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NATURAL STATE MODELING, STRUCTURE, PRELIMINARY TEMPERATURE AND CHEMICAL SYNTHESIS OF THE DIXIE VALLEY, NEVADA GEOTHERMAL FIELD

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ABSTRACT

A number of geothermal systems in the Basin and Range Province, like the ones in Dixie Valley, Nevada have subsurface temperatures in excess of 200°C, and even 250°C by 2–3 km depth. These systems are typically associated with Quaternary normal faulting. Many of these systems are non-magmatic in origin, based on the helium isotope ratios in the hot water (Kennedy et al., 2000). A recent seismic, gravity, magnetic, and thermal synthesis of the Dixie Valley, Nevada geothermal system has shown that the fault system is much more complex and 3-dimensional that previously thought.

We have utilized this integrated geophysical image to provide structural control on a natural state regional fluid flow model for the valley-range systems to investigate several outstanding issues related to fluid recharge, and the thermal evolution of the high temperature reservoir.

INTRODUCTION

Dixie Valley, Nevada has been the subject of extensive geoscience studies ever since the large earthquake events of 1954. The presence of large-scale geothermal energy resources in the area has led to an intensification of these efforts. As a result, the structure of the contact (a large displacement normal fault zone, >5 km vertically over about 8 My) between the Stillwater Range and Dixie Valley is probably the best explored normal fault system in the world. The area of the valley/range contact has been penetrated by over 20 deep drill holes, several thermal gradient surveys, numerous seismic reflection profiles, multiple gravity surveys, electrical sounding surveys, three levels of aeromagnetic surveys, and detailed geologic mapping (Blackwell et al., 2005). The situation differs from other extensively drilled and explored areas, such as Railroad Valley in eastern Nevada in that the target for geothermal activity is the fault zone itself.

Structural models of Basin and Range normal faults either predict high or low angle dipping structures, with the two end member cases both possessing strong support within the scientific community. The techniques utilized in geothermal exploration, particularly drilling, are critically dependent on the expected dip of structures related to the reservoir. So the uncertainty in the structure, based on the extremes of the generally accepted models, is a major factor in the drilling uncertainty, and ultimately the risk, involved in geothermal exploration and development. Structural models of the Dixie Valley system based on various interpretations in a wide variety of geological and geophysical data range from low angle (20° by 3 km) to high angle (>75° at 3 km) (see Blackwell et al., 2005).

Hence the Dixie Valley Producing Field (DVPF) and Dixie Valley Power Partners area (DVPP) examples are critical to our understanding of normal fault systems because in these two areas the geometry of the fault zone is now well understood from the numerous deep wells that have been drilled and consistent geophysical interpretations. The results of the synthesis of studies from these two areas are that:

1. A 20+ km strike length of the contact zone between the Stillwater Range and Dixie

Valley is presently the locus for fluid circulating at temperatures over 200°C (up to 285°C) at 2 - 3 km depth.

2. Areas along the zone have been intermittently to continuously active at time scales of ~100 ka.

3. The range/valley contact is a broad, complex zone with multiple fault strands both in the range and in the valley present in addition to the exposed range/valley bounding fault.

4. The dip of the individual fault strands is 60-75° or greater to a depth of at least 3 km.

5. As a consequence of point #4 *none* of the production wells in the field (located 2-3 km into the valley) produce from the exposed range/valley contact segment of the fault zone (the *Dixie Valley normal fault* as commonly defined), but from blind valley segments.

6. The surface expression of the fault zone (range-valley contact) does not reflect the subsurface structure in any simple way, so surface segmentation has limited relevance to locating the specific position of the geothermal resource or to earthquake hazard evaluation.

7. In general, the exposed fault along the topographic range front boundary *does not* accommodate the majority of the vertical displacement in areas of large vertical displacement.

8. Extensional strain in the Dixie Valley area is accommodated by the range bounding surface fault trace, and by the multitude of other range and valley structures present. Synclines in the valley fill delineate areas where buried extensional accommodation is focused.

9. Vertical as well as low angle structures can explain the complex surface shapes of the mapped scarps, but low angle faults cannot explain the thermal structure.

10. The Bend event (at 2 - 2.5 ka) probably affected the area of the power plant and the area to the north for several km, but the scarps were confined to the range and have either been erased by erosion or are not recognized because they do not cut Quaternary materials. The thermal regime along the fault may have affected the style of faulting there.

Numerous lines of evidence support the interpretation that faulting within the Stillwater/Dixie Valley system is a complex zone of deformation, rather than a simple planar surface (see Figure 1). First, there are numerous Quaternary/Holocene faults in the valley whose scarps are quickly erased by erosion. The evidence for these faults comes from seismic reflection profiles, the high-resolution aeromagnetic surveys, and detailed air photo interpretation. These numerous basement faults propagate upwards through the basin fill sediments to the surface or stop at very shallow levels just below the surface. Small vertical displacements and subsequent rapid resurfacing of the valley floor by alluvial, playa, and eolian sedimentation removes or subdues the surface evidence of these faults. The best methods for mapping the distribution of these faults are detailed mapping of subtle surface features (small scarps, lineaments, spring alignments) on high resolution air photos (with field checking) and high-resolution aeromagnetic surveys.

Also present, but rarely recognized are numerous large displacement Quaternary/Holocene? normal faults within the Stillwater Range block. These were mapped in the vicinity of the DVPP and DVPF areas and in the area of Well 66-21, but their age is difficult to establish because they do not cut Quaternary deposits.

The presently producing geothermal reservoir lies along a piedmont/ramp fault segment. A steeply dipping, multiple fault system is required by the gravity, temperature distribution, drilling, surface mapping, and aeromagnetic survey observations, so at least the segments near the DVPP and DVPF are steeply dipping. This geometry means that only a few of the fault strands have been penetrated by wells. The reservoir is made up of an unknown number of theses strands and their near vertical geometry means that some of them may not yet have been tapped unless they communicate with each other through fractures in the blocks bounding them. An additional complexity is that the present WNW-ESE direction of extension (since about 8 Ma) is superimposed on an earlier E-W episode of extension. A series of narrow grabens formed during the earlier episode. Some of the faults of that episode have been reactivated during the current extension resulting in additional structural complexity.

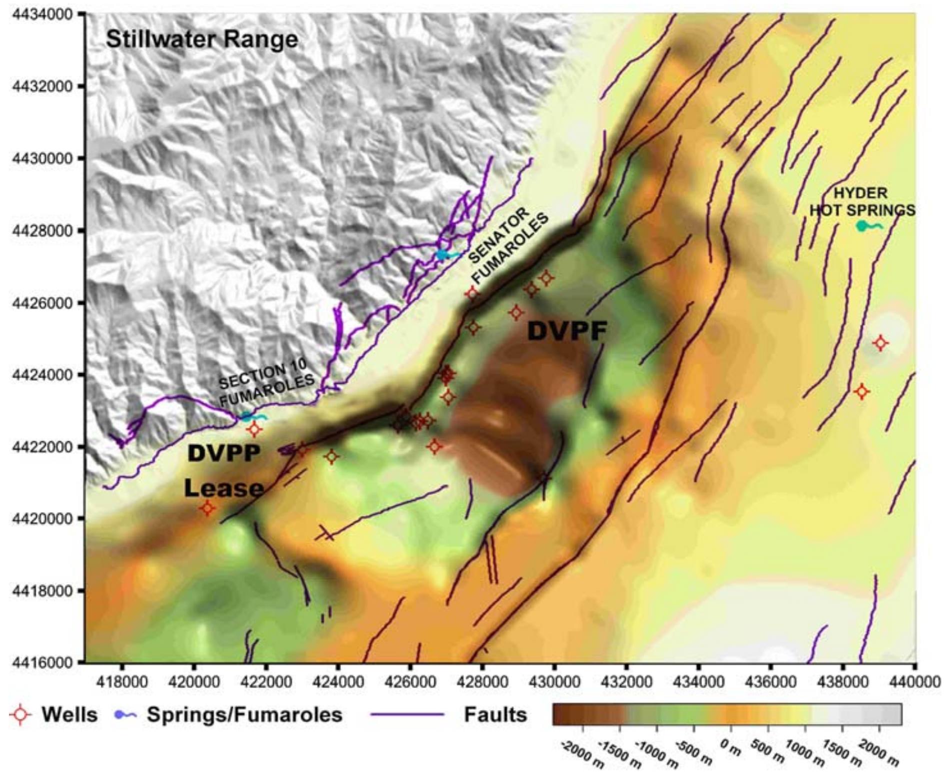

Figure 1. Dixie Valley mapped faults, well locations, and basin depth.

An area at least 5 km long and 2 km wide has temperatures of 225 to 245°C at depths near 2500 m and over 265°C below 3000 m. Fluid flow in this area has occurred over a sufficient time that the local thermal regime is nearly steady state in the upper 1- 3 km depth range. However, there are major variations in the local hydrologic regime. Some paths are not connected or barely connected on the time scale of pressure and temperature measurements in the field (almost 20 years). The variable geochemistry of the fluids sampled at different places in the system must result from effects operating over a much shorter time frame than the thermal evolution (which is still short geologically).

The position of the highest reservoir temperatures is almost directly below the range front at a depth of about 3 km. Thus, there is little doubt the fractures feeding the geothermal field are steeper than 75° within the upper 4 km of the crust.

There is every reason to assume that the steep dip is typical of the western Basin and Range (and other rift areas where basement lithology dominates). Thus the fault structure described in here represents a practical model for exploration in the western Basin and Range. Hence, exploratory drilling in these systems will be more effective using inclined drilling, which will increase the opportunities to intersect steeply dipping structures. Using inclined wells rather than vertical wells makes drilling more cost effective, which is an important impetus for utilizing Basin and Range geothermal systems (McKenna and Blackwell, 2004a).

TRUE-SCALE NATURAL STATE MODELS

The commonly-accepted conceptual model for fluid flow is a Basin and Range geothermal system is that upflow along a single range-bounding normal fault dipping at about 45-55° is responsible for most production, but this model ignores potential fluid flow associated with small displacement synthetic faults present in the valley and stratigraphically-bound aquifers in the valley fill, such as the Tertiary basalts present in Dixie Valley (see Benoit, 1999). So although the single fault model is conceptually attractive, it is not particularly useful as a working model. It is clear that the exposed range-bounding fault is only one of many fault components in the geothermal system from four aspects: (1) the pattern of breaks associated with historic earthquakes, (2) the extensive pattern of young faults mapped in Dixie Valley, (3) the surface mapping in the Stillwater Range, and (4) the low-level high-resolution aeromagnetic survey results. Thus it is more accurate to describe the deformation as *distributed across multiple zones* rather than a single plane.

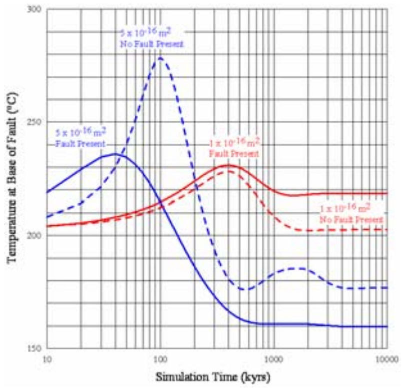

Figure 2. Temperature-time history of a cell at the base of the fault (3.85 km depth) for several bulk rock permeabilities utilizing a naturally convective media as the initial condition.

The fluid compositions in the Dixie Valley fluids are complicated and highly variable. It remains unclear how the fluid components interact and how the fluids have evolved with time and space. The chemistry (He and major elements in the fluids) suggests that several of the thermal manifestations in Dixie Valley have a common or similar source, even if they are not apparently directly connected. The natural state modeling requires a permeable basement (> 1 x 10 $^{-16}$ m^2) for deep flow to occur. The modeling also shows that the upflow can be confined to a limited portion of the system particularly if there is a short circuit present in the flow paths (i.e. a permeable fault), or it can be more wide spread if no high-permeability zones exist. Under some conditions, such as high-permeability in the basement rocks, or extremely heterogeneous permeability distributions, the flow could be more pervasive. The flow sometimes exists for some permeability distributions without a dominant (permeable) fault. In general, the upflow is composed of water that has sampled a large volume of the basement and thus possesses a complicated mixture of effects. The specific geothermal system in existence is tens to a few hundreds of thousands of years old based on the lack of evidence for temperature over-turns in the system, and the age dating of the sinters.

One implication of the structural model described is that much of the natural fluid loss in the geothermal system is apparently via leakage from the piedmont faults directly into the valley fill with minimal thermal indication. This extensive input of fluids of variable chemistry complicates the chemistry of the water in the valley fill and probably is at least partly responsible for the conflicting results observed in the natural spring geochemistry measurements in the valley.

Figure 2 shows the temperature-time histories for a cell located at the downdip edge of the fault, approximately 3.85 km below and 2.15 km to the right of the fault/valley contact in the classes of models discussed by McKenna and Blackwell (2004b). This particular cell essentially records the maximum fault modeled temperature. For models utilizing bulk rock permeabilities of 1 x 10^{-17} m^2 or less, the thermal regime is essentially conductive, and the temperature quickly reaches steady-state with only a few degrees of heating. For the higher bulk rock permeabilities, however, the temperature at the base of the fault varies strongly as a function of time. The maximum temperature for the cases where the starting regime is conductive is 255-275 °C. The temperature maximum does not occur at steady-state, but rather, within the first 100 ka for the 5 x 10^{-16} m^2 bulk rock permeability model, and ~400 ka for the 1 x 10^{-16} m^2 bulk rock permeability model. The transient behavior described above may help explain the lower than measured predicted temperatures (both bulk rock permeability models predict temperatures that are lower than the ~ 280 °C temperatures measured via precision temperature logs in Dixie Valley), and suggests that the relatively high reservoir temperatures observed in some extensional geothermal systems (> 280 °C) must be a function of oscillating high/low fault permeability maintained by seismicity along the range-bounding fault.

Therefore the high temperatures observed in the Dixie Valley system are matched only for a geologically brief period of time on the order of 50,000 to 300,000 years, which is consistent with the sinter dating. However, the Dixie Valley fault zone system has been in existence (at least intermittently) for several million years. Exposed fault gouges have quartz with fluid inclusion temperatures of about 300°C (Parry et al., 1991) similar to the temperatures seen today at depths below 3 km. The water that is being produced is dated at about 10,000 as (Nimz et al., 1999), but it is water that has a traversed a wide variety of flow paths so that age is certainly a mixing age of some sort.

At Dixie Valley, the present producing area consists of only two small areas even though the thermal anomaly is over 20 km long. These two areas are hydrologically separated from each other in the upper 3 km, and from the rest of the system in the DVPP area, even though all three appear to be nearly thermally identical at depth. Thus the model that seems to fit the results best is not a single fault plane or set of fault planes, rather a complex interfingering system of fractures that host a variable flow system confined to the most open parts of the system at this moment. This type of model is similar to the model of vein structure associated with ore deposits. In fact gold mineralization has been found associated with the geothermal systems.

The models examined by McKenna and Blackwell (2004b) and Wisian and Blackwell (2004) were generic Basin and Range type of models. To examine the actual Dixie Valley setting a true scale model specifically tailored to that area was constructed. From west to east it includes the Carson Sink, the Stillwater Range, Dixie Valley, the Clan Alpine Range, and the Edwards Creek Valley. The model incorporates the actual topography present along the model transect between the Dixie Comstock Mine to the south and the producing geothermal field to the north. Structurally, the model is close to the synthesis discussed in the introduction. Each valley hosts a relatively permeable basin about 5 km deep. Near the Stillwater Range-Dixie Valley contact, a steeply dipping 5 km wide zone of highly permeable rocks is present that simulates the multistrand, multi-faulting geometry constrained by the geophysical synthesis.

Figure 3 shows the true scale-model of the Dixie Valley system. The modeling parameters utilized appear in Table 1, The model geometry was developed utilizing PetraSim by Thunderhead Engineering Consultants and solved numerically with TOUGH2 (Pruess et al., 1999). and are similar to other models of the Dixie Valley system (see McKenna and Blackwell, 2004b) with the exception of the grid geometry discussed above, and the host rock permeability which is an order of magnitude smaller than in similar models. This is to prevent unrealistically high recharge beneath the areally significant ranges (17-21 km wide, as opposed to 5 km in previously published models (e.g., McKenna and Blackwell 2004b) from depressing the regional thermal gradient, since inclusion of the asymmetric topography strongly impacts the resulting flow system. The temperature predicted by the model after 1 Ma is shown in Figure 3. The predicted temperature at the base of the steeply dipping range-bounding fault is somewhat lower than observed (200 °C as opposed to the ~280 °C measured *in situ*) because significant downflow is present in the model.

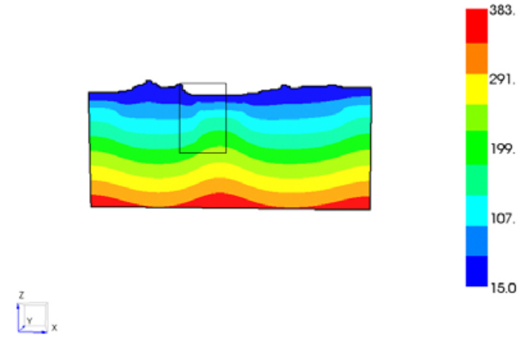

Figure 3. Modeled temperature in the Dixie Valley system at 1 Ma (V.E. is 3x). See Table 1 for model parameters and boundary conditions. The model domain consists of 23,435 elements, and is 65 km x 9 km (1km into the page). The rectangular area refers to the model domain in Figures 4-5.

Material	Wet Thermal Conductivity ($Wm^{-1}K^{-1}$)	Horizontal Permeability (m^2)	Vertical Permeability (m^2)
Basement	2.50	1.0E-17	1.0E-17
Fault	2.50	1.0E-14	1.0E-14
Fault Seal	2.50	1.0E-18	1.0E-18
Range Seal	2.50	1.0E-18	1.0E-18
Fractured Basement	2.50	1.0E-16	1.0E-15
Valley Fill	1.25	1.0E-15	1.0E-16
Volcanics	1.25	1.0E-15	1.0E-16

Table 1. TOUGH2 modeling parameters. A constant density, heat capacity, and porosity of 2650 kgm^{-3}, 1000 $Jkg^{-1}K^{-1}$, and 0.1, respectively, were utilized in the modeling. A basal heat flow of 90 mWm^{-2}, surface temperature of 20 °C, and surface pressure of 1.01 x 10^5 Pa were specified as boundary conditions. The low-permeability domains flanking the fault zone and at the range-tops are utilized to represent probable fault-sealing, and prevent unrealistically high recharge rates, respectively.

TRACER ANALYSIS

In Dixie Valley, the combination of groundwater isotope and minor-element chemistry with the mapped positions of Pleistocene Lake Dixie shorelines illustrates the importance of pluvial lakes in the recharge of Basin and Range geothermal systems. In addition to Dixie Valley production fluids, all the groundwater in the valley except for the shallowest unconfined aquifer near the Humboldt Salt Marsh, are Pleistocene waters that have remained isolated from meteoric recharge. On a regional scale, the distribution of known geothermal systems corresponds closely to the distribution of late Pleistocene pluvial lakes as defined by their preserved high stand shorelines. This suggests that contemporary precipitation is not sufficient and/or infiltration is so slow that it is ineffective at recharging valley aquifers and deeper geothermal systems. Therefore, a major proposed consideration for the exploration of unstudied valleys is whether or not a Pleistocene pluvial lake was present near the exploration target.

Isotopic ages of 12 to 20 ka for Dixie Valley geothermal waters (Nimz et al., 1999; Janik et al., 2002) have been interpreted to provide strong support for recharge of the system during latest Pleistocene time and minimal infiltration of younger waters during Holocene time. The topographic position of the high stand shows that the lake water would have had access directly into the range-bounding fault systems for much of their length, and through the sands and gravels that comprise the major portion of valley-fill sediments along the margins.

Isotopic and geochemical data show that shallow artesian aquifers have been augmented 15-25% by input from geothermal waters from depth. These aquifers (at depths of less than a hundred meters) feed the spring systems along intrabasin faults, which serve as conduits for the waters to rise to the surface. This water is also late Pleistocene in age (Nimz et al., 1999), and has remained very dilute during its residence time in the valley fill sediments. Although precipitation from the surrounding mountains is sufficient to recharge the shallow aquifers in the valley, very little of that water infiltrates these aquifers. Instead, it is removed by evapotranspiration in the mountains and valley floor, and moves by runoff into the Humboldt Salt Marsh area, were it leaves the system by evapotranspiration (Harrill and Hines, 1995).

In order to estimate the possible origin of produced fluids in the Dixie Valley geothermal system we modeled the length of time required for a non-reactive tracer to reach the production area given 2 end-member starting positions. The model results shown in Figure 3 are the initial conditions for the subsequent tracer models shown in Figures 4 and 5.

The results of simulations in which a 1 km x 300 m zone of tracer mass fraction = 1 are situated either at the top of the Stillwater Range, or base of the valley fill are shown in Figures 4 and 5, respectively. Each model shown is a 10 km x 7 km subset of the domain shown in Figure 3 and is comprised of about 6000 elements. Each simulation tracks the mass fraction of the tracer movement as it passes through the model domain. It is clear that the source of the fluids near the production area (i.e., within 1 km of the range/valley contact) is not meteoric recharge from the ranges, since it takes at least 2-5 Ma for these fluids to reach the production/valley area (see Figure 4). The tracer simulations also show that it takes fluids at least 10 ka to enter the valley fill from the underlying volcanics, and anywhere from 10-50 ka for 1 ppm of tracer to become entrained in the fault zone upflow (Figure 5). Hence the only possible source of production/valley fluids is the area below the valley fill. Lateral flow from the shallower levels of the valley fill may contribute, but because these fluids take significantly less time to appear in the production fluids than their isotopic age (i.e., 10 ka).

CONCLUSIONS

We discuss the geophysical, chemical, and seismic evidence for structural complexity in the Dixie Valley system and present the first true-scale natural state flow model of the system. The thermal data are strong constraints in the characteristics of the system. The flow characteristics through the system have been examined and it is clear that there are inconsistencies between the chemical and thermal results that need to be further investigated.

ACKNOWLEDGEMENTS

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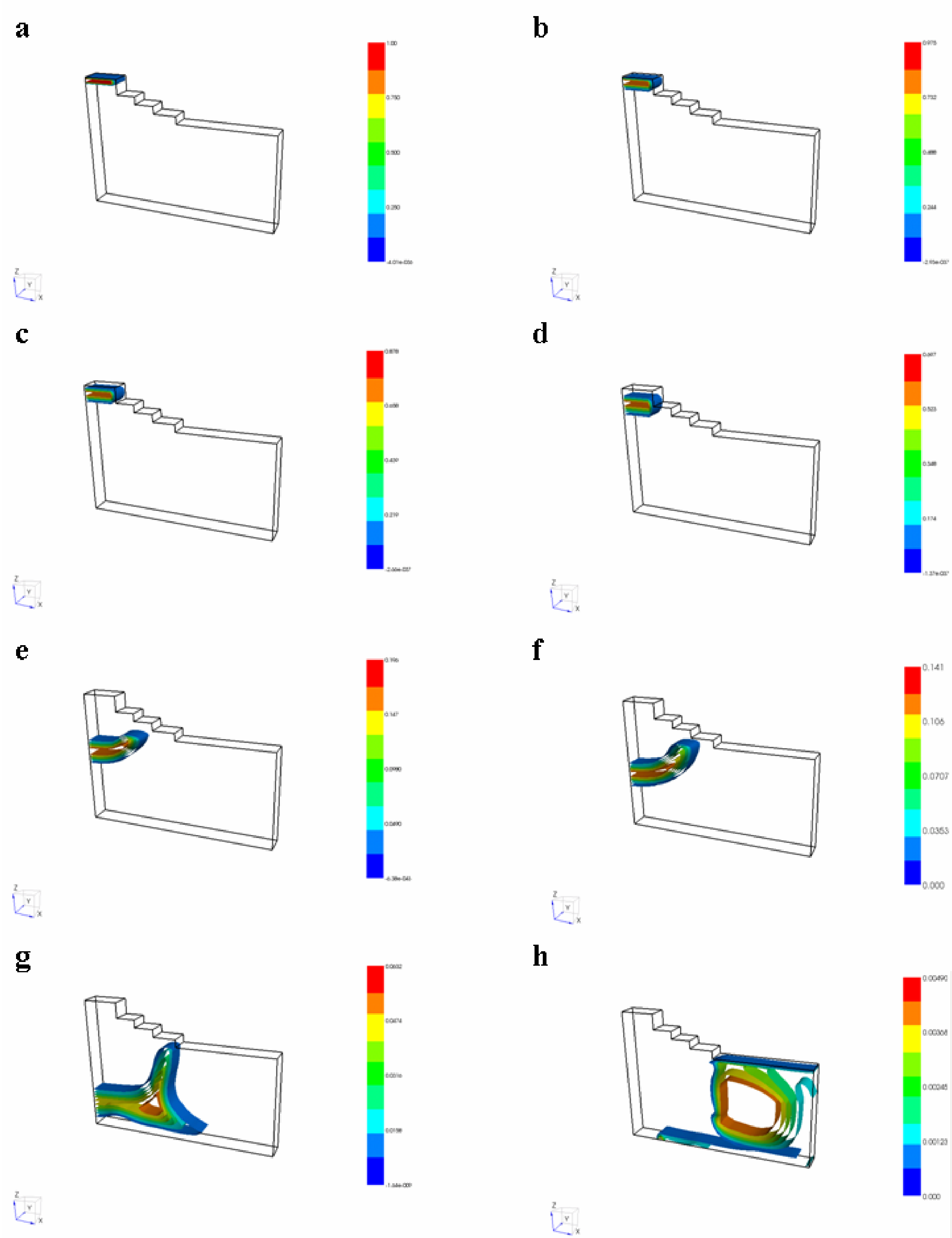

Figure 4. Results of tracer analysis with a 300 m thick, 1 km wide zone of tracer mass fraction = 1 situated the at the top of the Stillwater Range. Each model is a 10 km x 7 km subset of the domain shown in Figure 3 and represents about 6000 elements. The simulation times shown are (a) 0 ka, (b) 10 ka, (c) 50 ka, (d) 100 ka, (e) 500 ka, (f) 1000 ka, (g) 2700 ka, and (g) 10000 ka.

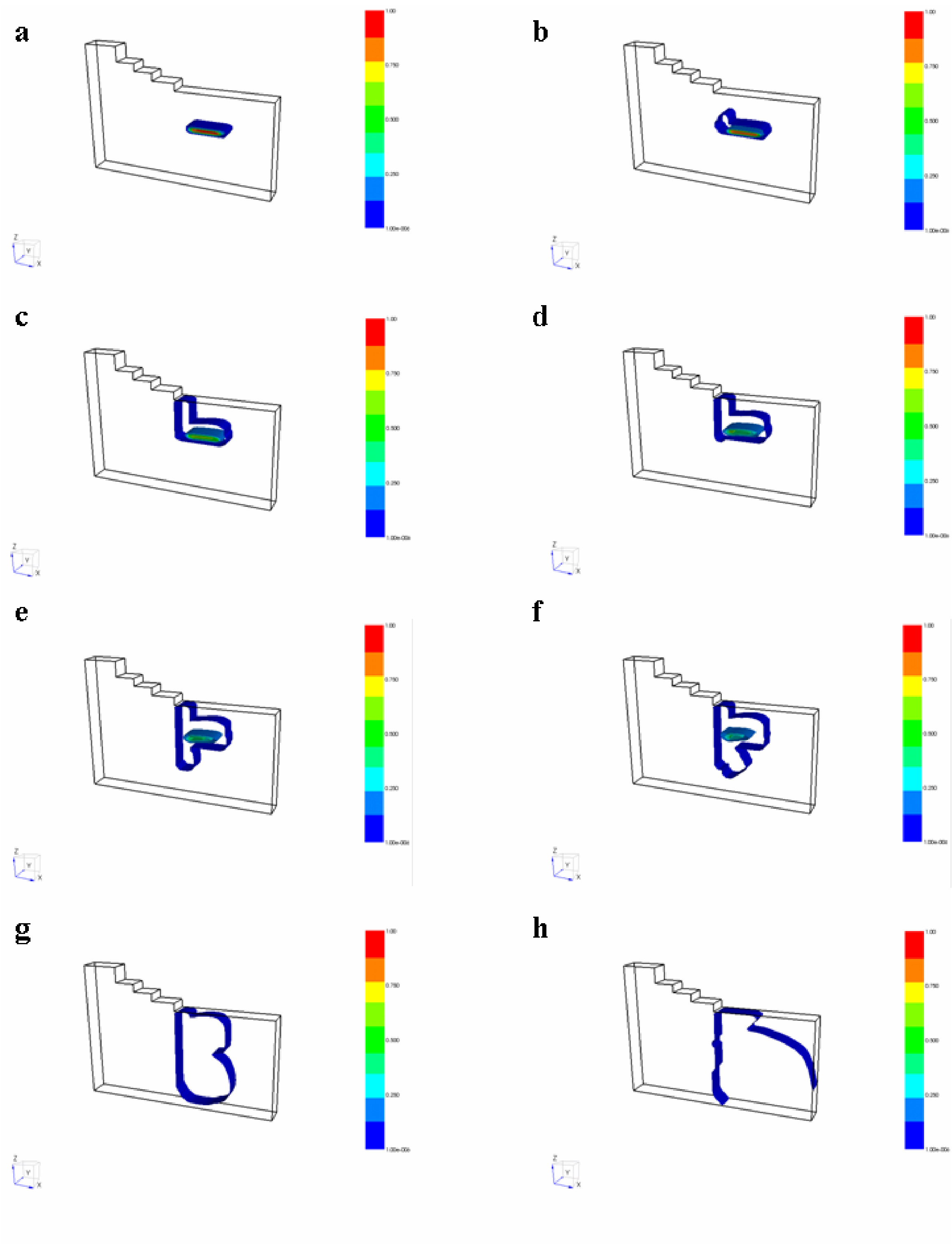

Figure 5. Results of tracer analysis with a 300 m thick, 1 km wide zone of tracer mass fraction = 1 situated the at top of the volcanics, and below the valley fill. Each model is a 10 km x 7 km subset of the domain shown in Figure 3 and represents about 6000 elements. The simulation times shown are (a) 0 ka, (b) 10 ka, (c) 50 ka, (d) 100 ka, (e) 160 ka, (f) 250 ka, (g) 500 ka, and (g) 1000 ka.