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A Look Into Geothermal Discoveries Across the Western United States

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ABSTRACT

Historically, most conventional hydrothermal geothermal systems have been discovered by drilling in the vicinity of surface geothermal features (e.g., fumaroles, hot springs, or paleo-geothermal deposits) or discovered accidentally during drilling for fossil fuel, mineral, or water resources. In this paper we highlight key insights into the history of exploration across the contiguous western U.S. from a comprehensive dataset of wells and springs from various industry, academic, and public sources. Our analysis focuses on the extent to which the subsurface, particularly fault zones, has been explored. Notably, we find that less than 10% of the contiguous western U.S. has been sampled for subsurface temperatures, most of which are at shallow depths (0-20 m). Of this subsurface data, early-stage geothermal exploration drilling has covered only about 0.4% of the contiguous western U.S. Additionally, fault zones remain largely unexplored, with two-thirds of Quaternary faults not restricted by protected land status lacking subsurface temperature data within a 1 km radius. This limited spatial coverage highlights significant gaps in the available data and underscores the need for targeted exploration efforts to identify and develop more resources.

Throughout the history of geothermal discoveries in this region more blind and hidden sites have been found by accident than on purpose. Accidental discoveries, primarily from water wells and mining activities, account for half of all utility-scale geothermal resources, and the majority of all the blind or hidden discoveries. Estimates from previous studies at the USGS, Department of Energy, and Great Basin Center for Geothermal Energy indicate that blind or hidden geothermal systems are likely to comprise most geothermal resources in the Great Basin and western U.S. This assertion is mainly corroborated by the historical rate of accidental discoveries, where historical water well drilling has accidentally discovered more than a third of known blind or hidden geothermal systems. Furthermore, because homesteading was ended in 1976 by the Federal Land Policy and Management Act, the rate of these accidental water well discoveries has slowed to a trickle. The industry's dependency on accidental discoveries for blind resources means that the available developable pipeline is small and is not sufficiently growing. This paper highlights the need for a new era of targeted greenfield campaigns to increase the rate of blind discoveries and expand the industry's development pipeline. Based on historical success rates, we estimate that drilling 100k new exploration holes could lead to more than 100 new blind or hidden geothermal discoveries.

1. INTRODUCTION

The western United States is a region of significant geothermal potential due to its active tectonics, widespread volcanism, and high heat flow. Conventional geothermal ("hydrothermal") resources are reservoirs that naturally contain hot fluids or steam in porous or permeable rocks. Once brought to the surface, the heat from geothermal fluid or steam can be used to generate electricity or used directly for various commercial purposes (e.g., to grow flowers or fish; see Milgro greenhouses in Newcastle, UT or Americulture's tilapia farm at Lightning Dock, NM). Over the past several decades, there have been multiple efforts to characterize the potential for hydrothermal development in the region (e.g., Williams et al., 2008; NREL, 2019). However, there has been little effort to analyze discovery trends to elucidate potential pipelines of undeveloped geothermal projects. This study addresses these gaps by examining how industry, academia, government and other drilling actors have made discoveries over the past century. We demonstrate insights from targeted field efforts in identifying blind geothermal resources and provide an assessment of the potential for new discoveries based on data coverage in explorable regions.

The information below was compiled from various academic and industry sources. Much of this work builds on the United States Geological Survey's (USGS) inventory of sites that are classified as moderate (90-150°C) to high temperature (≥ 150°C) geothermal resources (Godwin et al., 1971; Muffler et al., 1978; Williams et al., 2008). For this study, we have built out a more extensive list by adding sites from more recent academic studies (e.g., Shevenell et., al 2011; Mullane 2016;), previously unpublished industry explorers, and our internal exploration. Thus far, we have identified 370 unique sites with moderate to high temperature geothermal potential across the contiguous western U.S. (Fig. 1).

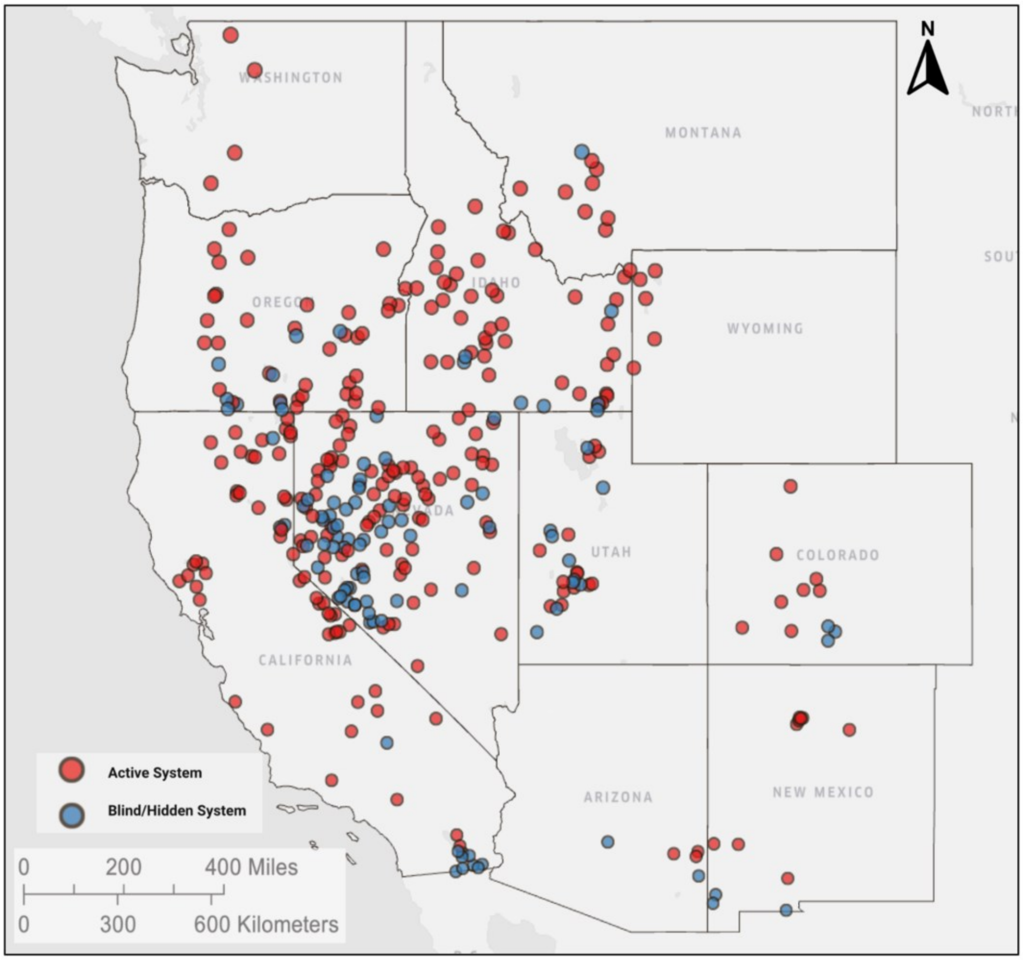

Figure 1: Map of electricity grade (90°C+) conventional hydrothermal discoveries across 11 western states. There are 258 active discoveries with surface features and 112 that are blind or hidden. Note that Zanskar discoveries are not shown on map.

For each site we conducted an extensive literature review to document its discovery date and key attributes. Our analysis highlighted significant insights, particularly regarding blind and hidden geothermal systems. Blind systems, which lack surface geothermal manifestations, and hidden systems, which may exhibit subtle alteration features or paleo-geothermal deposits such as opaline sinter, tufa, or silicic and argillic alteration, represent substantial untapped geothermal potential. Both types of systems pose significant discovery challenges due to their subtle or absent surface indicators. Active systems include sites hosting hot springs, mudpots, geysers, and fumaroles, which serve as clear surface indicators of geothermal activity.

Despite these challenges, blind and hidden geothermal systems offer unique opportunities for sustainable energy development. The estimated untapped resource base of blind and hidden systems in the western U.S. is thought to constitute three times the resource potential of identified systems in the western U.S., on the order of 30 GWe (Williams et al., 2008; Dobson et al., 2016). Historically, these sites also face fewer environmental and cultural hurdles to development than active sites (e.g., see recent case histories for geothermal development at Baltazor, NV, Dixie Meadows, NV, Fish Lake, NV, and Gerlach, NV).

In addition to analyzing discovery trends, this study integrates temperature and well data with findings from Zanskar's targeted exploration efforts, providing new insights into the geothermal resource potential of the western United States. This integrated approach contributes to a better understanding of how targeted exploration and improved data coverage could shape the trajectory of geothermal industry growth.

2. METHODS

Below we evaluate traits of discoveries in the western United States, as well as insights from a compilation of drilling data across the region. We focus on two key areas:

- Discovery Trends: We assigned discovery dates to each site based on the earliest documented classification or evaluation, enabling analysis of temporal discovery patterns and key exploration phases.
- Exploration Gaps: We analyzed well distribution, depth, and fault proximity to evaluate the proportion of the western U.S. that remains unsampled or inadequately sampled for subsurface temperatures.

This study integrates data from various sources, including government-funded compilations (e.g., Waring, 1915; 1917; 1965), academic studies (e.g., Shevenell et al., 2011), and industry exploration data (e.g., Sass et al., 1999). Out of the 370 identified sites, 112 were classified as hidden or blind systems based 1) on their lack of active surface features, and 2) more than 2.5 km from known sites or any active surface features (e.g., springs, geysers, mudpots, maars).

For this analysis, "wells" are broadly defined to include any recorded well—whether for oil, minerals, water, or geothermal exploration—and data from various temperature measurements, including bottom-hole, temperature gradient, and wellhead flow temperatures. While many hot spring sites were known to Indigenous groups long before written records, this analysis assigns discovery dates based on the earliest published evaluations by researchers and industry.

To represent spatial coverage, we grouped data into resolution 8 H3 (Uber, 2018) hexagonal grid cells, each covering an area of approximately 1 km^2. We also examined the relationship between mapped Quaternary faults and well data, whereby unsampled fault zones were identified as regions within ~1 km of a Quaternary fault without corresponding well data.

3. Results

3.1 Historical Trends

The exploration and discovery of geothermal resources in the western United States have progressed in distinct waves over the past century. Four primary discovery waves were identified: circa 1910-1920, 1960-1980, 2000-2015, and the 2020s (Fig. 2).

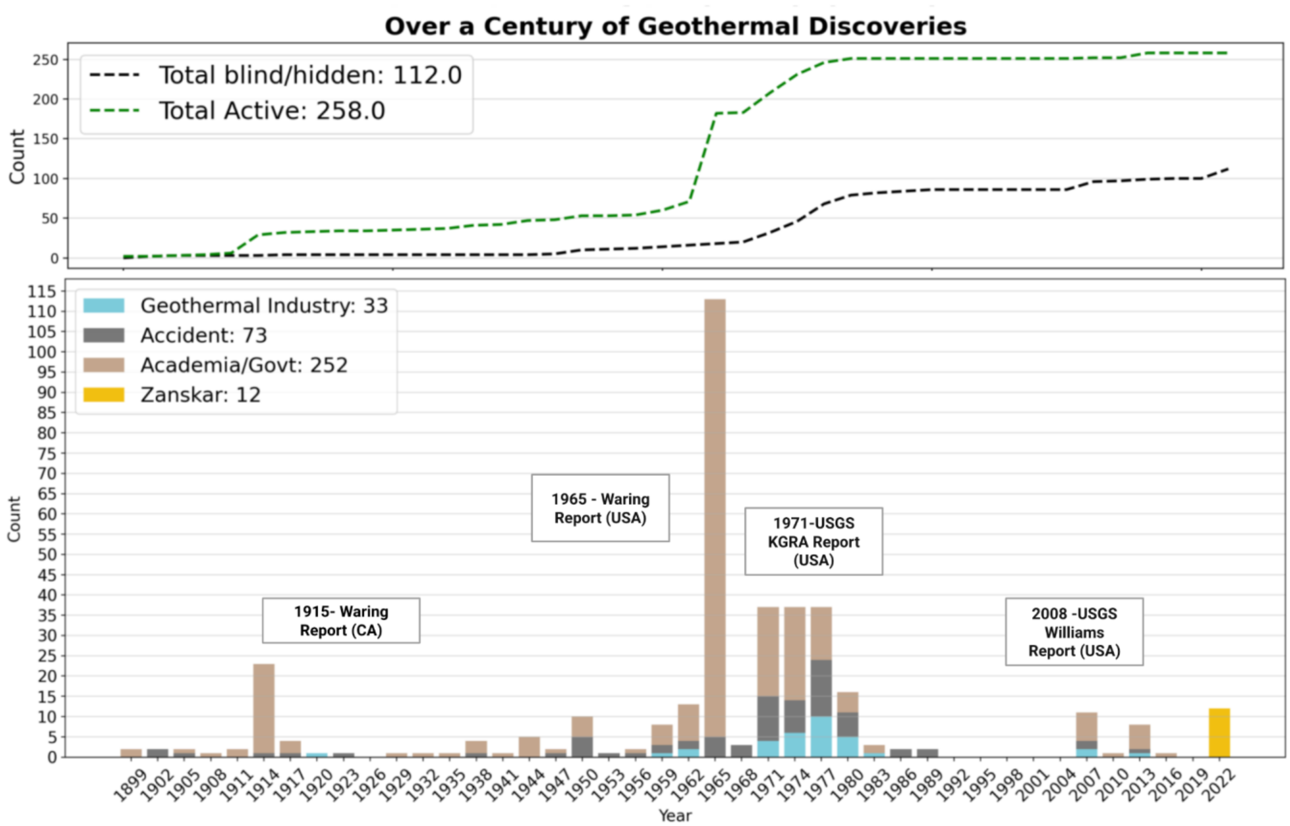

Figure 2: Plot of discovery count over the past century across the western U.S. Data is grouped into 3-year intervals. Totals for entities assigned to each discovery are in the legend. Text bubbles indicate release years of comprehensive research studies from the USGS.

1. **1910-1920:** Homesteading had been ongoing for roughly 60-70 years at this point across the western U.S., and as such, many accidental discoveries pre-date the 20th century (e.g., Hunters Hot Springs outside Lakeview, OR was discovered by Euro-

American homesteaders in the 1860's). Many of these "discoveries" ended up in 20th century USGS spring compilation reports. Nevada was homesteaded slower than surrounding western states, and as such, several notable accidental geothermal discoveries resulting from water well drilling in Nevada occurred during the 20th century, including Soda Lake, NV (1903), and Fly Ranch, NV (1916).

2. **1960-1980:** By the 1960s and 1970s, several geothermal power developments were underway, including at The Geysers (CA), Dixie Valley (NV), and Beowawe (NV). Exploration during this time primarily targeted resources with temperatures above ~180°C, deemed necessary for flash steam power plants. Shortly after the Geothermal Steam Act of 1970 which authorized leasing of federal lands for geothermal development, the USGS released detailed reports on Known Geothermal Resource Areas (KGRA) in 1971 and 1979, which identified numerous promising sites for development. These reports also highlighted geothermal exploration efforts and many accidental discoveries, such as those associated with oil and gas exploration in the Salton Sea, California. This period marks **the most successful stage of geothermal exploration and development in US history**.
3. **2000-2015:** This period was marked by advancements such as binary-cycle power plant technology, which led to expanded exploration efforts to include moderate temperature systems (≥90°C). Academic work to decrease the cost and timelines associated with exploration proved several new methods, including shallow temperature surveys (e.g., two-meter data studies; Coolbaugh et al., 2007), that resulted in the discovery of a small wave of new sites (e.g., Emerson Pass, NV and Teels Marsh, NV; Anderson et al., 2013; Zehner et al., 2012).
4. **2020-Today:** The Inflation Reduction Act of 2022 established new 10-year production and investment tax credits for geothermal development, invigorating a large increase of private capital flowing into geothermal operators and startups alike to pursue geothermal projects and new technologies. Most of this capital has flowed into work centered on "advanced" geothermal systems versus exploration (in contrast to the 1960-1980 period). As such, there has not been an observed uptick in new discoveries, besides those made by Zanskar; instead, interest has centered on brownfield acreage at operating or otherwise known sites.

Data surrounding the history and status of discoveries suggest the outlook for geothermal exploration is both promising and filled with opportunities for improvement. Key observations of our analysis include:

- **Value of blind and hidden resources:** More blind and hidden sites have been found by accident than on purpose (Fig. 3), while such sites constitute nearly half of all developed geothermal power plants (e.g., McGinness Hills, Blue Mountain), they represent just ~30% of identified resources.
- **Land Use Constraints:** A significant portion (~25%) of high-potential geothermal sites are off-limits due to conservation designations under PAD-US status 1 and 2 (i.e., within a wilderness area, national park, wildlife refuge, for more information see https://www.usgs.gov/programs/gap-analysis-project/science/pad-us-data-overview). The majority of sites that are off-limits have surface features. Any projects at sites with surface features present elevated cultural and environmental project risk.
- **Thinning Pipeline:** Two-thirds of identified sites are either off-limits or already operational, leaving a tight pipeline of undeveloped sites for future exploration and development. Moreover, many undeveloped sites are controlled by existing industry stakeholders (e.g., under a BLM geothermal lease), and as such, there's a very thin available supply of geothermal sites for new explorers and developers.

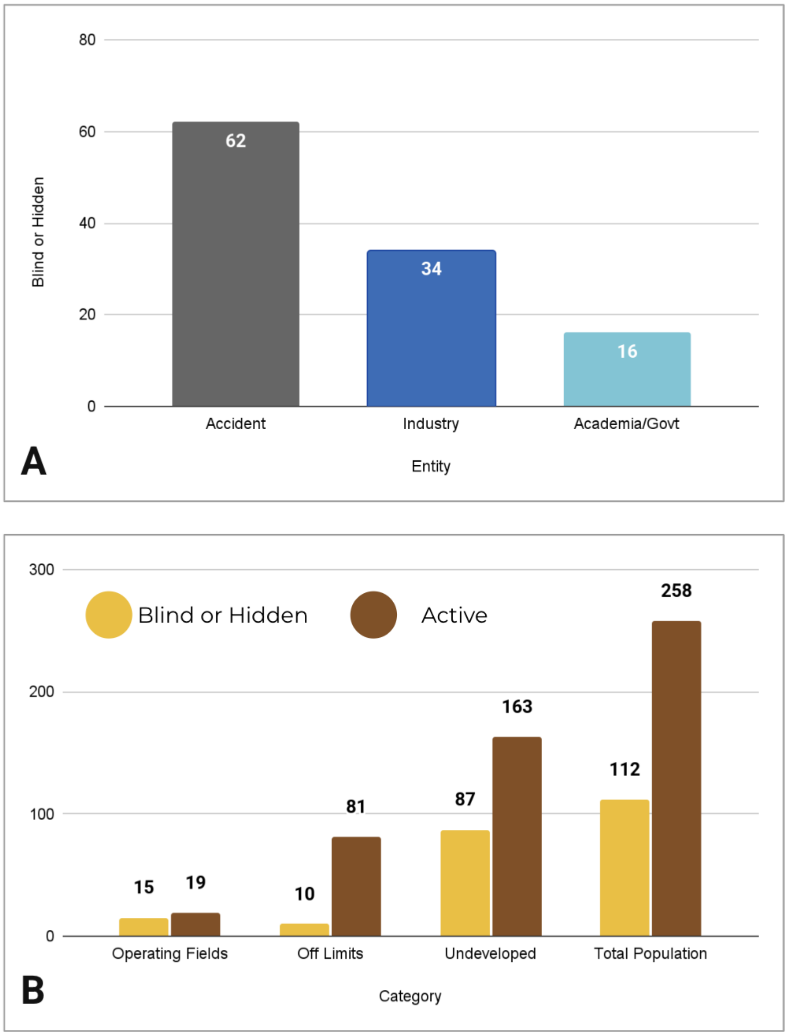

Figure 3: Discovery ratios of (A) blind or hidden accidental discoveries vs industry and academic/government research discoveries, and (B) blind or hidden vs active discoveries for operating sites (currently hosting a geothermal plant), sites that are off-limits (protected GAP status of 1 or 2 under the U.S. PADUS system), sites that are undeveloped, and the total population of sites.

Two primary exploratory drilling methods were identified as essential to making new discoveries; namely, temperature gradient measurements in shallow to intermediate depth holes (~10-300 meters; "TG") as well as 2-meter depth ("2M") temperature measurements:

- TG surveys: The largest TG campaigns in geothermal history were conducted by oil and gas companies during the 1960-1980 period (e.g., Phillips, Chevron, Hunt), which consisted of dozens of TG holes per site, covering several dozen sites, and resulted in many hundreds of thousands of feet of drilling and sampling. This work resulted in the discovery and characterization of many sites, including Desert Peak, Desert Queen, Dog Valley and many others. Modern usage of TG surveys has shifted towards a mix of shallower and intermediate depth holes as follow-up campaigns at known sites, versus as a discovery tool (e.g., Colado, Humboldt House, McGee Mountain).
- 2M surveys: First introduced in the late 1970s (Trexler, 1977) and further refined and more widely adopted in the early 2000's (e.g., Zehner et al., 2012), this shallow technique uses 2-meter-long hollow rods to measure near-surface ground temperatures. While it is a quick and cost-effective method for broad regional assessments, it is prone to high rates of false positives and false negatives, limiting its reliability without additional corroborative data. Despite these limitations, the method has been important to the discovery of several new blind or hidden systems, including Gabbs Valley (Craig et al., 2017) and Teels Marsh, NV (Zehner et al., 2012).

While these methods differ primarily in depth and cost, they represent incremental refinements in geothermal exploration, reflecting a shift toward prioritizing data collection cost and speed and supplementing data uncertainty with volume and modern statistics.

In Fig. 5 we illustrate the spatial distribution of exploration drilling for the three temperature sampling methods over the last century. Several significant surges in geothermal exploration coverage occurred during this time. In the 1970s and 1980s, TG drilling by Chevron, Phillips, Hunt, and other companies marked the first industry approach to explore and characterize commercial grade hydrothermal resources. From 2000 to 2020, exploration efforts led by the University of Nevada, Reno, focused on shallow temperature drilling using 2M surveys to more cheaply identify near-surface anomalies. Since 2020, Zanskar has focused on the combination of shallow TGs and 2M surveys. Despite these efforts, only about 0.4% of the western U.S. has been covered by exploratory drilling, which is arguably the most direct and comprehensive method for hydrothermal prospecting purposes. This limited spatial coverage highlights a significant gap in the extent and resolution of data required to fully understand geothermal potential across the region and to guide future exploration efforts.

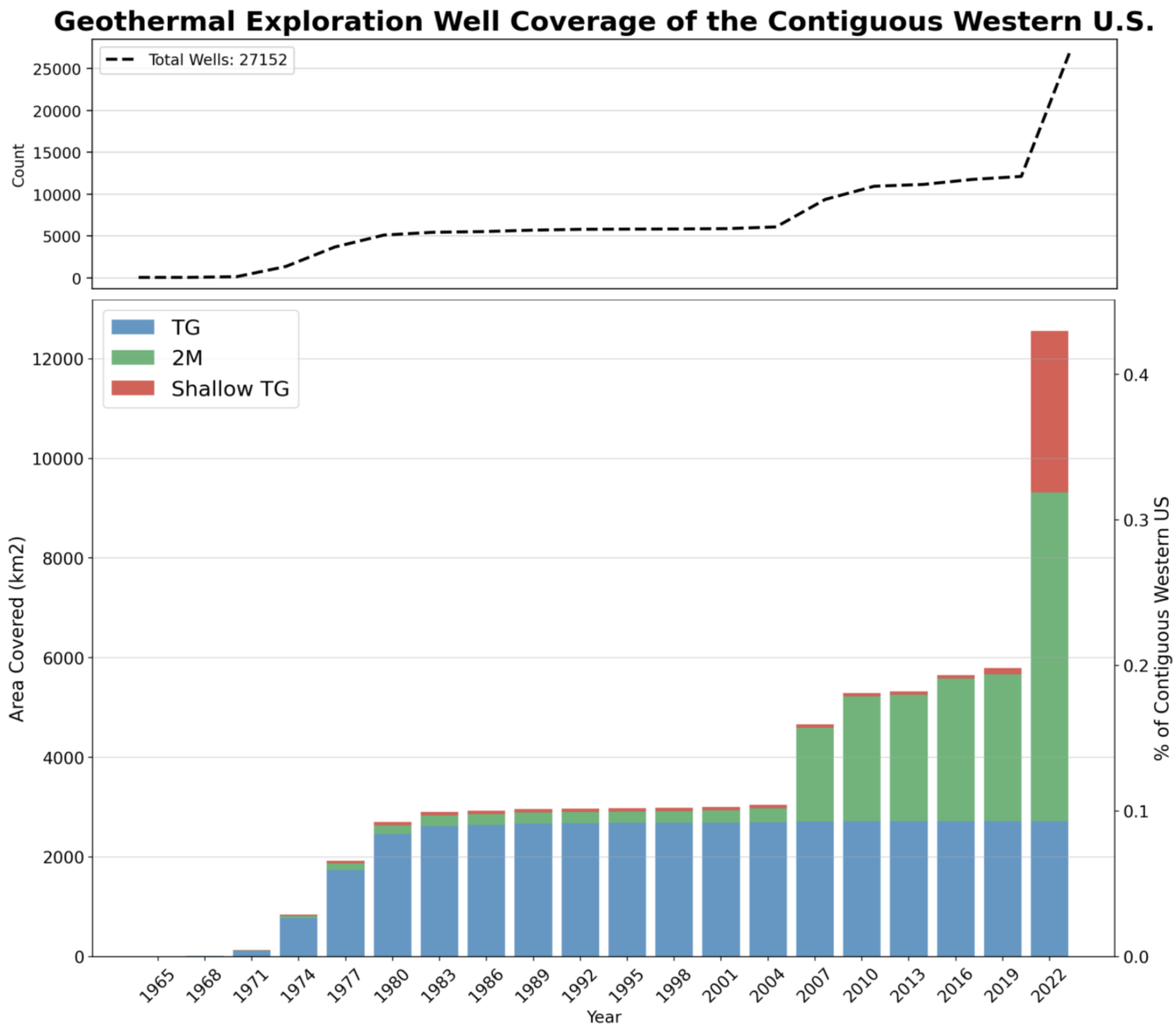

Figure 4: Plot of the time (3 year intervals) versus cumulative number of early stage geothermal exploration wells drilled, area covered (km2), and percentage of contiguous western U.S. covered. In total there are ~27,000 drill samples in this analysis. Wells are grouped by earliest date onto 1 km grid cells to demonstrate change in coverage over time. Acronyms include TG: temperature gradient and 2M: 2-meter temperature rods.

3.2 Spatial and Statistical Modeling

The map below (Fig. 6) highlights well locations with temperature data and depths across the western U.S. One of the most striking insights from this view is that the Great Basin region, an area of known high geothermal potential, is relatively unexplored and poorly sampled.

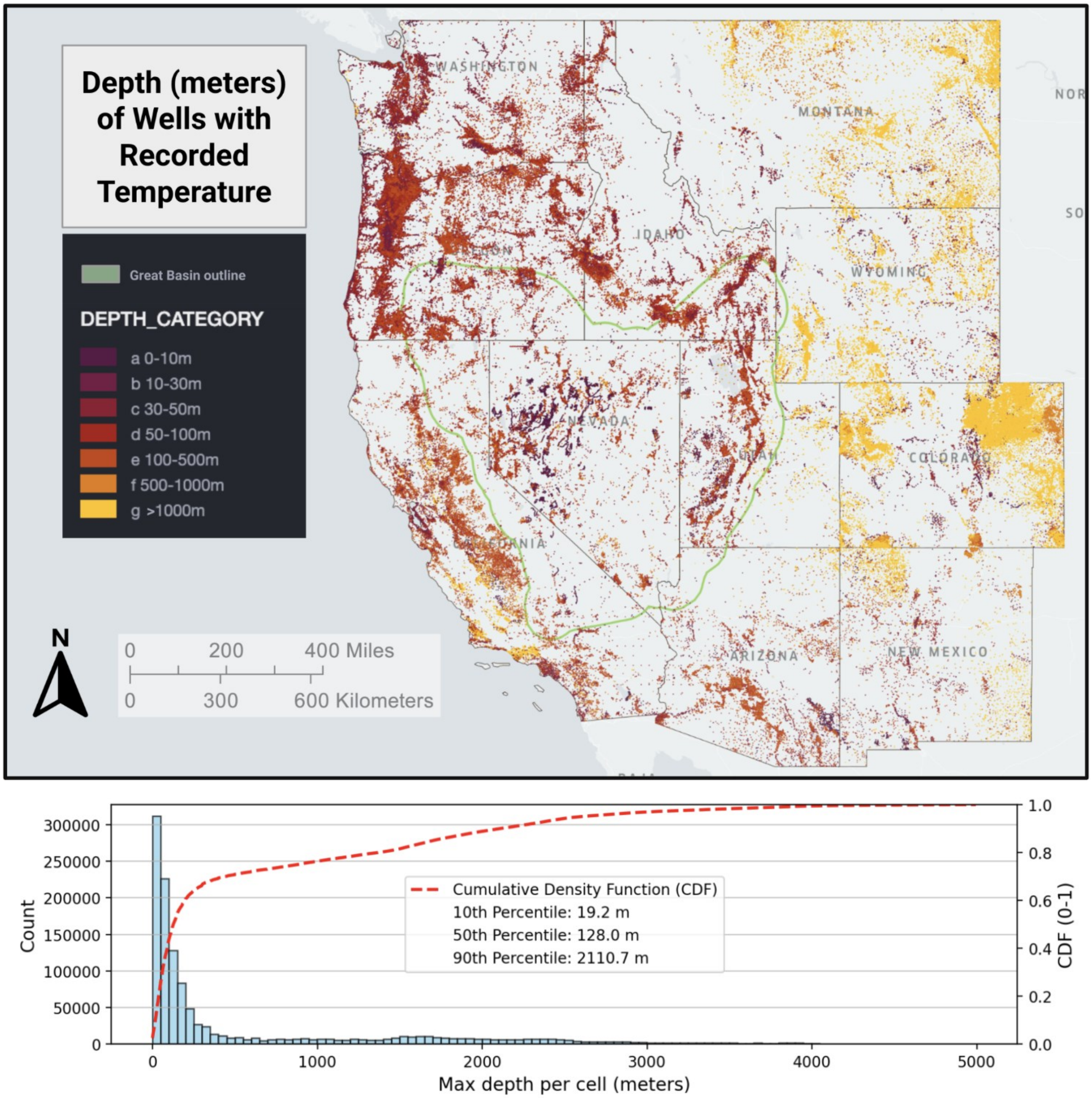

Figure 5: Map and histogram of well depths. These are well points with recorded temperatures. A reference outline of the Great Basin region is included (green). Each point represents a 1km grid cell, where the max well depth of any well at that cell is displayed.

Utilizing H3 grid cells we calculated that approximately 10% of both the western U.S. and the Great Basin have recorded subsurface temperature data. Furthermore, the majority (90%) of the sampled H3 grid cells only have wells that are less than 20 meters deep. Visually there are also clear clusters of samples with more coverage in populated areas and regions that have seen more water (e.g., western Oregon) and oil and gas drilling activity (e.g., eastern Colorado and Wyoming). Sparse coverage is observed in much of the Great Basin and areas that are off-limits under PADUS status 1 or 2, such as national parks, forests, and monuments, which restrict drilling. Notably, 25% of the western U.S. falls within these PADUS status categories, further limiting exploration.

Faults and fractures serve the role of localizing permeability and acting as channels for geothermal fluids (Jolie et al., 2021). Our spatial analysis of fault data (Figs. 6-7) revealed that two-thirds of Quaternary faults remain unexplored, with no wells within a ~1 km radius (Fig. 7). These unexplored areas, which are outside PAD-US restrictions, represent significant opportunities for future exploration of blind or hidden systems. Adding recorded temperatures in these areas could provide critical evidence of geothermal anomalies.

However, many faults are unmapped, and observable temperature anomalies may extend beyond 1 km of mapped faults and should focus on targeting favorable structural settings that are most conducive to hosting hydrothermal systems (e.g., Faulds et al., 2015).

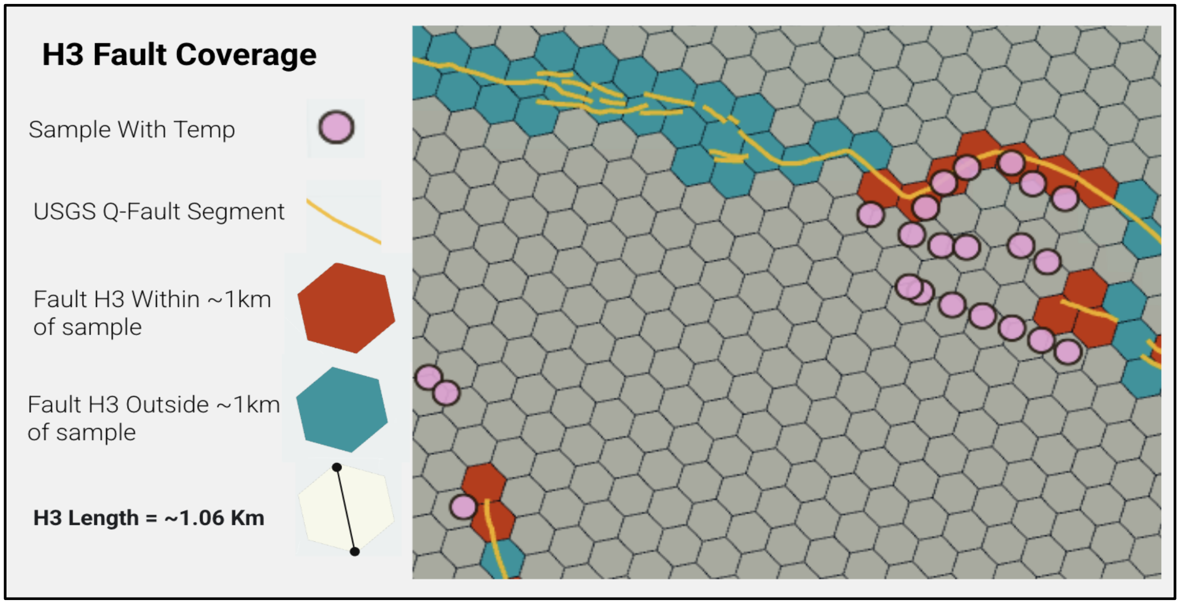

Figure 6: Map of fault and well locations and samples with well depths. These are well points with recorded temperatures and Quaternary faults from the USGS quaternary faults catalog (USGS, 2020). The figure illustrates spatially how H3 grid cells are used to analyze distance between points on equidistant hexagonal grid cells, where each cell is ~1km in length.

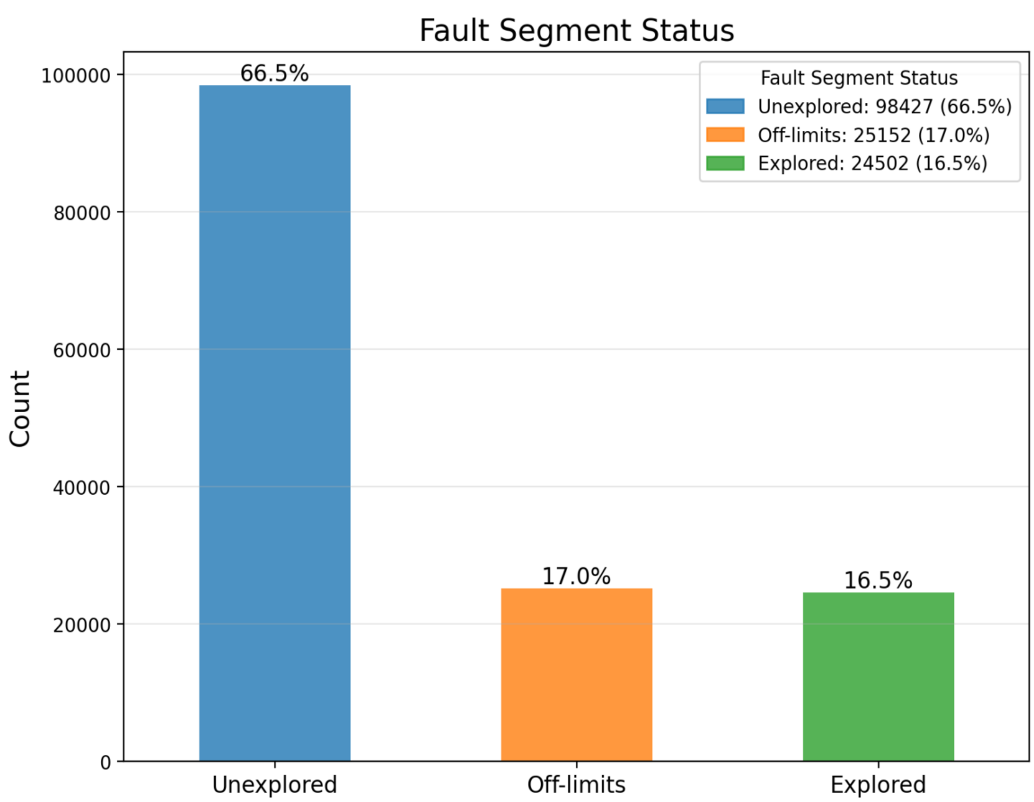

Figure 7: Fault length segment coverage. Bars represent 1 km portions of USGS quaternary faults that are unexplored (no wells with temperature within 1km), off limits (protected status 1 or 2), or explored (wells with temperature within 1 km).

4. DISCUSSION

Targeted surveying for blind and hidden systems have proven to be effective as seen in our analysis of discoveries across different entities (Fig. 8). Academia has seen a notable increase in the number of new discoveries in the past two decades despite very limited budgets and resources. Targeted surveying at Zanskar has allowed it to outpace the 1960-1980 vintage of explorers (e.g., Phillips, Hunt and Chevron) in three years.

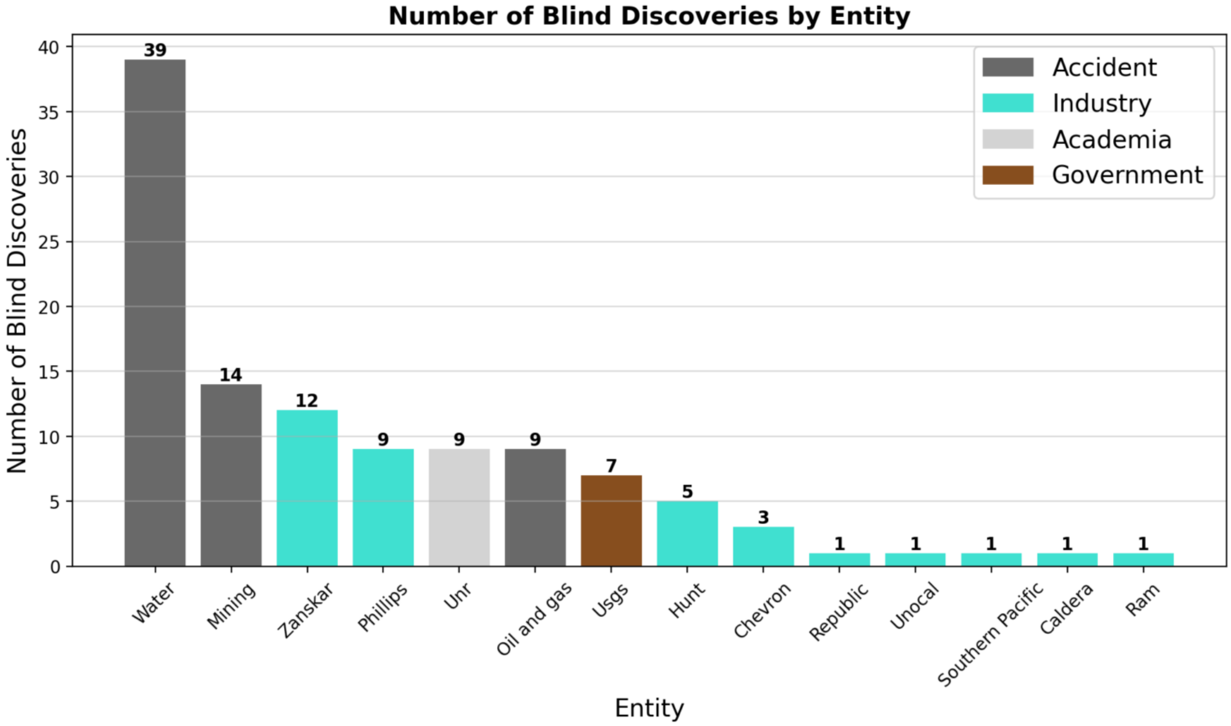

Figure 8: Number of discoveries per entity. Dark gray bars are accidental discoveries from mining, water wells, and oil and gas drilling. Light blue are companies that drilled into new blind systems as part of a geothermal exploration program. Grey are academic institutions (University of Nevada, Reno), and blue is the USGS.

Quantifying the number of undiscovered systems remains a complex challenge, requiring estimates based on historical discovery rates and exploration density. A conservative estimate, using a discovery rate of **0.181%** (49 blind systems identified out of 27,000 drill samples, see Fig. 4), suggests that drilling 100,000 additional exploration holes could yield >100 new geothermal sites (Fig. 9). However, many historical discoveries were made with limited data, and it's likely that some industry discoveries are confidential, meaning our estimates may understate the industry's true number (P. Dobson, personal communication, 2025).

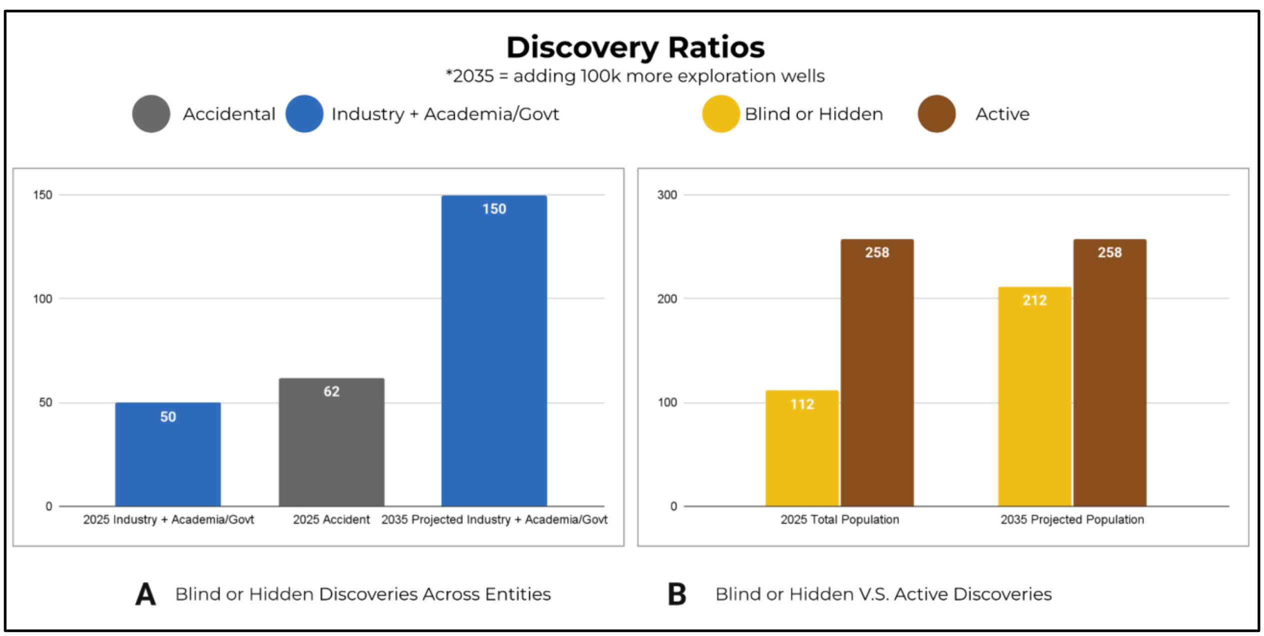

Figure 9: Discovery ratios comparing current values to adding discoveries (estimate of 2035) from 100 k more exploration holes (shallow TGs and/or 2 meter). From left to right: the ratio of blind or hidden accidental discoveries vs industry discoveries, and the ratio of all sites blind or hidden vs active.

Future exploration campaigns, guided by more robust data and analyses, are likely to achieve higher success rates. We believe that evidence of the recent success of academia and industry exploration indicates a clear path to finding more resources. Furthermore, investing in targeted field campaigns the industry can quickly reach goals of sampling an extensive portion of the western U.S. and Great Basin region (Fig. 10).

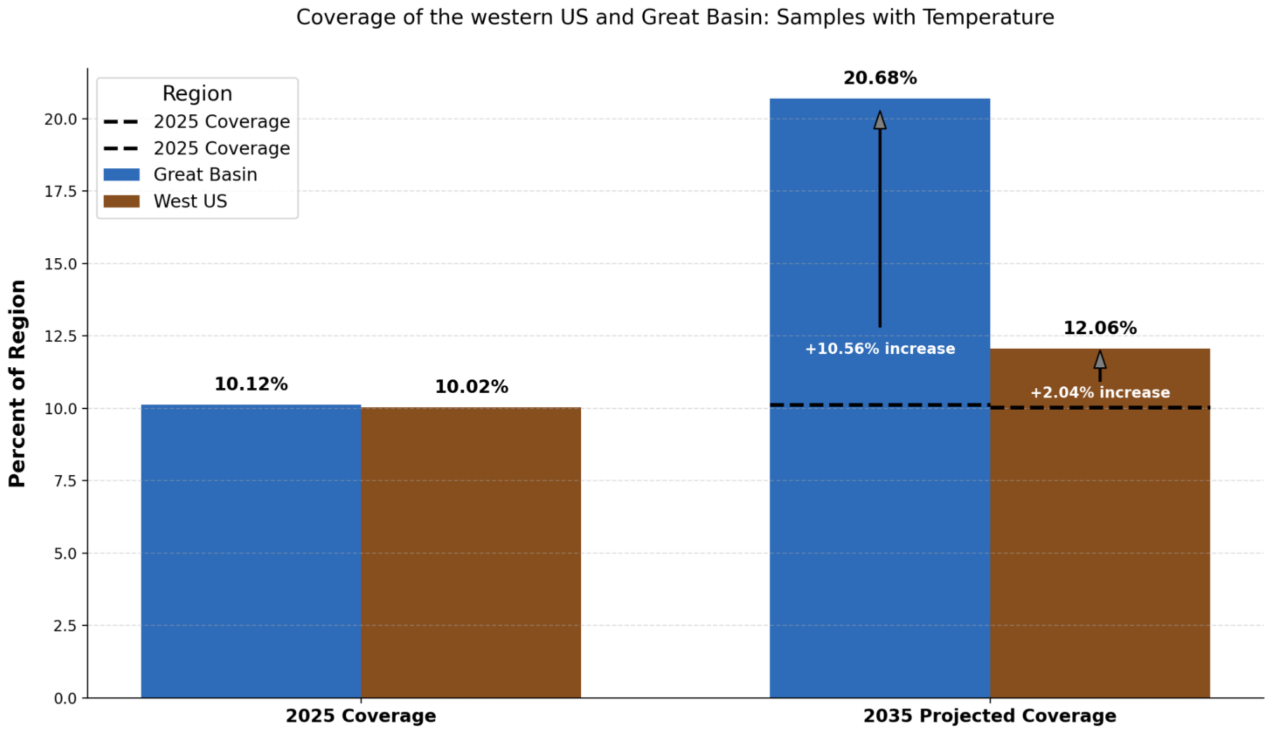

Figure 10: Wells and holes with temperature coverage across the western U.S. (blue) and Great Basin (brown) regions. Wells and holes are grouped into a 1 km grid cell. The bar plot values show the coverage estimate of adding ~100 k new exploration holes (shallow TGs and/or 2 meter).

Assuming a cost of $1000 per sample site (mix of shallow TGs and 2M), a ~$100-million-dollar investment could allow for the discovery of >175 new sites at a discovery cost of <$600,000 per new site. Assuming each new site could generate ~30 MWe (a conservative estimated average of geothermal power plants developed or repowered within the last 15 years (McGinness Hills, Neal Hot Springs, Tuscarora, Don A. Campbell, Patua, Lightning Dock, Tungsten Mountain, Star Peak), the discovery cost would be <$20,000/MWe. The 2019 Geovision report estimates a discovery pace of ~1% discovery rate per year of the undiscovered blind or hidden resource base, indicating that in the western U.S. there may be just over 1 blind discovery per year. Historical data shows that periods of focused investment in exploratory drilling led to a much higher discovery rate, far exceeding the multi-decadal average, even though current market forces differ from those in the past. Our analysis indicates that the industry could far outpace the Geovision estimate, returning ~10 times the yearly discoveries, given a ~$100-million-dollar investment for exploration drilling.

Table 1: Table of estimated metrics for discovery, cost, and power potential in the year 2035.

Metric	Estimate	Details
Discovery Rate	0.181% per well	Based on 49 blind systems identified out of 27,000 drill samples (Fig. 4).
Investment for Discovery	$100 million = 100k new holes	An investment of $100 million at an assumed cost of $1000 per a mix of shallow TG and 2M sample sites.
Number of New Discoveries (Estimated)	181 new geothermal sites	Estimated by drilling 100,000 additional exploration holes based on a 0.181% discovery rate.

Estimated Coverage	+10.56% coverage of Great Basin, +2.04% coverage of western U.S.	Exploration efforts could target unexplored regions. Percent assumes assigning a ~1km area coverage per hole.
Cost per New Discovery	<$600,000	If >100 sites are found, each site costs <$0.6M given the assumed investment of $100 million.
Estimated Geothermal Power per Site	~30 MWe	Conservative estimate of average geothermal power capacity for plants developed or repowered in the past 15 years (e.g., McGinness Hills, Neal Hot Springs, etc.).
Cost per kWe of New Discovery	<$20,000/MWe	The discovery cost per kilowatt of geothermal power for new sites based on a conservative power estimate (~30 MWe per site).
10 year power addition	~3 GWe	Estimated by assuming 100 new discoveries at 30 MWe power capacity. This value is only 10% of the USGS estimated blind/hidden resource base in the western U.S.

5. Conclusion

Despite several, periodic surges in geothermal exploration activity since the 1960's, the western United States holds vast untapped geothermal potential, particularly with undiscovered blind and hidden systems. This study provides a comprehensive assessment of historical discovery trends, exploration gaps, and future opportunities for systematic geothermal development. Key conclusions include:

1. **Blind discoveries are essential**: The majority of new geothermal resources must come from blind systems, as basically all active sites have been found. Our analysis shows that more than half of utility-scale geothermal sites were found unintentionally through water well drilling, mining, or oil and gas exploration. Given that these sources of accidental discovery have declined since the end of homesteading in 1976, a shift towards targeted exploration campaigns is essential to boosting geothermal industry growth.
2. **Exploration gaps represent opportunities**: Unsampled fault zones and regions lacking temperature data present prime opportunities for discovery. Strategic investments in drilling campaigns, supported by spatial and statistical modeling, could significantly accelerate resource identification. Our study estimates that drilling 100,000 new exploration holes, primarily shallow TGs and 2M surveys, could lead to more than 100 new blind or hidden geothermal discoveries. With a discovery rate of approximately 0.181% per drill hole, a ~$100 million investment in exploratory drilling could provide enough new sites to add approximately 3 GWe of new geothermal capacity over the next decade. This would significantly outpace recent industry growth projections and provide a foundation for long-term geothermal development.
3. **Policy and industry collaboration is crucial**: Federally managed lands offer significant geothermal potential but face regulatory and environmental challenges. Streamlining leasing and permitting processes and optimizing regulatory timelines could double geothermal capacity by 2050 (NREL, 2019).

Geothermal exploration in the western United States is at an important inflection point. Without a boost of investment into systematic exploration, the geothermal industry will continue to rely on a shrinking pipeline of known resources. This study employs conservative assumptions, meaning the actual potential for new discoveries is likely even greater than estimated. The findings emphasize the potential of systematic exploration in realizing the untapped geothermal resources of the western United States. While the western U.S. is one of the most extensively studied geothermal regions, similar blind resource bases likely exist in other geologically active areas, such as East Africa, Central Asia, and South America. Applying systematic exploration strategies worldwide could reveal significant geothermal potential, accelerating global efforts toward sustainable, baseload renewable energy.

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