The EGS Collab Hydrofracture Experiment at the Sanford Underground Research Facility – Campaign Cross-Borehole Seismic Characterization

D. C. Linneman[1, 2], H. A. Knox[2], P. C. Schwering[2], C. R. Hoots[2] and the EGS Collab Team
[1]Scripps College, Claremont, CA; [2]Sandia National Laboratories, Albuquerque, NM

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1. Abstract

An Enhanced Geothermal System (EGS) allows for the generation of electricity using the Earth's heat by improving (i.e., 'enhancing' or 'stimulating') the fracture permeability of rock and flowing fluid through the optimized medium. The complex behavior of EGS fracture systems and heat flow processes are being studied at various scales to determine the practical capabilities of EGS technology. The EGS collaborative (Collab) project is focused on experimentation of intermediate-scale (i.e 10's of meters) EGS reservoir generation processes and model validation at crystalline rock sites. A key phase of the project involves seismic characterization of a rock mass intended to be representative of EGS reservoir rock. A suite of boreholes was drilled from inside a mine drift on the 4850-foot (~1.5 km) level of the Sanford Underground Research Facility (SURF) in Lead, South Dakota. The boreholes, comprised of one stimulation (injection) well, one production (extraction) well, and six monitoring wells, were each nominally drilled approximately 200 feet (~60 meters) deep into the surrounding crystalline rock formation near the location of a previous experiment at this site (kISMET). Active source seismic data were collected using an electrical sparker source and an electro-mechanical impulse source to generate compressional (P-) wave and shear (S-) wave energy, respectively, at varying depths in the stimulation well. Seismic receivers were deployed in the sub-parallel production well, in addition to receivers installed in the monitoring wells, to detect P- and S-wave arrivals. A second survey used sources in the production well. These data and their associated 3D P- and S-wave velocity models of the rock mass are presented here with a discussion on seismic acquisition in horizontal boreholes in hard rock environments. These velocity models are critical to constraining the elastic parameters used for modeling and monitoring seismic hypocenters that are associated with fracture propagation during EGS stimulation activities.

2. Data Acquisition

P- and S- wave seismic surveys were performed between the injection and production wells, with shots in the injection well being recorded by receivers in the production and monitoring wells, as well as shots from the production well being recorded in the monitoring wells (see Figure 2).

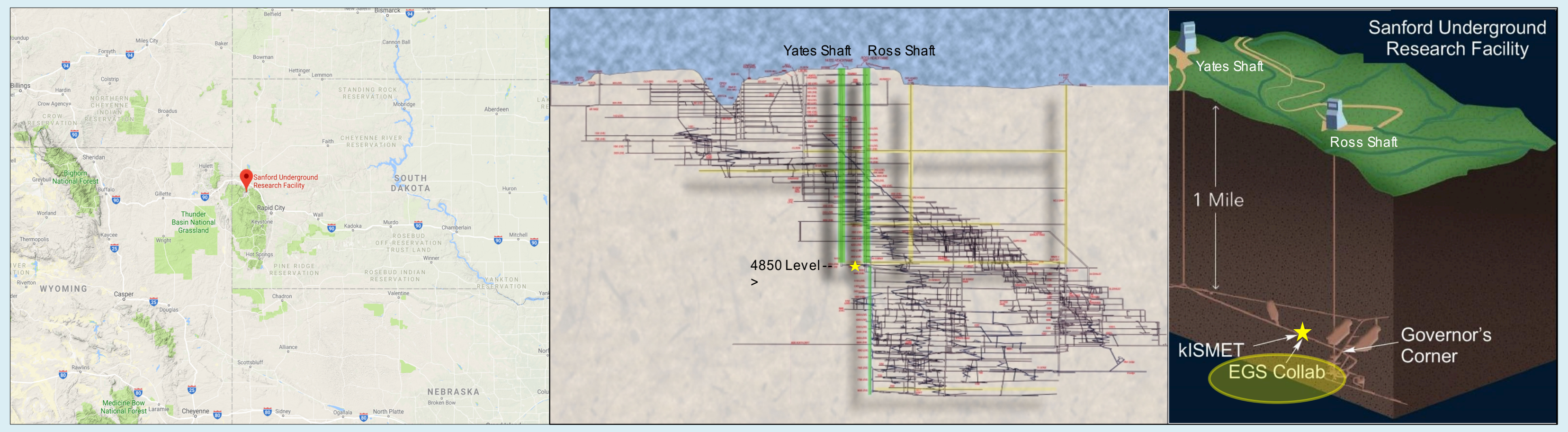

Figure 1: Site maps; left– map showing location of Sanford Underground Research Facility; center – schematic illustration of SURF mine drifts, with approximate location of EGS Collab (adapted from SURF, 2017); right – 3D illustration of SURF highlighting Yates and Ross access shafts to 4850L and approximate location of EGS Collab team's first experiment (adapted from Kneafsey et al., 2018).

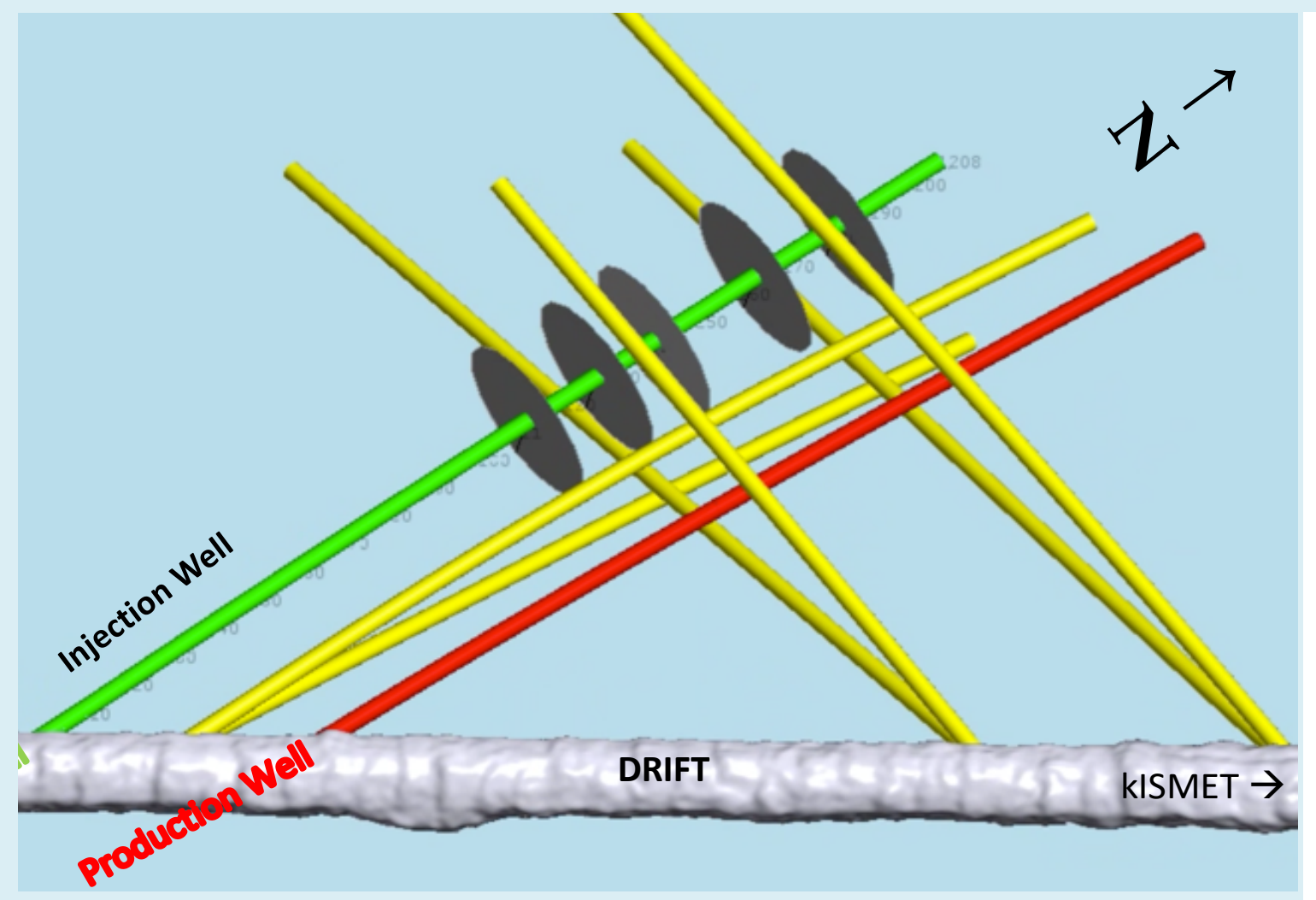

Figure 2: 3D model of well paths emanating from the west drift of 4850L (white/grey tube), looking downward and to the northwest, showing the injection well (green), the production well (red), the six monitoring wells (yellow). The five gray disks are potential stimulation/flow targets along injection well.

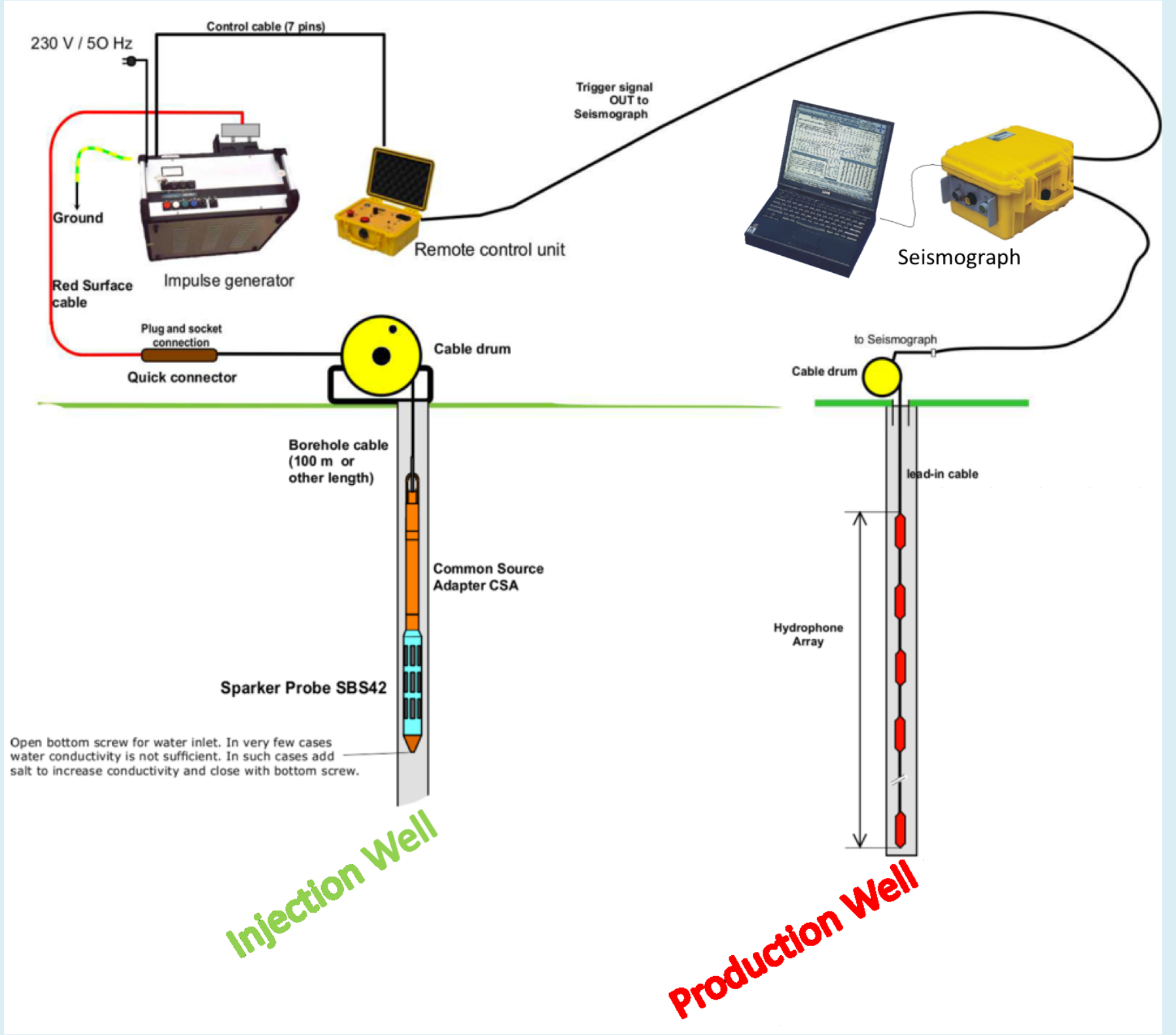

Figure 3: Schematic diagram of P-wave seismic survey setup and instrumentation with source in injection well and receivers in production well.

3. Processing

3a. Tomography

Raw data are assigned geometry and merged into shot gathers for arrival picking using Seismic Processing Workshop (SPW) software by Parallel Geoscience Corporation.

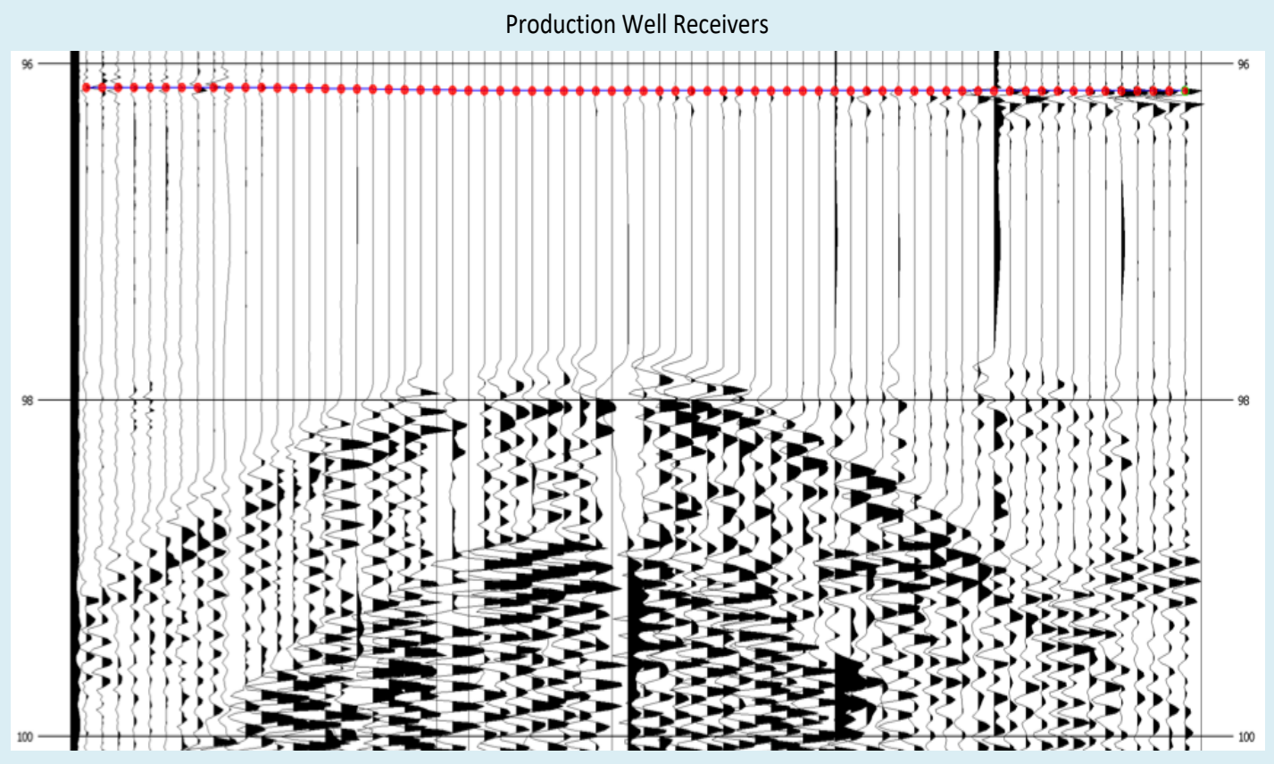

Figure 4: Sample P-wave SPW shot gather from injection well shot at 54 meters deep. The electrical sparker source produces an electromagnetic pulse (EMP) upon activation, and the EMP is recorded on the receiver array (highlighted by red circles)

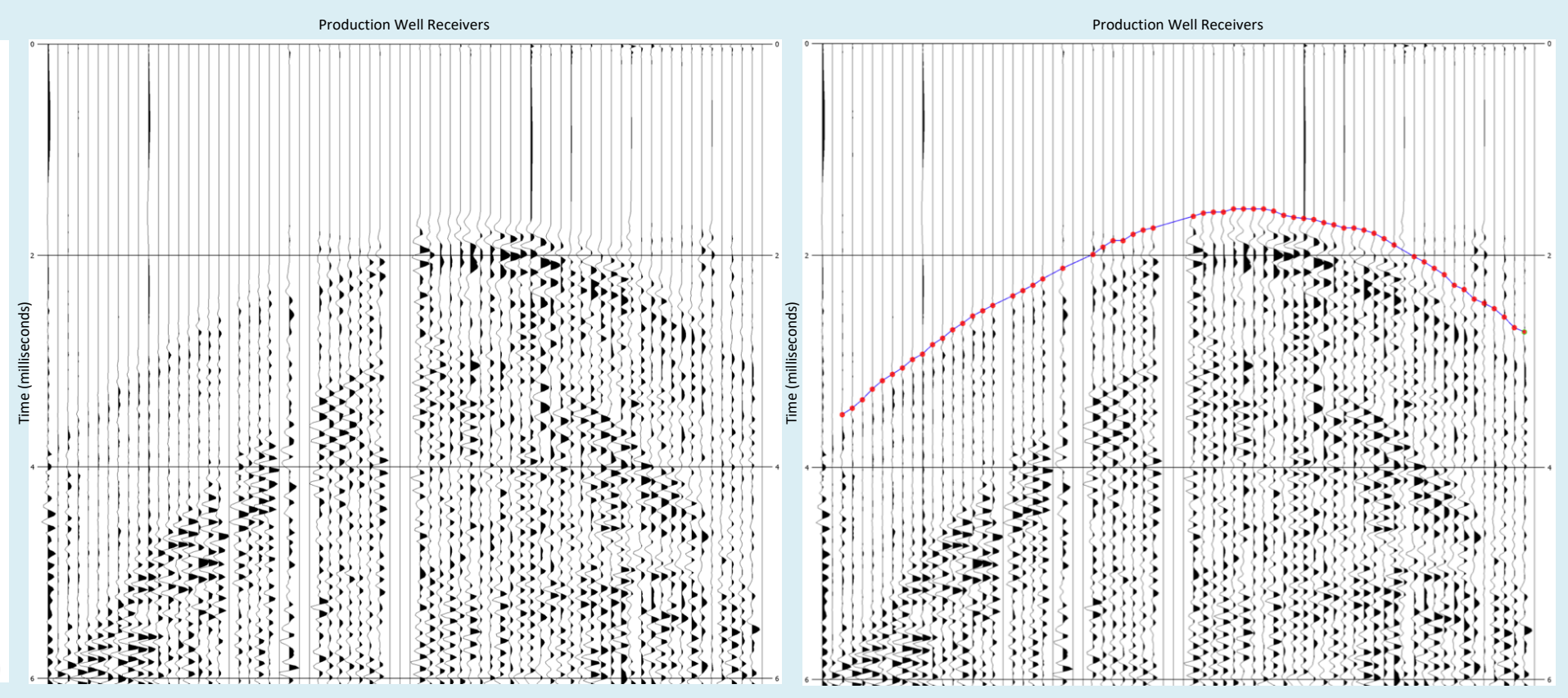

Figure 5: Sample P-wave SPW shot gather at left, aligned and shifted to EMP (zero-time) from injection well shot at 59 meters deep; same image at right with P-wave arrival picks overlain (red circles). First arrivals for each shot depth are manually picked and evaluated.

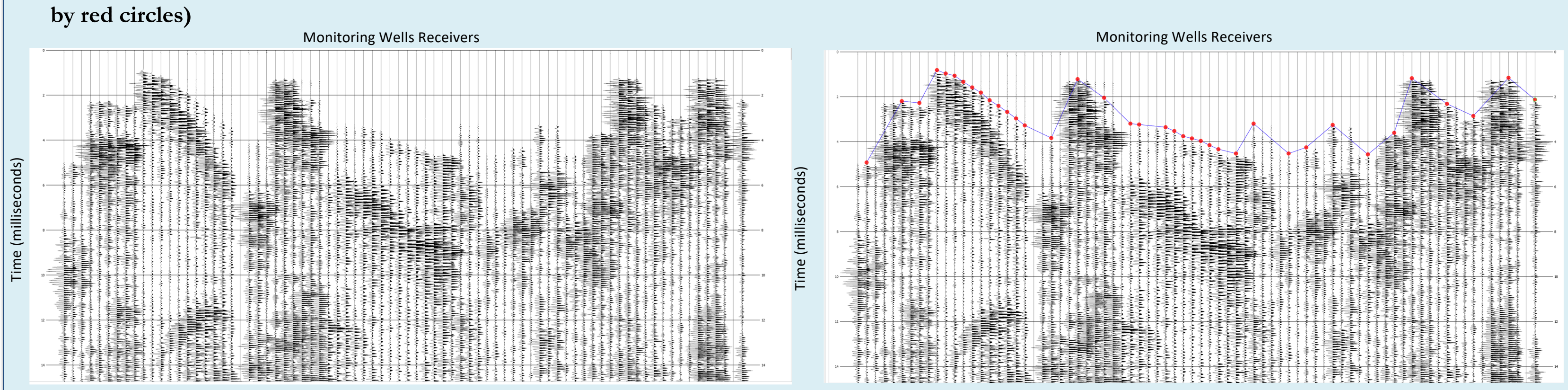

Figure 6: Sample P-wave SPW shot gather at left, aligned and shifted to EMP (zero-time) from production well shot at 23 meters deep; same image at right with P-wave arrival picks overlain (red circles). The receivers in the monitoring wells are a combination of three component accelerometers and hydrophone lines. Traces are organized by receiver location, and due to the complex geometry there is not a visible normal move out. First arrivals for each shot depth are manually picked and evaluated.

P-wave velocity (V_P) models are inverted using Sandia code that exploits a 3D ray-based (eikonal) P-wave travel-time tomographic inversion methodology. Input P-wave arrival data is normalized by estimated error and the expression of error is left uniform (equal weighting on all observations). Model parameters are continuously evaluated up to a pre-defined set of convergence criteria through an iterative inverse procedure using incremental changes in model parameters based on travel-time residuals (i.e., observed minus calculated). After model convergence criteria are met, the output is a 3D V_P model. This code has the ability to simultaneously invert using S-wave arrival picks to produce a 3D S-wave velocity (V_S) model.

The density of the rock used was based on density measurements from the rock cores recovered from the borehole drilling. Samples were taken from 22 different locations in the borehole array, and the laboratory density measurements are remarkably consistent. The mean density value is 2764 kg/m^3 with a standard deviation of 22 kg/m^3.

3b. Elastic Moduli

The seismic velocities (V_P ,V_S) and the density of the rock can be used to determine elastic moduli critical to rock mechanics modeling. Rearranging the relationships

$$V_P = \sqrt{\frac{K+(\frac{4\mu}{3})}{\rho}} \qquad V_S = \sqrt{\frac{\mu}{\rho}}$$

we find the values of K, the bulk modulus and μ, the shear modulus, where ρ is the rock density:

$$K = \rho({V_P}^2 - \frac{4}{3}{V_S}^2) \quad \text{and} \quad \mu = {V_S}^2\rho .$$

These values are used to find the value of Young's modulus (E),

$$E = \frac{9K\mu}{3K+\mu} \ .$$

4. Results

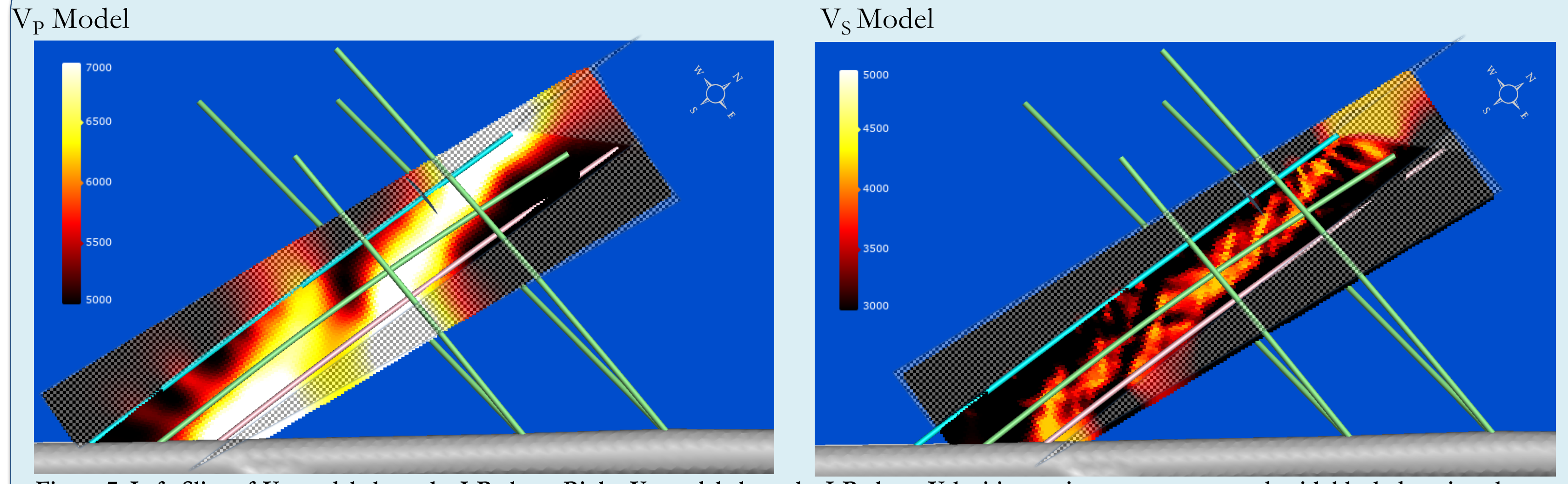

Figure 7: Left: Slice of V_P model along the I-P plane. Right: V_S model along the I-P plane. Velocities are in meters per second, with black denoting slowest velocities and white denoting fastest velocities. The areas of the model domain that are not between the injection and production wells had poor ray coverage, so the model velocity values are not realistic. These areas are marked with a checkerboard pattern in the model figures.

V_P – Profile

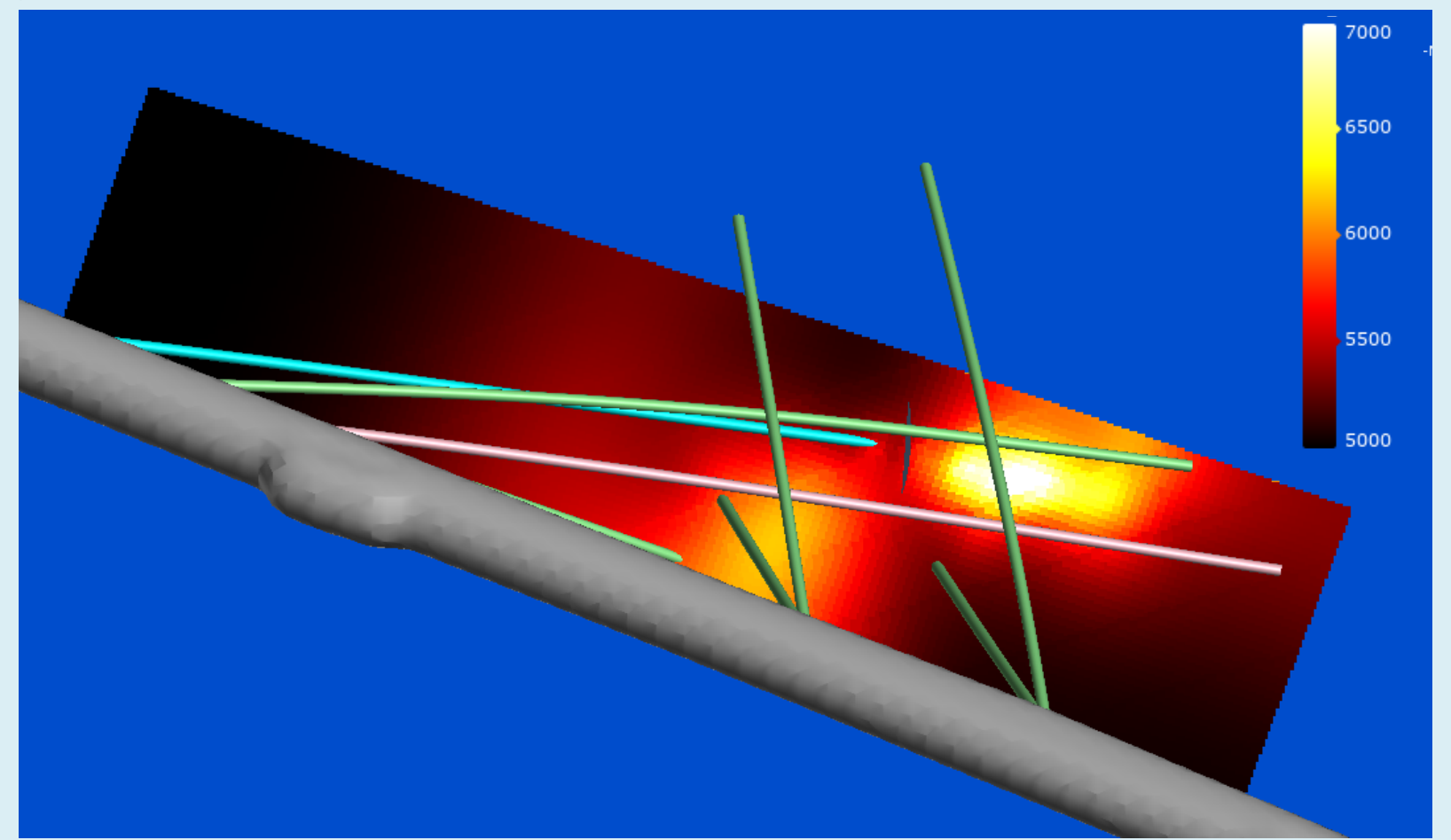

Figure 8: A profile slice of the 3D V_P model parallel to the drift. The drift runs NE-SW, so this view is from the E looking downward to the W.

3D $V_p > 6600$ m/s

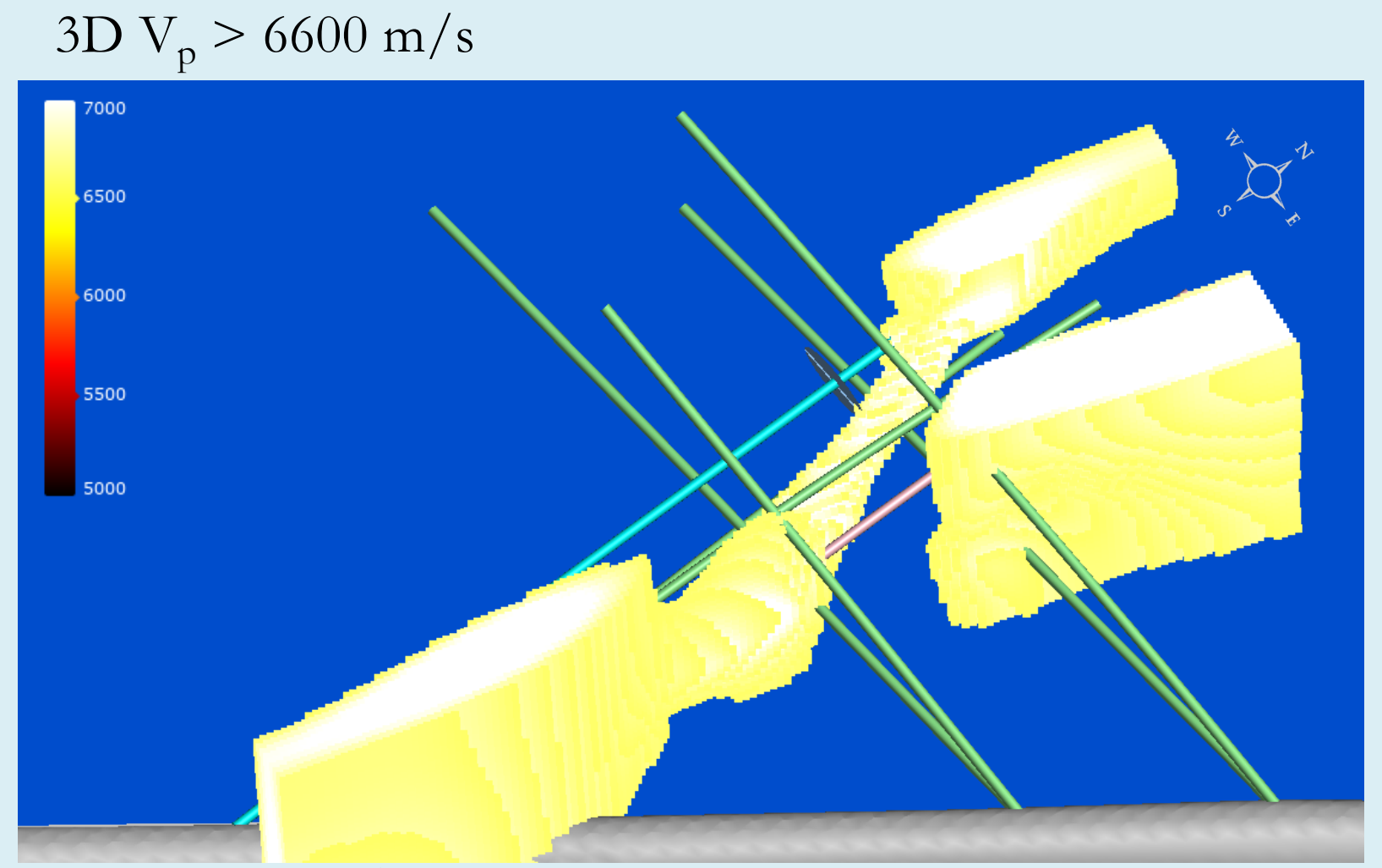

Figure 9: 3D V_P model with only velocities greater than 6600 meters per second displayed. The semi-linear high velocity zone trends northwest.

Young's Modulus (E)

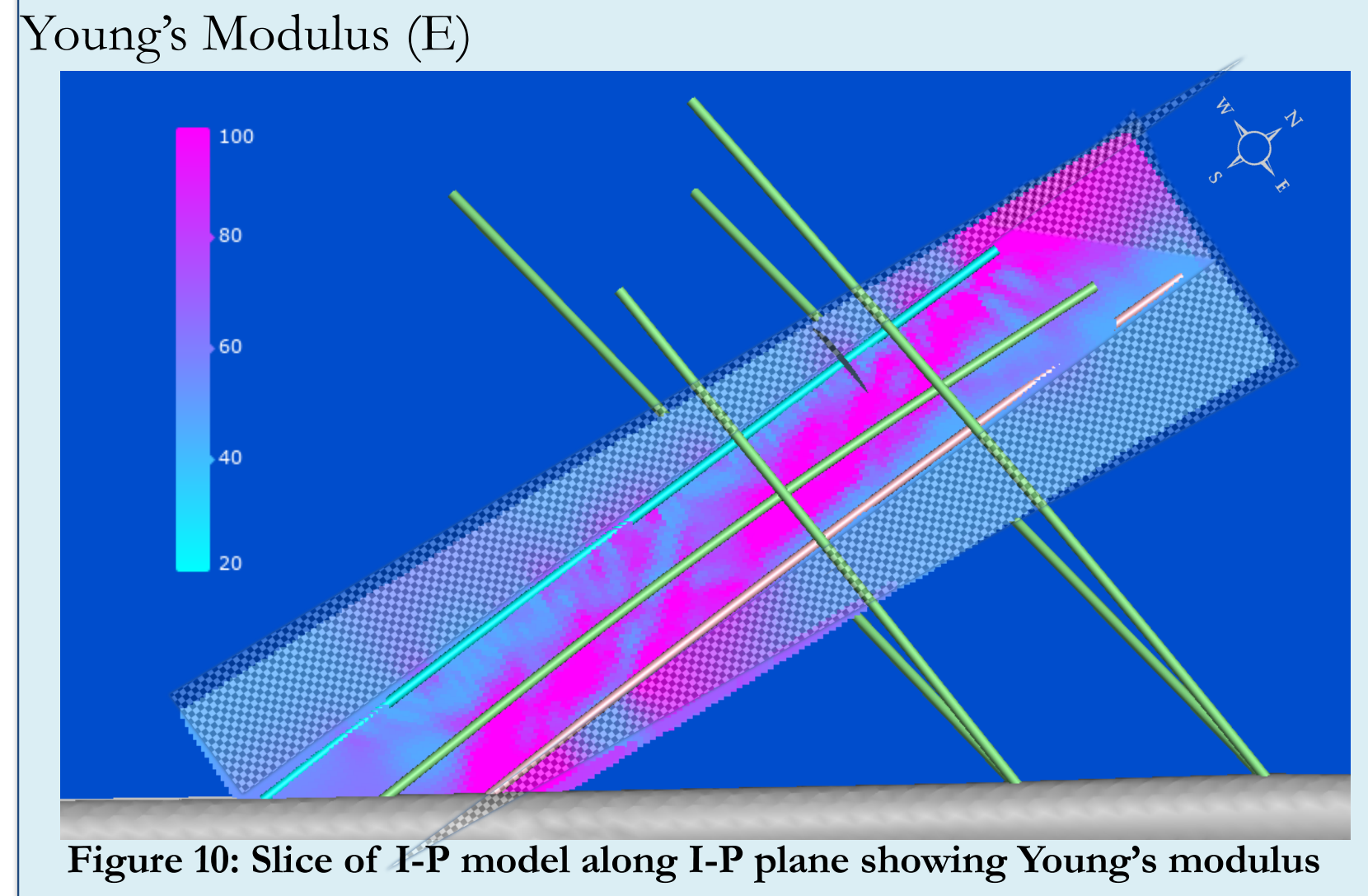

Figure 10: Slice of I-P model along I-P plane showing Young's modulus (E) values in GPa calculated from the shear and bulk moduli models.

V_P/ V_S Ratio

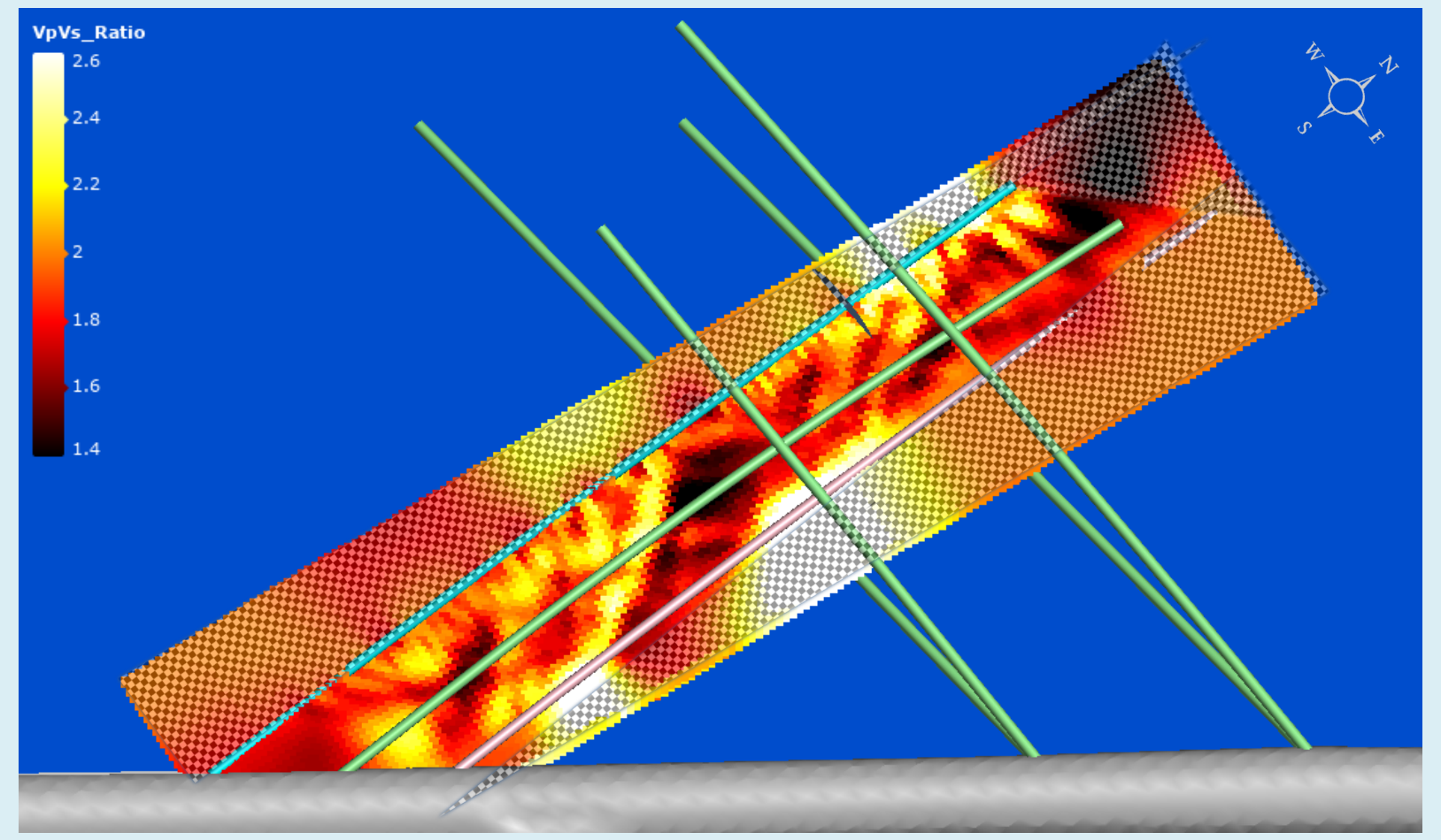

Figure 11: A slice of the 3D model showing the ratio between V_P and V_S.

5. Discussion

- The velocity values produced by our V_P and V_S models are within a reasonable range for crystalline rock. NW-SE velocity trends seem to align with the broader "fabric" of the rock (e.g., local fractures and regional intrusions). The heterogeneities are mostly concentrated in the rock above the horizontal plane of the drift (see Figure 8).
- The seismic survey appears to image vertical anisotropy in the rock. The two lower monitoring Collab wells and the sub-vertical kISMET wells intersected relatively homogenous, unfractured rock. The sub-horizontal Collab wells, however, encountered fractured rock with more varied mineralization. The velocity models reveal a similar pattern.
- The mean value of Young's modulus calculated from our velocity models is 66 GPa, which is comparable to the lab measurement of properties of the kISMET cores (about 60 GPa).
- The amount of data culled because of wide take-off angles was significant (~55%), and resulted in low ray coverage in areas outside the bounds of the injection and production wells. The model results within the I-P bounds are self-consistent and more robust as data coverage was concentrated between the I-P wells.
- Velocity and elastic values illustrate how the rock is significantly more complicated than was anticipated. These measurements will be critical for constraining modeling parameters and enhancing hypocenter mapping.

Acknowledgments

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