane. Within this category, 81.3% step right and 56.2% overlap. The average relay ramp width in this group is 2.0 km. About 63% of hard-linked step-overs in the Walker Lane occur along northerly oriented faults, with 75% on east-dipping fault zones. Soft-linked step-overs make up 40.7% of all step-overs in the Walker Lane. These step-overs preferentially step right (63.6%), underlap (63.6%), and have an average relay ramp width of ~2.0 km. They occur more commonly between faults oriented north to north-northeast (54.5%) and main fault strands dipping east (54.5%).

Right- and left-stepping step-overs in the Walker Lane are characterized by different attributes. About 74% of all Walker Lane step-overs are right-stepping. These structures are more commonly hard-linked (65%) and do not have main fault segments that preferentially overlap or underlap. These step-overs have an average relay ramp width of 2.1 km, are most commonly between faults that strike north (45%), and faults that dip east (70%). In contrast, left-stepping step-overs in the Walker Lane are more commonly soft linked (57.1%) and underlap (57.1%). They, have average relay ramp widths of 1.6 km, generally lie between main fault strands striking north (71.4%), and more commonly reside on faults dipping east (57.1%).

Overlapping step-overs in the Walker Lane account for 48.2% of all step-overs in this region. Within this group, step-overs preferentially step right (76.9%), are hard-linked (69.2%), are between main fault strands oriented north (69.2%), and occur along faults dipping east (69.2%). This subset has an average relay ramp width of 2.1 km.

By a slight margin, step-overs in the Walker Lane more commonly underlap (51.9%). Within this subset, these step-overs preferentially step right (71.4%), are between main fault strands oriented north to north-northeast (64.3%), and occupy east-dipping faults (64.3%). Underlapping step-overs in the Walker Lane have an average relay ramp width of 1.9 km and have no preference on linkage style (50/50 hard vs. soft-linked).

5.3 Central Nevada Seismic Belt

Step-overs are the most common structural setting identified in this area (51.6%) and preferentially step right (59.4%), overlap (54.7%), are hard-linked (56.3%), and straddle main fault strands oriented north to north-northeast (78.1%) and dipping west (65.6%) (Figure 6B). These step-overs have an average relay ramp width of 3.5 km. Fault zones hosting step-overs in the central Nevada seismic belt have ruptured in the past 1.6 Ma, with 40.1% in <130 ka, 28.1% <15 ka, and 6.3% <150 years.

Over 56% of all step-overs in the central Nevada seismic belt are hard-linked. Within this subset, these step-overs more commonly step right (66.7%) and do not preferentially overlap or underlap. Hard-linked step-overs most commonly occur along fault strands oriented north to north-northeast (80.6%) and dipping west (63.9%). They have an average relay ramp width of 3.5 km.

Soft-linked step-overs represent ~44% of all step-overs in the central Nevada seismic belt. This group of step-overs more commonly overlaps (60.7%) and does not have a preferential step direction. All soft-linked step-overs in the central Nevada seismic belt are associated with fault zones striking north to northeast, with ~68% of the faults dipping west. These step-overs have an average relay ramp width of 3.4 km.

Approximately 59% of all central Nevada seismic belt step-overs step right. This group of step-overs more commonly are hard-linked (63.2%) and overlap (60.5%). All occur along main fault strands oriented north to north to northeast, with 63.2% on west-dipping faults. Right-stepping step-overs in the central Nevada seismic belt have an average relay ramp width of 3.9 km.

Approximately 41% of all step-overs in the central Nevada seismic belt are left-stepping. This group of step-overs are more commonly soft-linked (53.9%), underlap (53.9%), and lie between main fault strands that strike north (61.5%) and dip west (69.2%). This group has an average relay ramp width of 2.8 km, which is over 1 km less than the average width of right-stepping step-overs in this area.

Overlapping step-overs account for 50% of all step-overs in the central Nevada seismic belt. Within this subset, step-overs are more commonly right-stepping (65.7%), hard-linked (51.4%), and situated between faults that strike north to north-northeast (74.3%) and dip west (62.9%). This group has an average relay ramp width of 3.9 km.

Underlapping step-overs also make up 50% of all step-overs in the central Nevada seismic belt. This group more commonly steps right (51.7%), is hard linked (62.1%), and straddles faults striking north (51.7%) and dipping west (69%). This group has an average relay ramp width of 2.9 km, which is significantly less than that of overlapping step-overs in this region.

5.4 Western Great Basin

Step-overs are the most common structural setting identified (39.7%) in the western Great Basin and preferentially step right (51.8%), overlap (55.3%), and are soft-linked (51.8%), albeit by slight margins. These step-overs are more commonly situated along fault zones that are oriented north to north-northeast (72.9%) and dip east (56.2%) (Figure 6C). The average relay ramp width is 2.5 km.

Over 48% of all step-overs in the western Great Basin are hard-linked. Within this group, these step-overs more commonly step right (51.2%) and underlap (56.1%). Hard-linked step-overs most commonly lie between fault zones oriented north (53.7%) but also occur along north-northwest (24.4%) and north-northeast-striking (19.5%) fault zones. This group has a slight preference for west-dipping fault zones (51.2%). The average relay ramp width is 2.6 km.

About 52% of observed step-overs in the western Great Basin are soft-linked. This group more commonly steps right (52.3%) and overlaps (65.9%). Soft-linked step-overs most commonly lie between fault zones that are oriented north to north-northeast (72.7%) and dip east (63.6%). The average relay ramp width is 2.4 km.

Approximately 51.8% of all step-overs in the western Great Basin step right. By slight margins, this group of step-overs are more commonly soft-linked (52.3%) and overlap (56.8%). Right-stepping step-overs more commonly occur between fault zones that are oriented north to north-northeast (75%) and dip west (52.3%). The average relay ramp width is 3 km.

Left-stepping step-overs account for 48.8% of all observed step-overs in the western Great Basin. This group is more commonly soft-linked (51.2%) and overlapping (53.7%) but again by slight margins. Left-stepping step-overs are more commonly found within fault zones that are oriented north (46.3%) and secondarily north-northwest (24.4%) and north-northeast (24.4%), with east-dipping faults dominant (65.9%). This group has an average relay ramp width of 2.0 km.

Overlapping step-overs account for 56.2% of all step-overs in the western Great Basin. Within this group, step-overs preferentially step right (54%) and are soft-linked (62%). They most commonly occur between fault zones oriented north to north-northeast (68%) and dipping east (52%). The average relay ramp width of this group is 2.8 km.

Underlapping geometries account for 44.7% of all step-overs in the western Great Basin. This group is more commonly hard-linked (60.5%) and has no preferential step direction. Underlapping step-overs in this region more commonly occur between fault zones that are oriented north to north-northwest (81.6%) and that dip east (60.5%). The average relay ramp width of underlapping step-overs in the western Great Basin is 2.2 km.

5.5 Great Basin Carbonate and Alluvial System

Step-overs in the Great Basin carbonate and alluvial aquifer system are more commonly hard-linked (51.8%), right-stepping (52.2%), and underlap (51.8%). Most lie within fault zones striking north to north-northeast (77.5%) and dipping west (64.7%). The average width of the relay ramp is 2.7 km (Figure 6D). Fault zones hosting step-overs in the Great Basin carbonate and alluvial aquifer systems have all been active in the Quaternary, with 38.2% rupturing in the past 130 ka and 24.1% since 15,000 ka.

About 52% of step-overs in this domain are hard-linked. Within this group, step-overs preferentially step right (54.3%) and underlap (51.2%). These step-overs more commonly lie between fault strands oriented north to north-northeast (79.1%) and dipping west (64.3%), while having an average relay ramp width of 2.8 km.

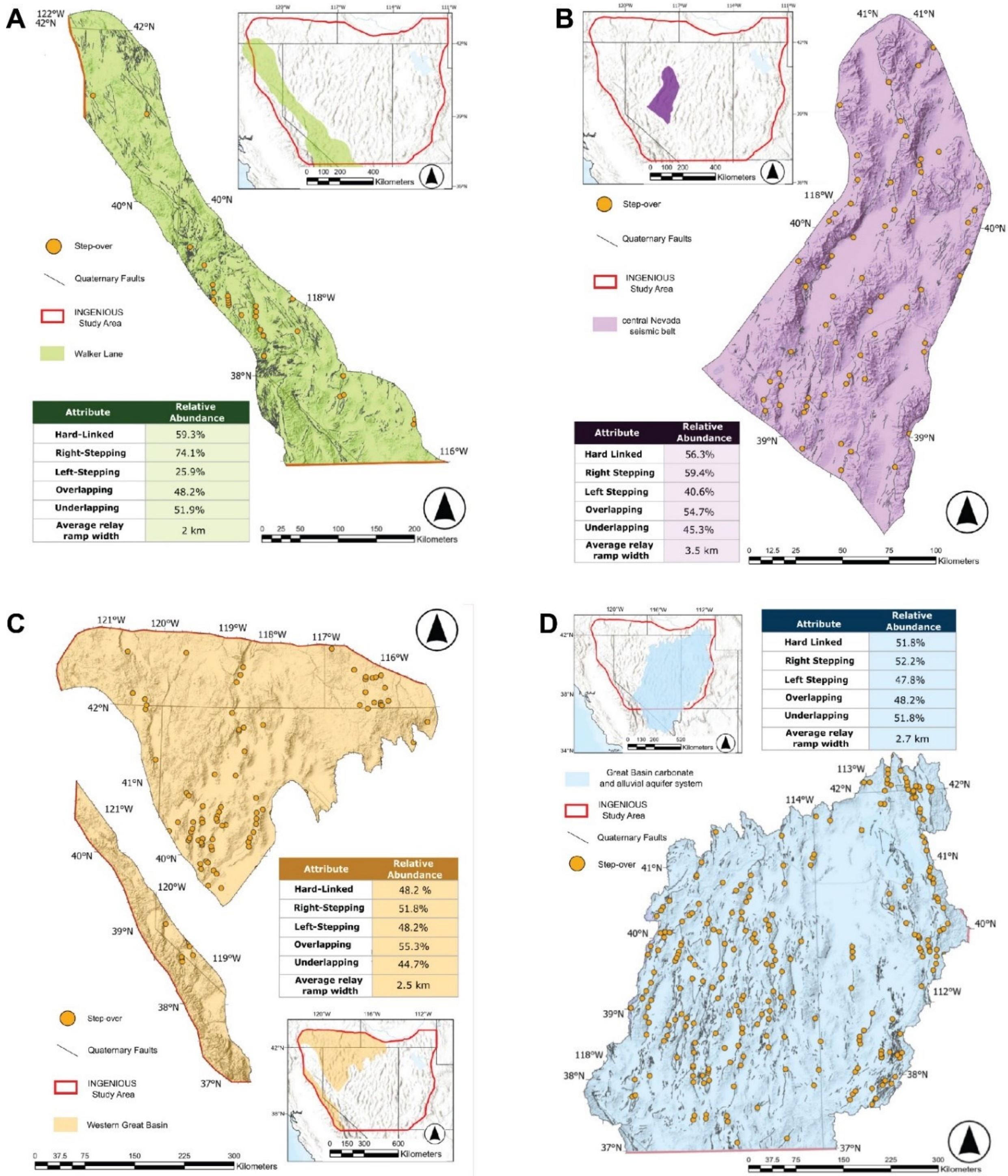
Soft-linked step-overs account for ~48% of all such structures identified in the Great Basin carbonate and alluvial aquifer system. Within this group, step-overs do not have a preferential step direction and are slightly more commonly underlapping (52.5%). Soft-linked step-overs in the area most commonly occupy fault zones that strike north to north-northeast (75.8%) and dip west (65%). The average relay ramp width is 2.7 km.

Over 52% of all step-overs identified in the Great Basin carbonate and alluvial aquifer system are right stepping. Within this subgroup, hard-linked (53.9%) and overlapping (51.5%) step-overs are slightly more common. These step-overs generally lie between fault strands oriented north to north-northeast (76.2%) and dipping west (62.3%). The average width of the relay ramp is 3.0 km.

Step-overs stepping left make up ~48% of all step-overs in the Great Basin carbonate and alluvial aquifer system. This group is more commonly soft-linked (50.4%) and underlapping (55.5%). The left-stepping step-overs most commonly reside in fault zones striking north to north-northeast (79%) and dipping west (67.2%), while displaying an average relay ramp width of 2.5 km.

Step-overs that have main fault strands that overlap account for ~48% of all step-overs identified in the Great Basin carbonate and alluvial aquifer system. This group of step-overs preferentially steps right (55.8%) and is hard-linked (52.5%). These step-overs most commonly straddle faults oriented north to north-northeast (78.3%) and that dip west (60%). They have an average relay ramp width of 3.2 km.

Underlapping step-overs account for ~52% of all step-overs in the Great Basin carbonate and alluvial aquifer system. This group of step-overs preferentially steps left (51.2%) and is hard-linked (51.2%) but by slight margins. These step-overs are most commonly situated along fault zones that strike north to north-northeast (76.7%) and dip west (60%). The average relay ramp width of this subset is 2.3 km.



A.

Attribute	Relative Abundance
Hard-Linked	59.3%
Right-Stepping	74.1%
Left-Stepping	25.9%
Overlapping	48.2%
Underlapping	51.9%
Average relay ramp width	2 km

B.

Attribute	Relative Abundance
Hard Linked	56.3%
Right Stepping	59.4%
Left Stepping	40.6%
Overlapping	54.7%
Underlapping	45.3%
Average relay ramp width	3.5 km

C.

Attribute	Relative Abundance
Hard-Linked	48.2 %
Right-Stepping	51.8%
Left-Stepping	48.2%
Overlapping	55.3%
Underlapping	44.7%
Average relay ramp width	2.5 km

D.

Attribute	Relative Abundance
Hard Linked	51.8%
Right Stepping	52.2%
Left Stepping	47.8%
Overlapping	48.2%
Underlapping	51.8%
Average relay ramp width	2.7 km

Figure 6: Relative abundance of various attributes of step-overs in tectonic and hydrogeologic domains of the Great Basin region. A. Walker Lane (27 total). B. Central Nevada seismic belt (64 total). C. Western Great Basin outside the Walker Lane and central Nevada seismic belt (85 total). D. Great Basin carbonate aquifer and alluvial system (249 total).

6. DISCUSSION

6.1 Entire INGENIOUS Study Area (Great Basin Region)

This study revealed that spatial distributions of all identified step-overs (those associated with known geothermal systems and others identified for potential hidden systems) across the Great Basin region are more commonly associated with range-front faults (~91.9%). There is potential bias in this, as step-overs along range-front faults are more easily identified due to steep topographic gradients. Numerous step-overs were observed, for example, along major range-front faults within central Nevada and along the Wasatch front in Utah. Step-overs on less conspicuous normal faults in areas with less pronounced topography are more difficult to identify. Step-overs are particularly uncommon in the low strain area of western Utah, which is characterized by sparse Quaternary faults and relatively subdued topography.

Evolutionary stages (e.g., Figure 4; Peacock and Sanderson, 1994) can be applied to the step-overs in the Great Basin region. Underlapping, soft-linked step-overs are within stage 1 and account for 23.3% of all step-overs identified. Stage 2 is characterized by fault strands that overlap and are soft-linked (25.8%). Stage 3 involves overlap and linkage of the main fault strands. Stage 4 is the complete detachment of the upper and lower ramp. About 24% of all step-overs in the study area are in stages 3 and 4. However, there is another commonly observed "different" geometry that does not fit into the traditional 4 stage categories – that is, underlapping and hard-linked step-overs account for 26.9% of all step-overs in the INENIOUS study area.

Step-overs associated with known geothermal systems in the INGENIOUS study area have slightly different characteristics. Approximately 23.4% are in stage 1 (soft-linked and underlapping), 19.5% are in stage 2 (soft-linked and overlapping), and 26% are in stages 3 and 4 (hard-linked and overlapping). Over 31% of step-overs associated with known geothermal systems fall into the aforementioned "different" category, characterized by hard-linkage and underlapping.

In the INGENIOUS study area, 6.9% of known geothermal systems host operating power plants, with a total of 10, or 40% of power plants residing in step-overs. Step-overs that host producing power plants have relay ramps widths that range from 0.6 km (Soda Lake, Nevada) to 9.5 km (Summer Lake Hot Springs, Oregon), with an average of 3.4 km.

More than 90% of step-overs with operating geothermal power plants reside in fault zones oriented north to northeast. Similarly, all step-overs associated with higher-temperature geothermal systems (>120°C) share this preference in fault orientation. Both groups have <10% of step-overs within north-northwest-striking fault zones and no stepovers associated with northwest oriented fault zones.

Step-overs with operating power plants are preferentially hard-linked (72.7% %), left-stepping (63.6%), overlapping (54.5%), and within east-dipping fault zones (54.5%). Higher-temperature (>120°C) systems within step-overs also are preferentially hard-linked (70.4%), overlapping (55.5%), and within east-dipping fault zones (55.6%), but slightly more commonly step right (55.6%). The spatial distribution and varying tectonic regimes could be the cause of this difference in step-direction.

6.2 Regional Characteristics

Compared to the other domains, the Walker Lane displays some unusual characteristics with respect to step-overs and fault orientations. It is the only domain where step-overs are not the most common favorable structural setting. The Walker Lane has an abundance of both normal and dextral faults (Faulds and Henry, 2008). Therefore, this difference in relative abundance of normal-fault step-overs is likely due to the regional tectonic setting. Fault orientations within Walker Lane also differ from that of other domains. Previous studies have shown that the Walker Lane has the most diverse range of fault orientations associated with geothermal systems (Cashman et al., 2012). Cashman et al. (2012) found that about 75% of geothermal systems in the Walker Lane are within fault zones oriented north to east-northeast (and dominantly northeast to north-northeast), whereas only ~25% are oriented northwest. This study yielded similar results for step-overs, whereby step-overs preferentially strike north to north-northeast (>65%), and the remainder strike north to north-northwest.

There are some key differences between step-overs in the Walker Lane compared to all step-overs identified in other parts of the Great Basin region. Over 66% of the step-overs within the Walker Lane occur along east-dipping fault zones. This contrasts with other step-overs in the Great Basin region outside of the Walker Lane, where over 59% reside within west-dipping fault zones. The Walker Lane step-overs also have the smallest average relay ramp width (1.9 km) of all domains investigated, almost 1 km smaller than the average for the entire study area (2.8 km). Interestingly, there are no step-overs with operating power plants in the Walker Lane. This suggests that step-overs in the Walker Lane are not the most preferential structural setting for hosting higher-temperature geothermal systems.

Step-overs are the most common favorable structural setting found in the central Nevada seismic belt (Giddens, 2024). The step-overs in this region have the widest average width of relay ramps (3.5 km). Relay ramp width varied greatly between step directions. On average, right-stepping step-overs were 1 km wider than left-stepping. Left-stepping step-overs were also 0.7 km narrower than average for all step-overs observed in the region. Similar to step direction, overlapping and underlapping step-overs had varying relay ramp widths. On average, underlapping step-overs were 1 km narrower than overlapping step-overs. Therefore, there is likely a link between step direction and overlap on relay ramp widths that could be investigated further in future studies.

The orientation of controlling fault zones for step-overs differs slightly in the central Nevada seismic belt compared to other regions. The primary preferred fault orientation in step-overs in the central Nevada seismic belt is north, followed by north-northeast, similar to other domains in the INGENIOUS study area. However, the central Nevada seismic belt has no step-overs along northwest-striking fault zones, whereas the other domains have small fractions (~1 to 14%) along northwest oriented faults.

Step-overs associated with higher-temperature systems (>120°C) in the central Nevada seismic belt have some notable attributes. These step-overs are more likely to occur in fault zones striking northeast (57%) compared to either north-northeast- (28.5%) and north-striking (14.3%) fault zones. Over 85% of these step-overs are also right-stepping. Another interesting attribute of this group of step-overs is that the only higher-temperature system in a left-stepping step-over is also the only one oriented north, whereas the rest are oriented north-northeast to northeast. In addition, the step-overs hosting higher-temperature systems in the central Nevada seismic belt are all hard-linked. The average relay ramp width for these higher-temperature step-overs is 4.4 km, which is larger on average than higher-temperature step-overs within other domains.

There are specific attributes of power producing step-overs in the central Nevada seismic belt. All are associated with step-overs that are right-stepping, hard-linked, and oriented north-northeast to northeast. Approximately 66.7% of these step-overs are underlapping, with an average relay ramp width of 3.1 km. These results suggest that right-stepping, hard-linked step-overs in fault zones oriented north-northeast to northeast have the greatest potential for hosting a higher-temperature geothermal system in the central Nevada seismic belt.

Step-overs identified in the western Great Basin are preferentially right-stepping (51.8%), overlapping (55.3%), and soft-linked (51.8%), all by relatively slight margins. Step-overs in all other domains are preferentially hard-linked. Step-overs within the western Great Basin have similar fault orientations to step-overs in other domains (north to northeast) but more commonly occur within east-dipping fault zones. The only other domain where step-overs are more commonly found on east-dipping faults is the Walker Lane. Similarities in this preference may be attributed to regional tectonics, including the general dominance of east-dipping normal fault zones proximal to the Sierra Nevada along the western margin of the Great Basin.

Step-overs associated with higher-temperature (>120°C) geothermal systems in the western Great Basin domain preferentially step left (58.3%), are hard-linked (66.7%), and overlap (58.3%). Similar to all step-overs in the western Great Basin region, higher-temperature step-overs prefer faults oriented north to north-northeast (75%) and east-dipping faults (58.3%). The western Great Basin has the largest number of step-overs with operating geothermal power plants. The preferred attributes of these step-overs are left-stepping (85.7%), hard-linked (57.1%), and overlapping (71.4%). About 71.4% of these step-overs occupy fault zones oriented north to north-northeast, with 57.1% on east-dipping faults. These findings reveal that left-stepping, hard-linked, and overlapping step-overs within fault zones oriented north to north-northeast have a greater potential for hosting economically viable geothermal systems in the western Great Basin.

Step-overs within the Great Basin carbonate and alluvial aquifer system are preferentially hard-linked (51.8%), right-stepping (52.2%), and underlapping (51.8%), albeit all by slight margins. These statistics are consistent with the findings of identified step-overs within the entire INGENIOUS study area. Almost all higher-temperature step-overs in this domain are hard linked (83.3%). The regional strain rate varies significantly across the Great Basin carbonate and alluvial aquifer system. Regions of lower strain within this area, such as western Utah, possess lower relative abundances of favorable structural settings. Conversely, areas with elevated strain rates, such as the Wasatch front, have higher relative abundances and greater diversity of step-overs. Due to this, and the size of the domain, future analyses could consider further subdividing this region based on tectonic characteristics.

6.3 Implications

Step-overs associated with higher-temperature (>120°C) geothermal systems have specific attributes that may make them more commercially viable. For example, over 90% of higher-temperature step-overs are within fault zones oriented north to northeast. No higher-temperature system step-overs occupy northwest-striking faults, and only 7.4% lie within north-northwest-striking faults. North- to northeast-striking faults are oriented perpendicular to the least principal stress direction (west-northwest extension), and therefore these faults are optimally oriented to experience slip and dilation compared to north-northwest- and northwest-striking faults.

Another characteristic of higher-temperature systems within step-overs is their tendency to reside in east-dipping versus west-dipping normal fault zones. However, this is only by a slight margin (55.6% dip east). Notably, over 88% of the higher-temperature step-overs are located in the western half of the Great Basin region, where east-dipping fault zones are generally more abundant than in the eastern Great Basin region. Strain is also elevated in the western Great Basin region. Previous studies have linked both the density of higher-temperature geothermal systems and geothermal power plant capacity to areas of high strain (Faulds et al., 2012). Both elevated strain and relative abundance of east-dipping normal faults may explain the slight affinity for higher-temperature systems with east-dipping normal fault zones.

Other attributes of higher-temperature step-overs include linkage and overlap. Over 70% of these step-overs are hard-linked. Additional faults breaching relay ramps add to the structural complexity and increase the density of fractures, faults, and fault intersections, all of which serve to enhance permeability. Overlap is also an attribute that is favored by higher-temperature step-overs, albeit only by a slight margin (~56%). Similar to breaching faults, overlapping faults create structural complexity that can enhance permeability. Interestingly, the central Nevada seismic belt is the only domain where higher-temperature step-overs are more commonly underlapping. Nonetheless, the general preference for overlap and hard-linkage suggests that step-overs in the third stage of evolution (overlapping and hard-linked faults) are more likely to host a commercially viable geothermal system compared to other step-overs. Focusing exploration efforts on identifying step-overs in the third stage of evolution (Figure 4) may therefore prove useful in discovering hidden higher-temperature geothermal systems.

6.4 Limitations

Limitations of this study include scale, precise domain boundaries, data resolution, and data availability. Step-overs can occur at varying scales, from centimeters to many kilometers wide. For this project, step-overs ranging from over 100 m to 15 km were identified. Due to the size of the study area (~499,178 km^2) and lack of widespread high-resolution Quaternary fault data, Lidar, and/or detailed geological mapping in many areas, it is likely that many smaller step-overs have been missed. In addition, the regional scale of the project presented a need to separate the study area into tectonic/hydrogeologic domains, but it is not that simple. Domains used in this study, such as the Walker Lane and central Nevada seismic belt, do not have precise boundaries.

Another limitation to this study was resolution for geophysical datasets. These datasets proved helpful if used in combination with other datasets to determine the locations and extent of many of the step-overs. However, such datasets cannot be used alone and work best if combined with higher resolution geological datasets, such as geological maps and Quaternary fault data. Continued integration of newly acquired or available higher resolution geophysical datasets is essential for identifying hidden geothermal systems.

The greatest limitation to this project was available data. High resolution LiDAR was only available for portions of the study area. Many areas that lacked Quaternary fault data were supplemented with available geological maps. However, not all areas have large-scale (1:24,000) geological maps that adequately show structural relations, particularly the location, patterns, and age relations of Quaternary faults. With the continued acquisition of high-resolution LiDAR across the region and slow but steady progress on filling gaps in detailed geological mapping, additional step-overs can be identified and added to the database in the future.

7. CONCLUSIONS

This study showed that certain geometries and attributes of step-overs are associated with higher-temperature geothermal systems. Specifically, step-overs located in regions of elevated strain, within fault segments oriented north to north-northeast, and those that are hard-linked have a higher likelihood of hosting higher-temperature geothermal systems. Both right-stepping and overlapping fault segments are associated with higher-temperature systems, but only by a slight margin. Regional tectonics can also affect the spatial distribution and characteristics of step-overs. For example, in areas experiencing transtension, such as the Walker Lane, higher-temperature geothermal systems are more likely to reside in dilational parts of strike-slip fault systems (e.g., pull parts and displacement transfer zones) and less likely to occupy step-overs in normal-fault systems. In contrast, step-overs in normal fault zones generally serve as the primary host of higher-temperature geothermal systems in more purely extensional regions, such as the central Nevada seismic belt. These regional differences suggest that a tailored approach to exploration is essential.

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