

PS Characterization of Tensleep Reservoir Fracture Systems Using Outcrop Analog, Fracture Image Logs and 3D Seismic*

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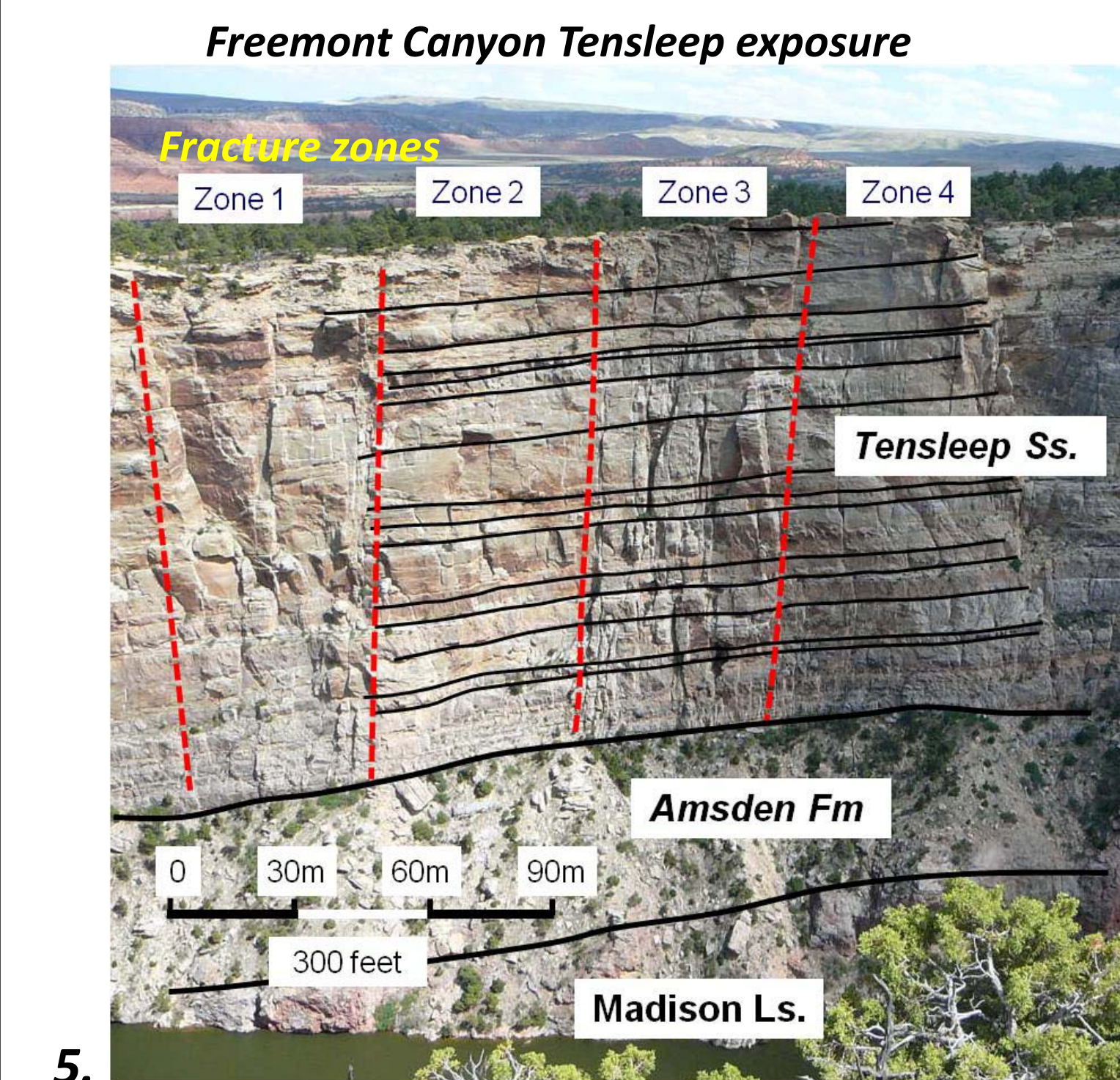
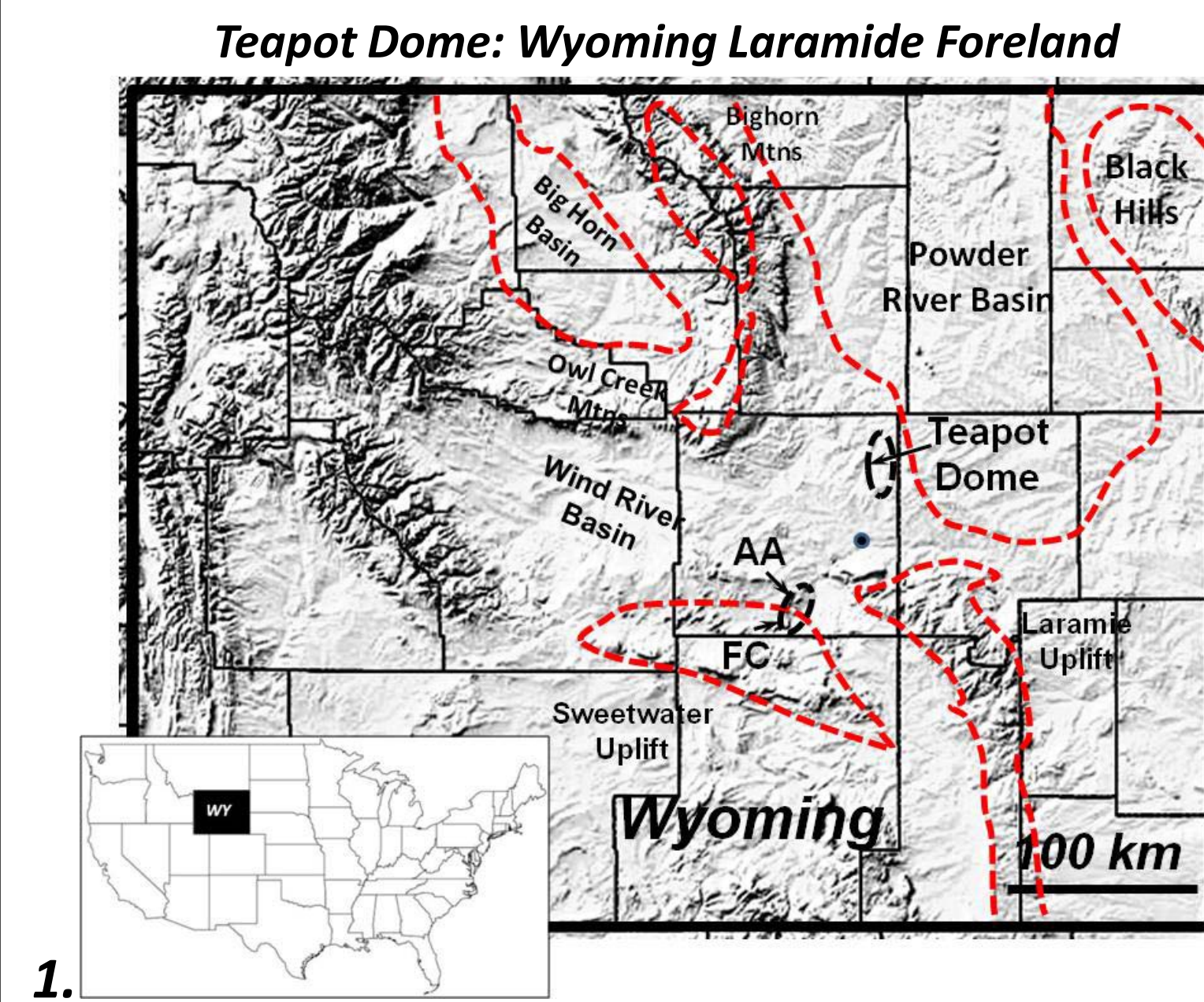
Abstract

We develop a model of the discrete fracture network in the Tensleep Sandstone reservoir, Teapot Dome, Wyoming, using design approaches and criteria that may have general applicability to characterization of naturally fractured unconventional reservoirs. Seismic discontinuities related to fracture zones and small faults are extracted from 3D seismic over the dome. Fracture image logs (Formation MicroImager (FMI) logs) provide information about open fracture trends, aperture and present-day orientation of SHmax. We also incorporate field observations of fracture height, length and spacing from Tensleep exposure in the Fremont Canyon area of southern Wyoming. The field analog was compiled from outcrop measured fracture trends and analysis of outcrop photos and WorldView satellite imagery. Fracture height distributions observed in Fremont Canyon on the NE flank of Granite Mountain anticline generally exhibit power law behavior. Decreased power in more intensely fractured zones suggests increased probability of greater fracture height. The power within fracture zones was about -1.6, while that in less intensely fractured zones was about -2.2. Spacing distributions exhibit power law response over a limited range of scales. The power is increasingly negative for larger spacings. Fracture intensity ranges from 0.02/m to 0.075/m. Fracture intensity within fracture zones varies from about 0.05/m to 0.06/m while that in less intensely deformed zones varies from about 0.025/m to 0.03/m. Geometric mean spacing varies from about 11 to 14 meters in fracture zones and from about 19 to 26 meters in less deformed zones. Geometric mean spacing, layer-by-layer, varies from about 10 meters to 27 meters. Length distribution determined from satellite imagery follows a power law (power -1.85), as does the distribution of discontinuity lengths measured in 3D seismic data over the dome (power -2.29). Aperture distributions obtained from FMI logs exhibit limited power law behavior for apertures larger than 0.05 mm, but overall their distribution is more accurately characterized as log-normal. SHmax (present-day maximum horizontal compressive stress) determined from drilling induced fractures observed in fracture image logs trends ~N76W. The dominant open fracture trend in the Tensleep reservoir, inferred from image log interpretations, parallels SHmax. These fracture parameters combined with output from 3D seismic workflows are used to build a reservoir fracture model.

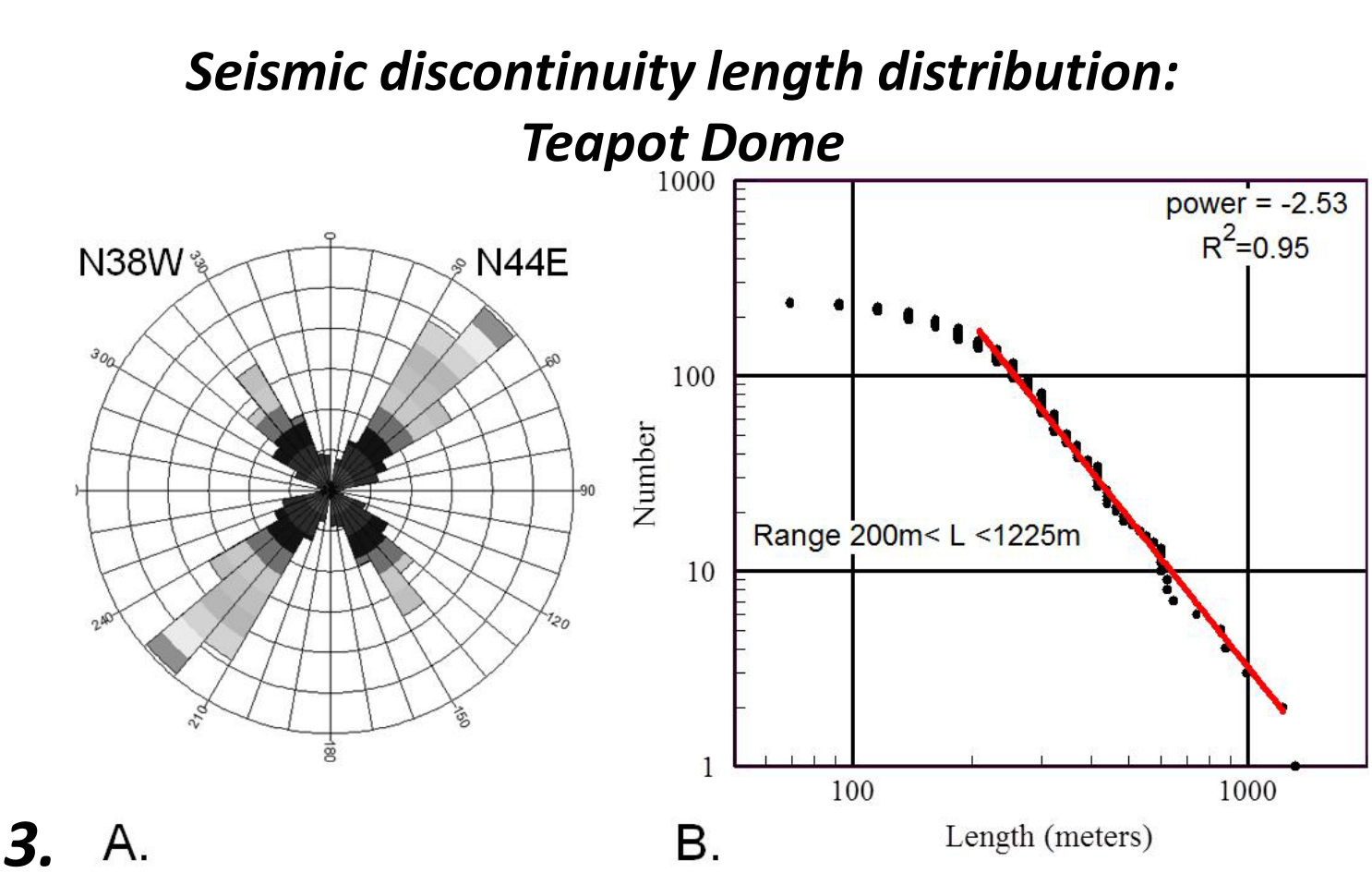
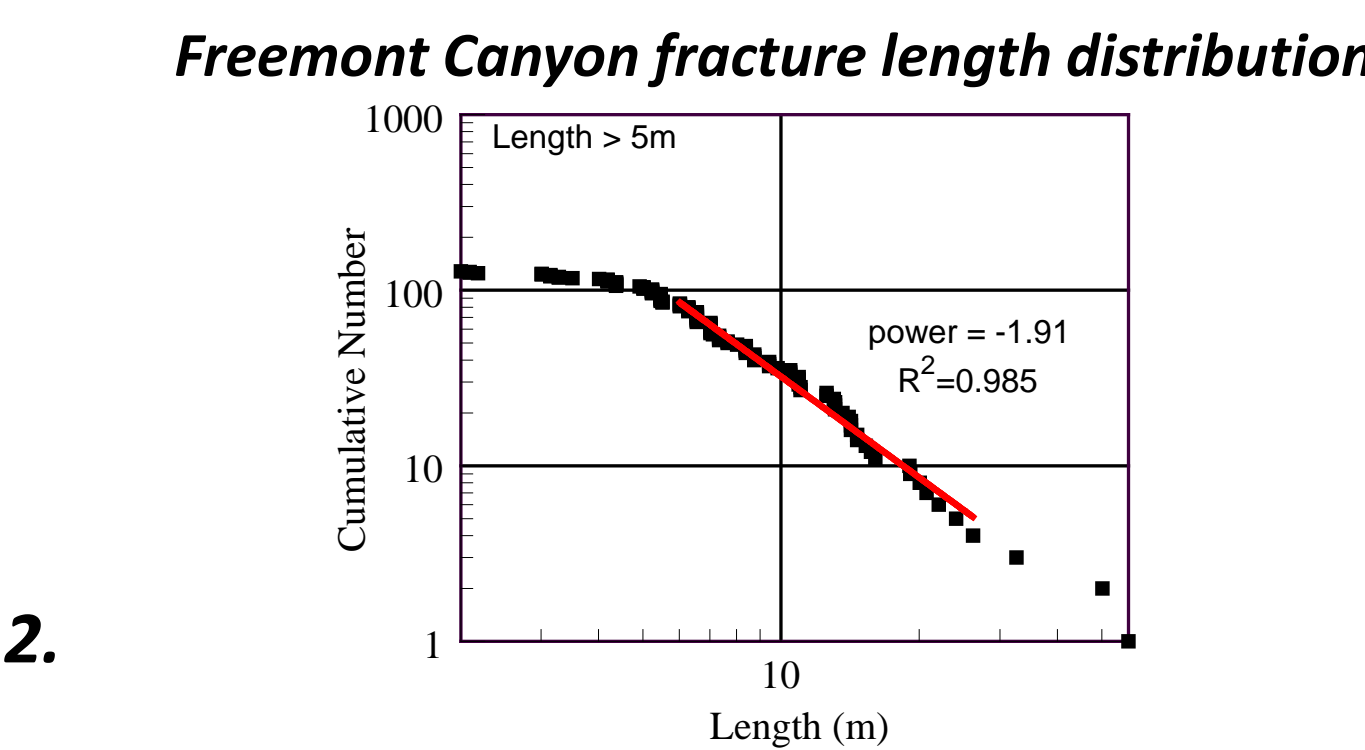
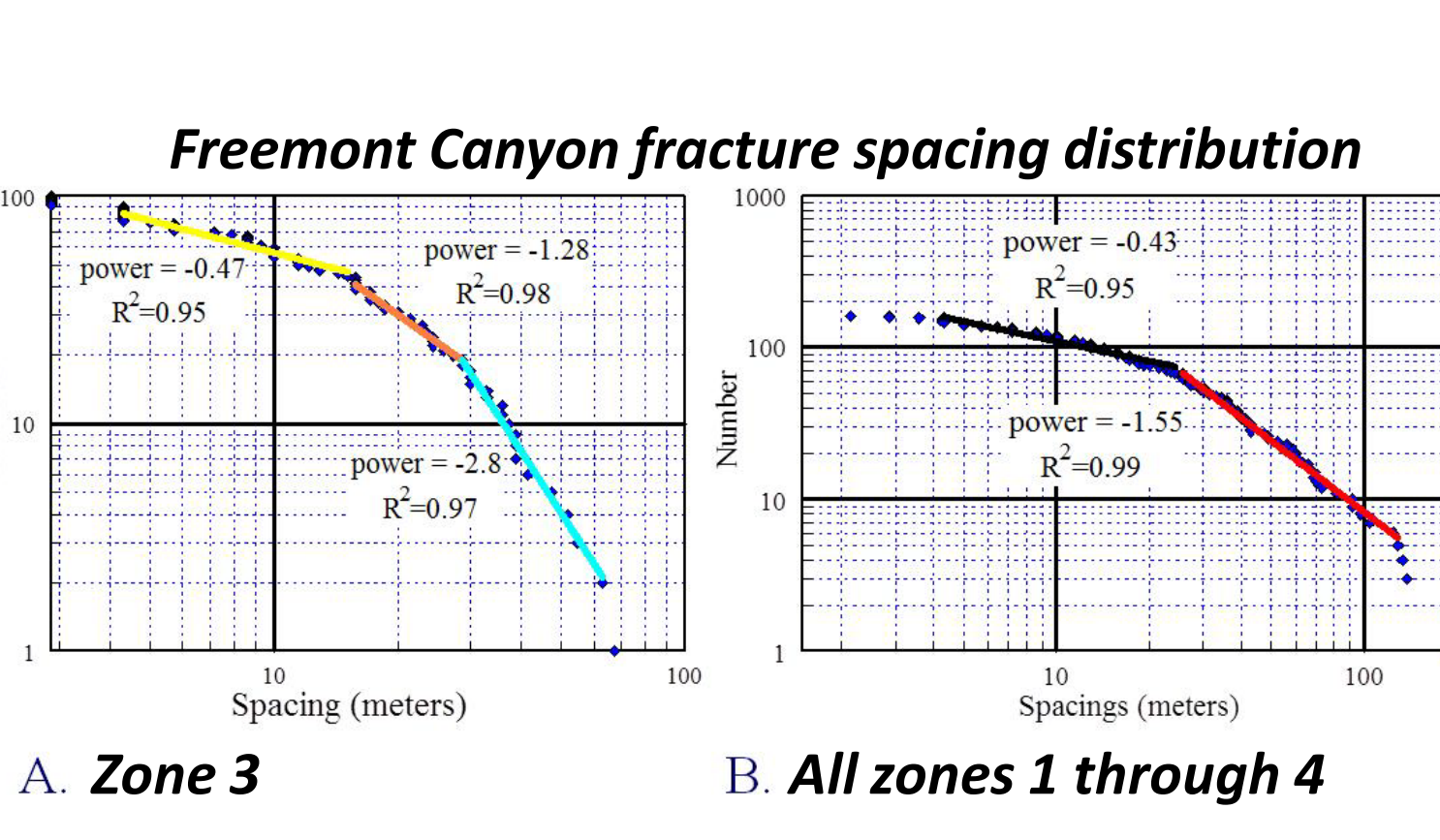
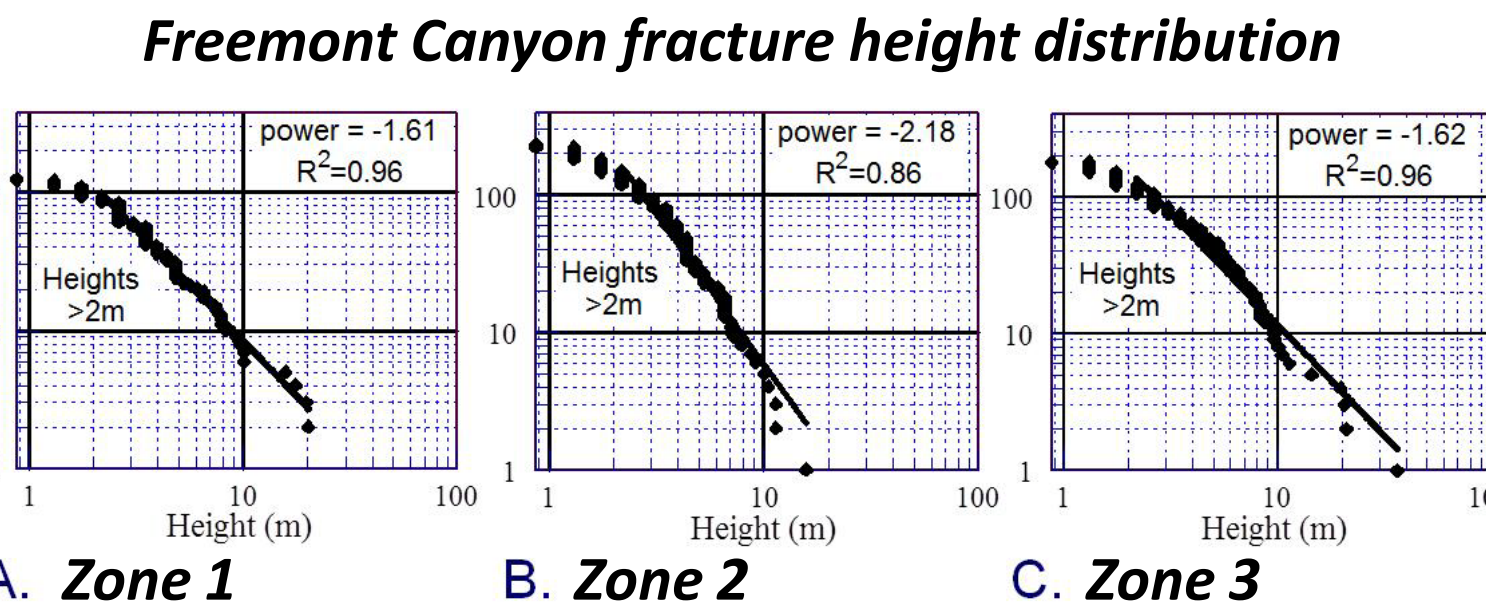
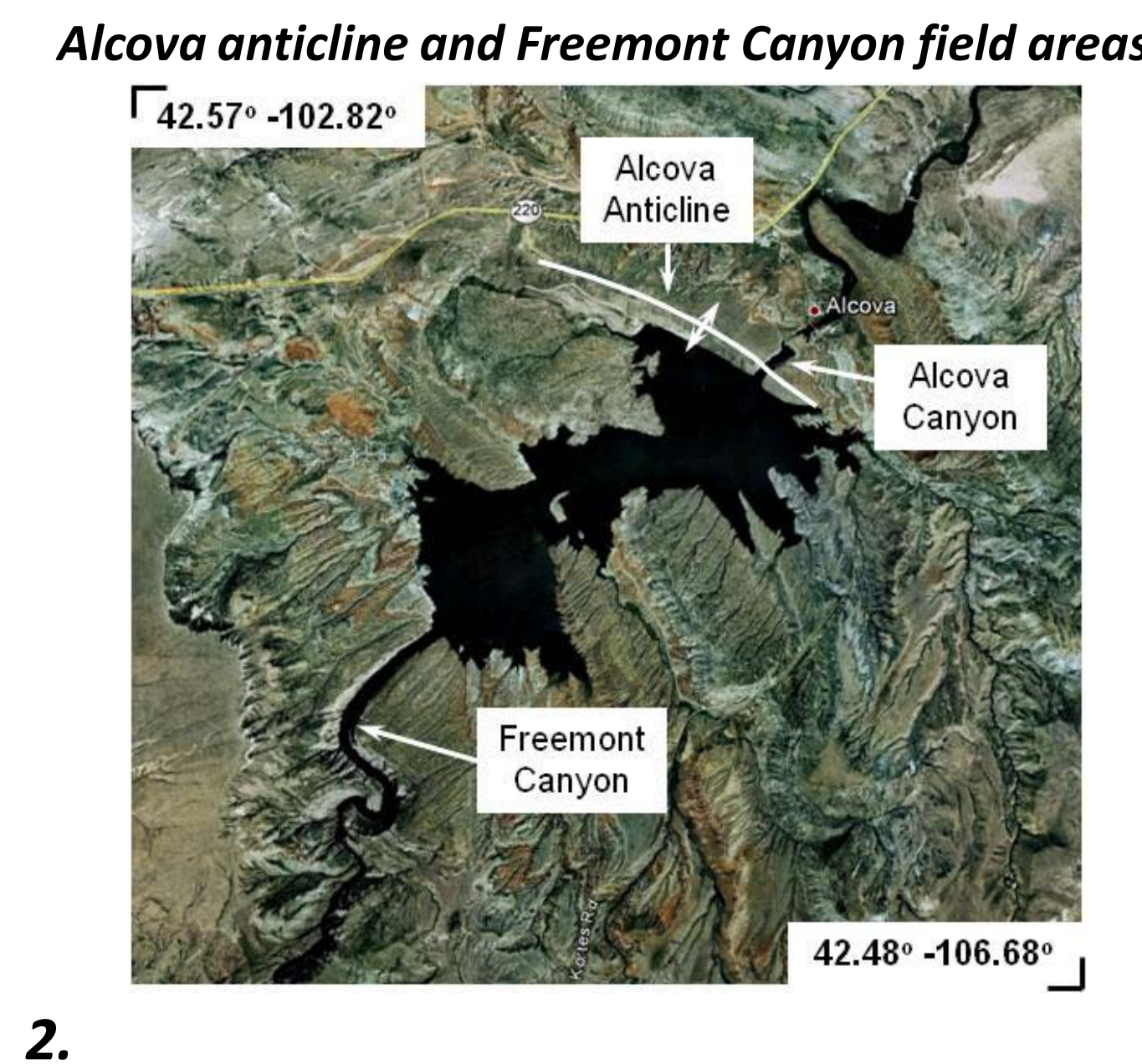
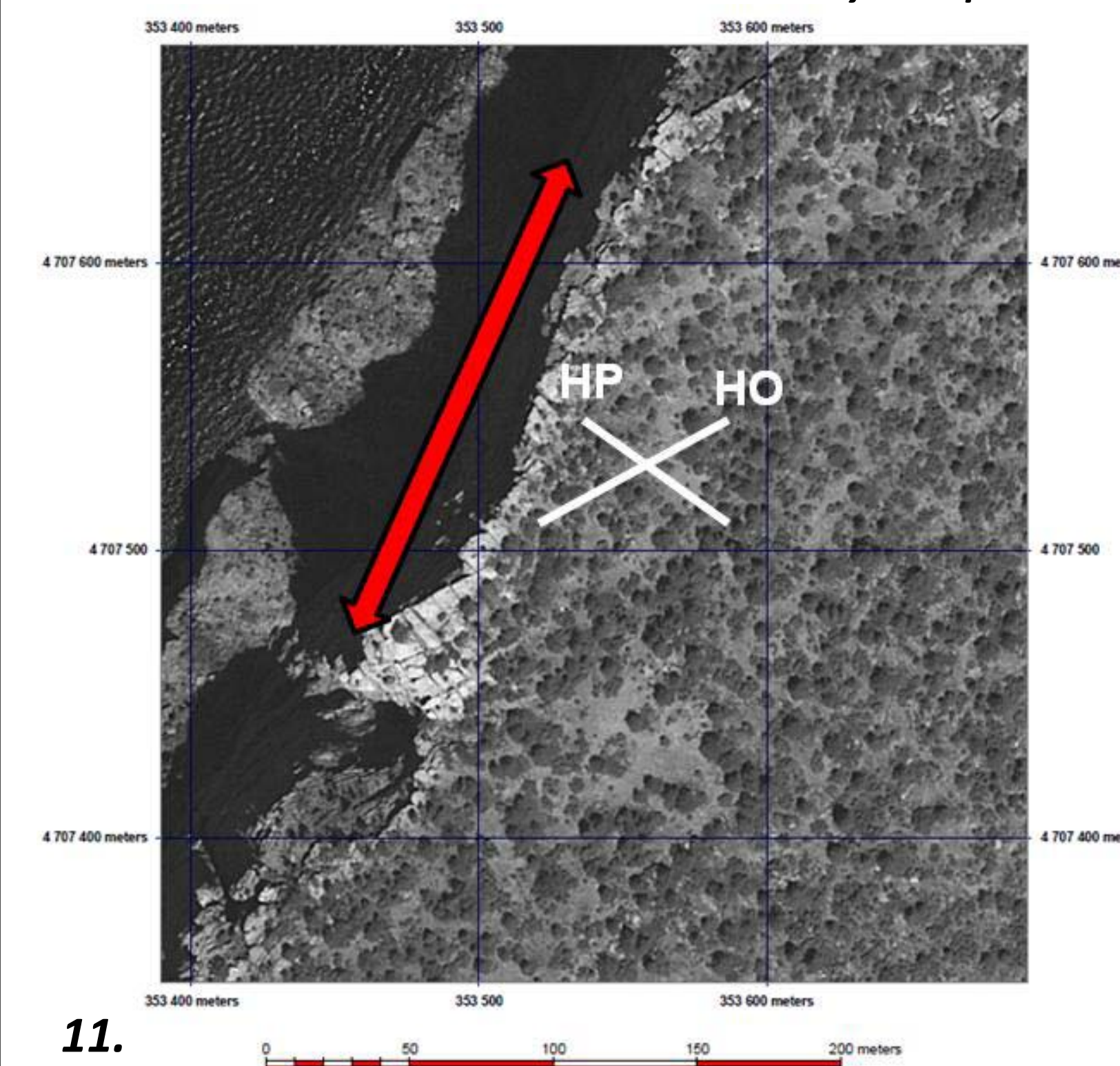
Abstract

We develop a model of the discrete fracture network i(see panel 2) n the Tensleep Sandstone reservoir, Teapot Dome, Wyoming (1), using design approaches and criteria that may have general applicability to characterization of naturally fractured unconventional reservoirs. Seismic discontinuities, related to fracture zones and small faults, are extracted from 3D seismic over the dome. Fracture image logs (Formation MicroImager (FMI) logs) provide information about open fracture trends, aperture and present-day orientation of S_{Hmax} . We also incorporate field observations of fracture height, length and spacing from Tensleep exposure in the Fremont Canyon area of southern Wyoming. (1, 2 & 5). The field analog was compiled from outcrop measured fracture trends and analysis of outcrop photos and WorldView satellite imagery. (11)

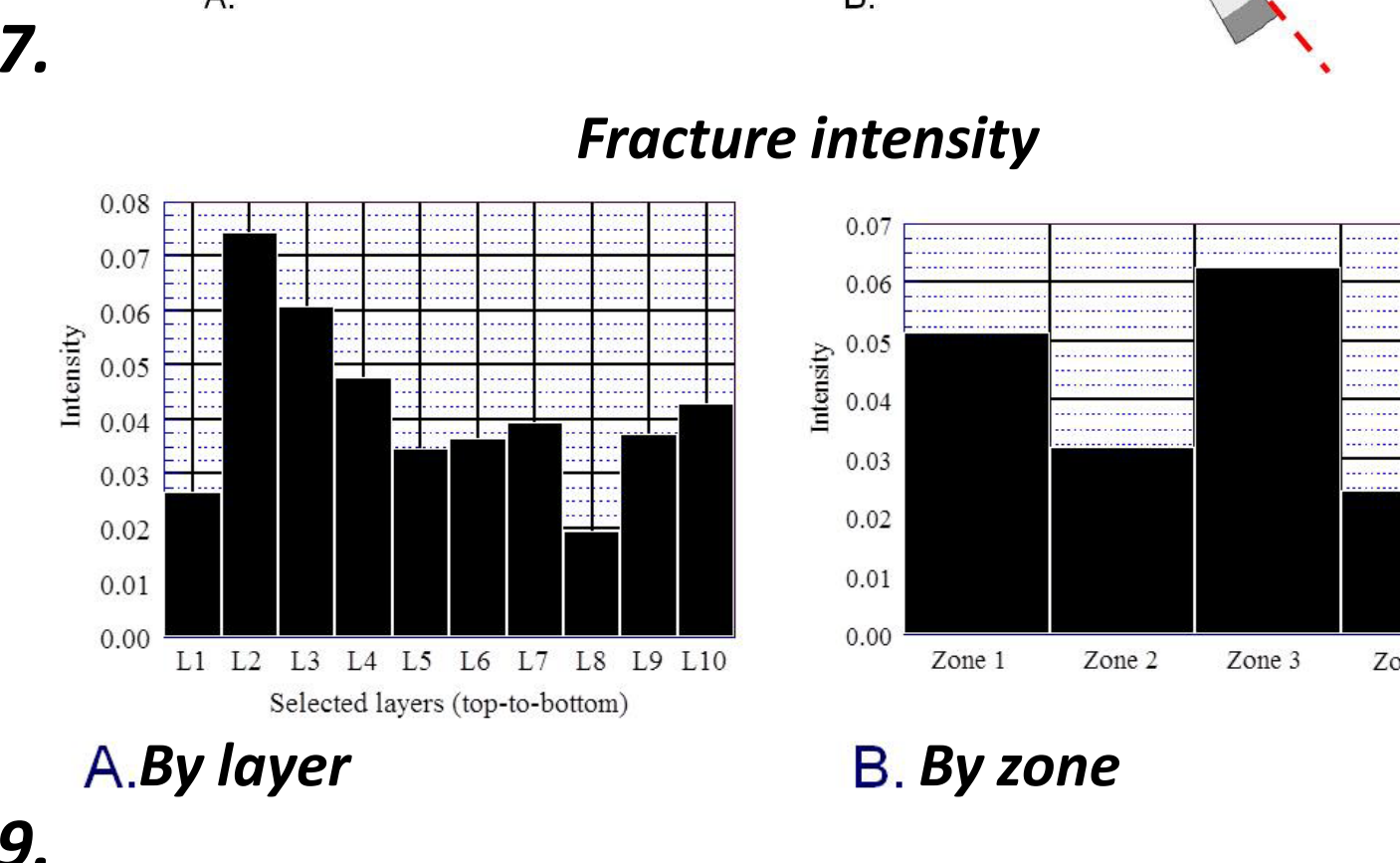
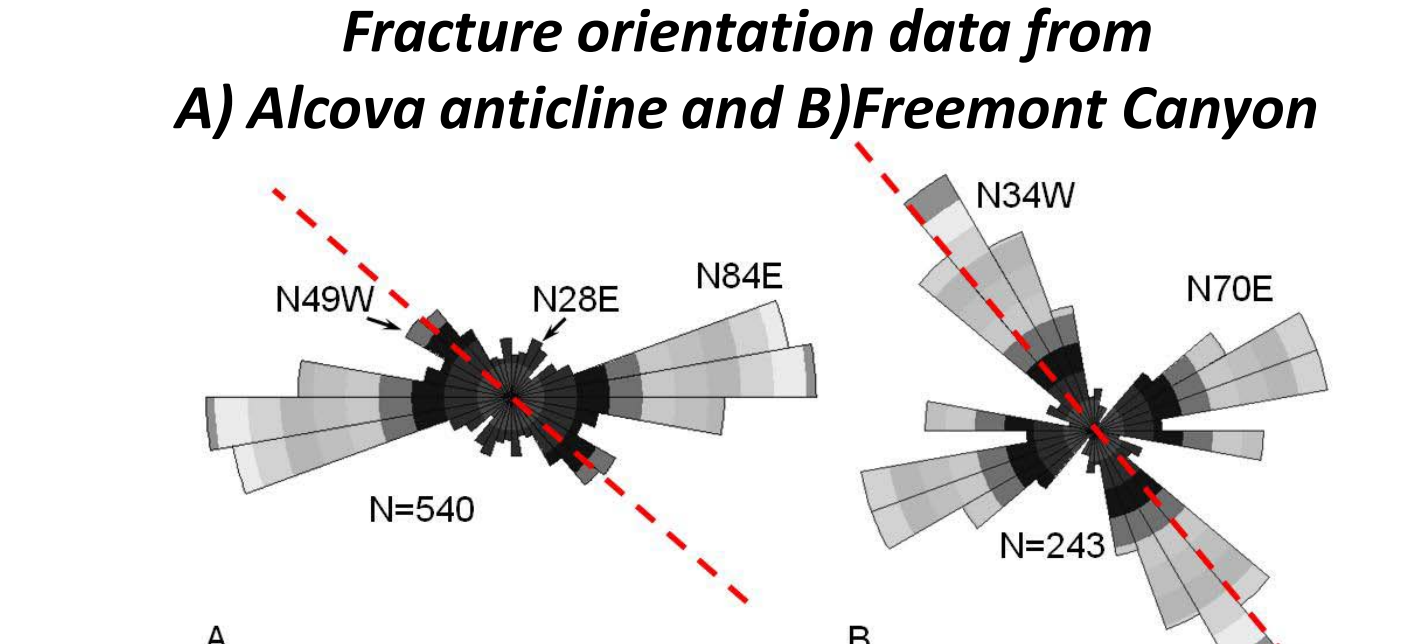
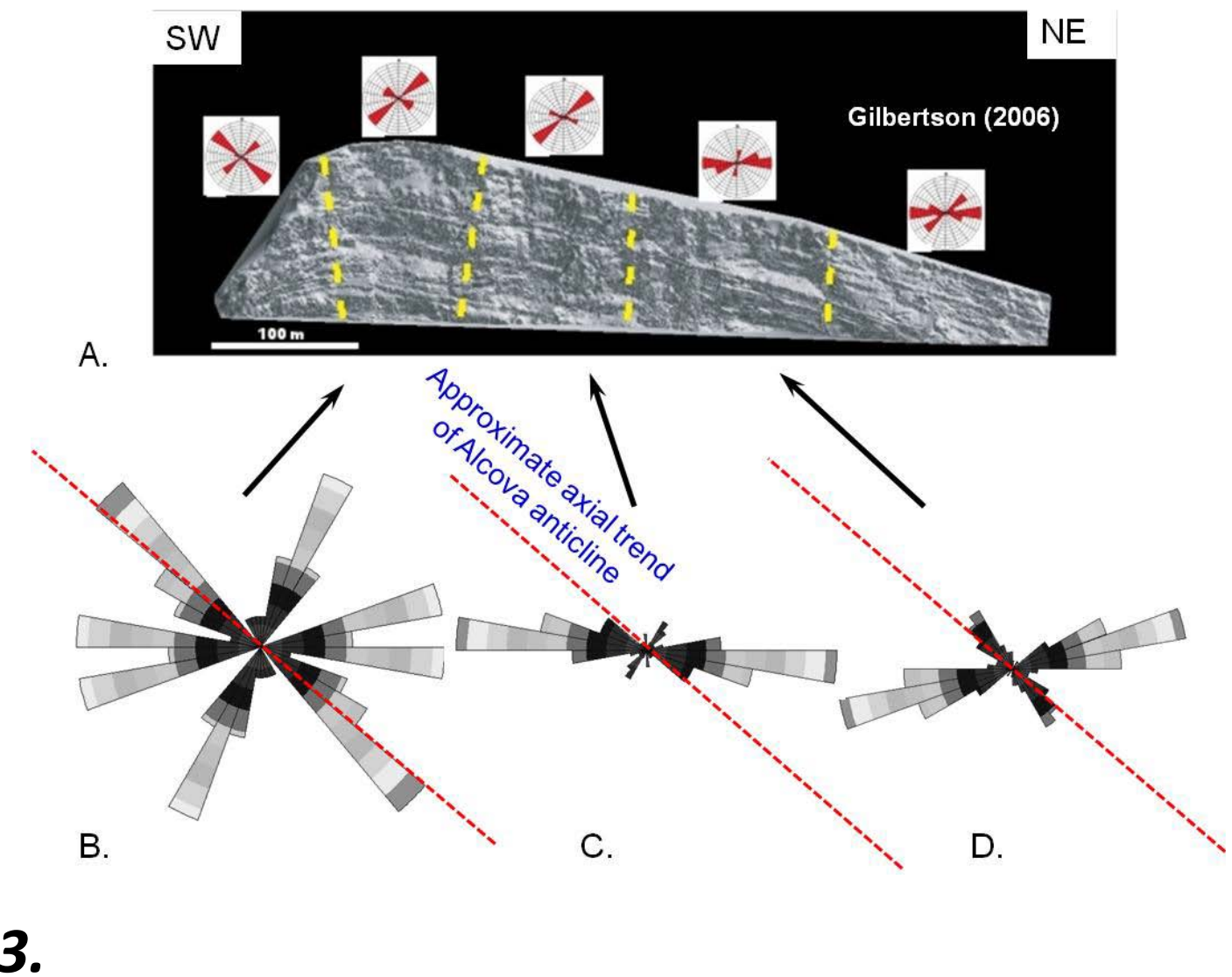
Fracture height distributions observed in Fremont Canyon on the NE flank of Granite Mountain anticline generally exhibit power law behavior (6). Decreased power in more intensely fractured zones suggests increased probability of greater fracture height. The power within fracture zones was about -1.6, while that in less intensely fractured zones was about -2.2. Spacing distributions exhibit power law response over a limited range of scales (8). The power is increasingly negative for larger spacings. Fracture intensity ranges from 0.02/m to 0.075/m (9). Fracture intensity within fracture zones varies from about 0.05/m to 0.06/m while that in less intensely deformed zones varies from about 0.025/m to 0.03/m (9). Geometric mean spacing varies from about 11 to 14 meters in fracture zones and from about 19 to 26 meters in less deformed zones. Geometric mean spacing, layer-by-layer, varies from about 10 meters to 27 meters. Length distribution determined from satellite imagery (11) follows a power law (power -1.85), as does the distribution of discontinuity lengths measured in 3D seismic data over the dome (power -2.29) (12 & 13). Aperture distributions obtained from FMI logs exhibit limited power law behavior for apertures larger than 0.05 mm, but, overall their distribution is more accurately characterized as log-normal (15). S_{Hmax} (present-day maximum horizontal compressive stress) determined from drilling induced fractures observed in fracture image logs trends $\sim N80^{\circ}W$ (8). The dominant open fracture trend in the Tensleep reservoir, inferred from image log interpretations, parallels S_{Hmax} (8). These fracture parameters combined with output from 3D seismic workflows are used to build a reservoir fracture model (see panel 2).



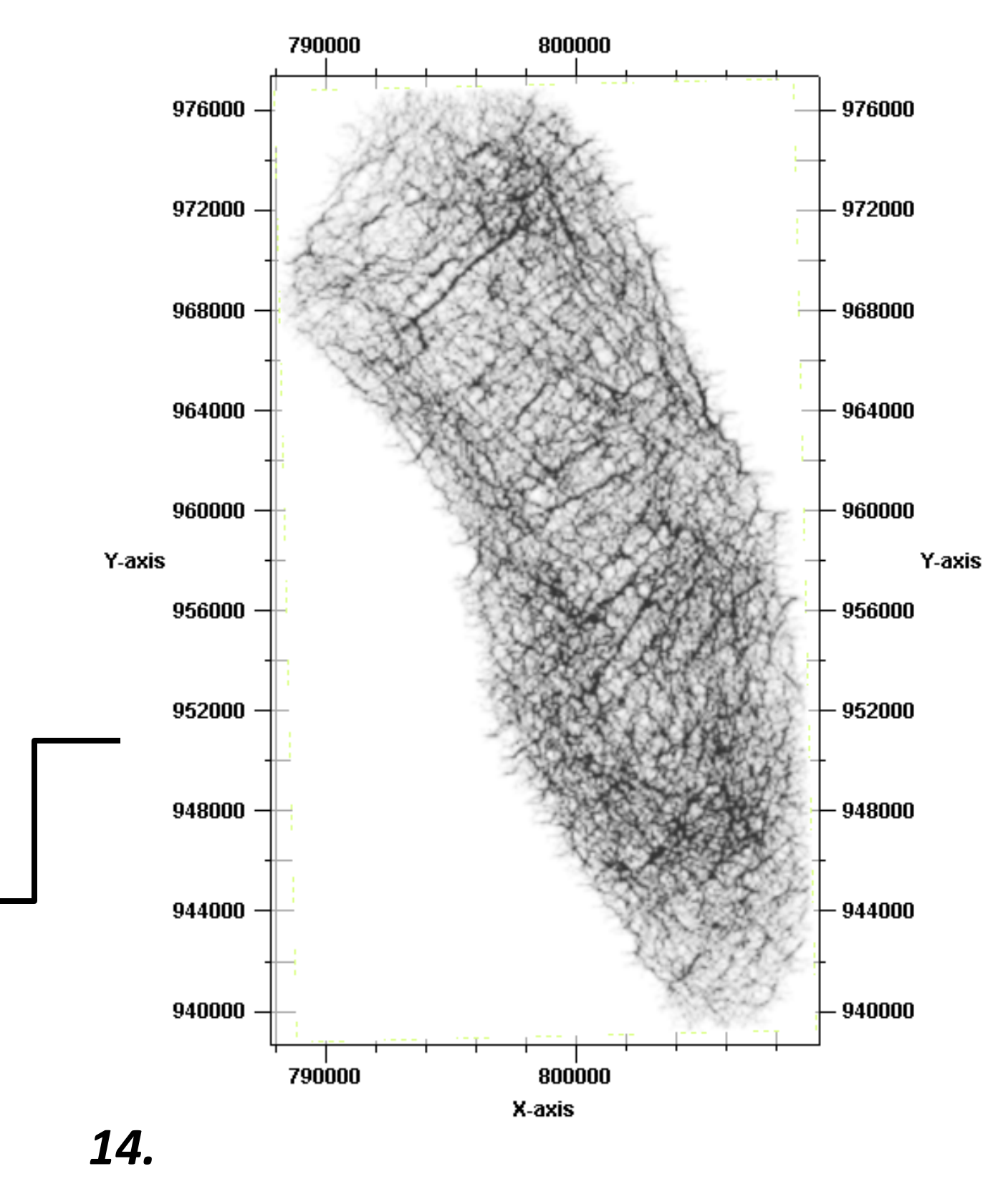
WorldView image allows measurement of fracture lengths. The scene looks down on the Freemont Canyon exposure.



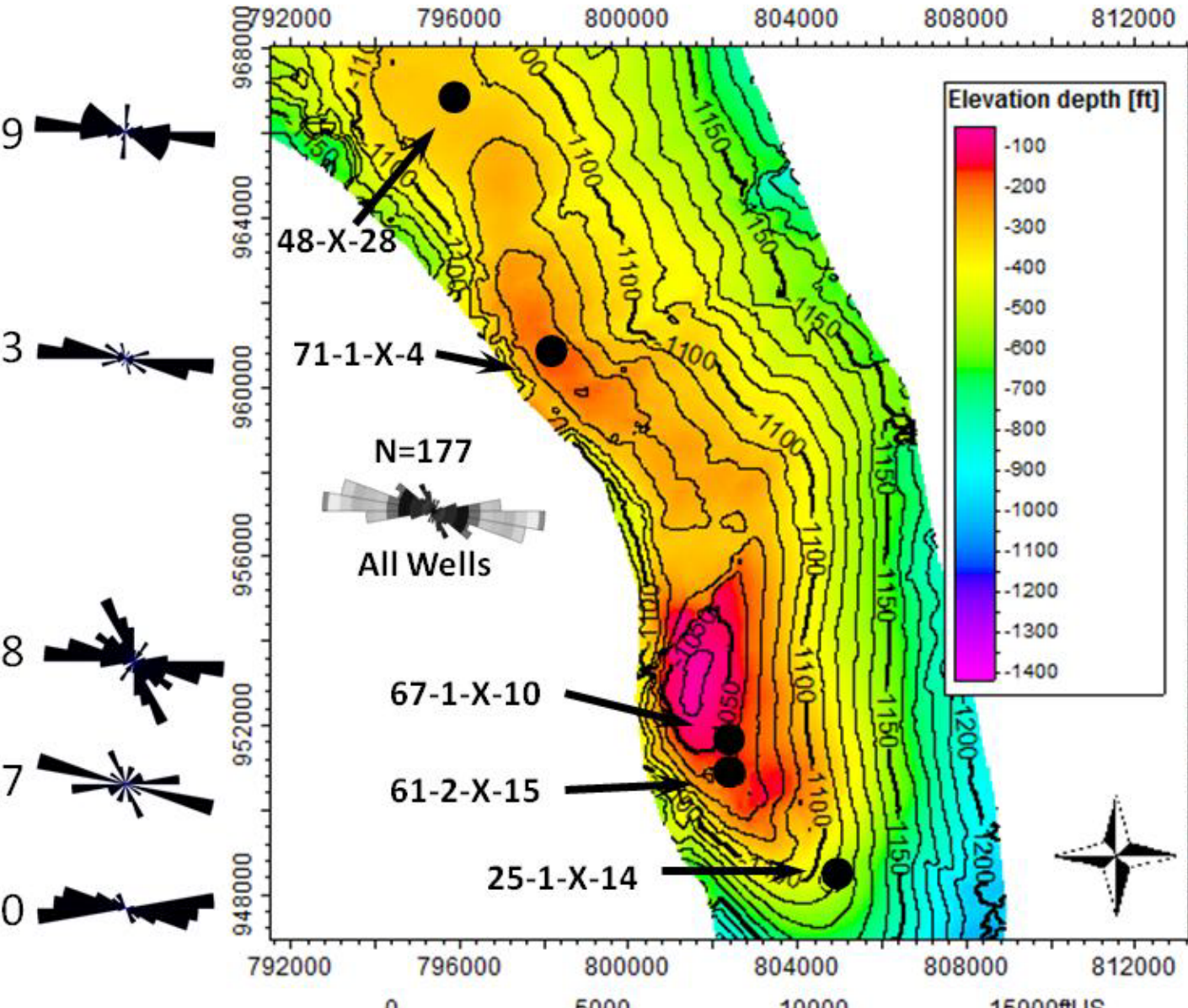
Comparison of fracture observations: A) Gilbertson (2006); B-C) this study



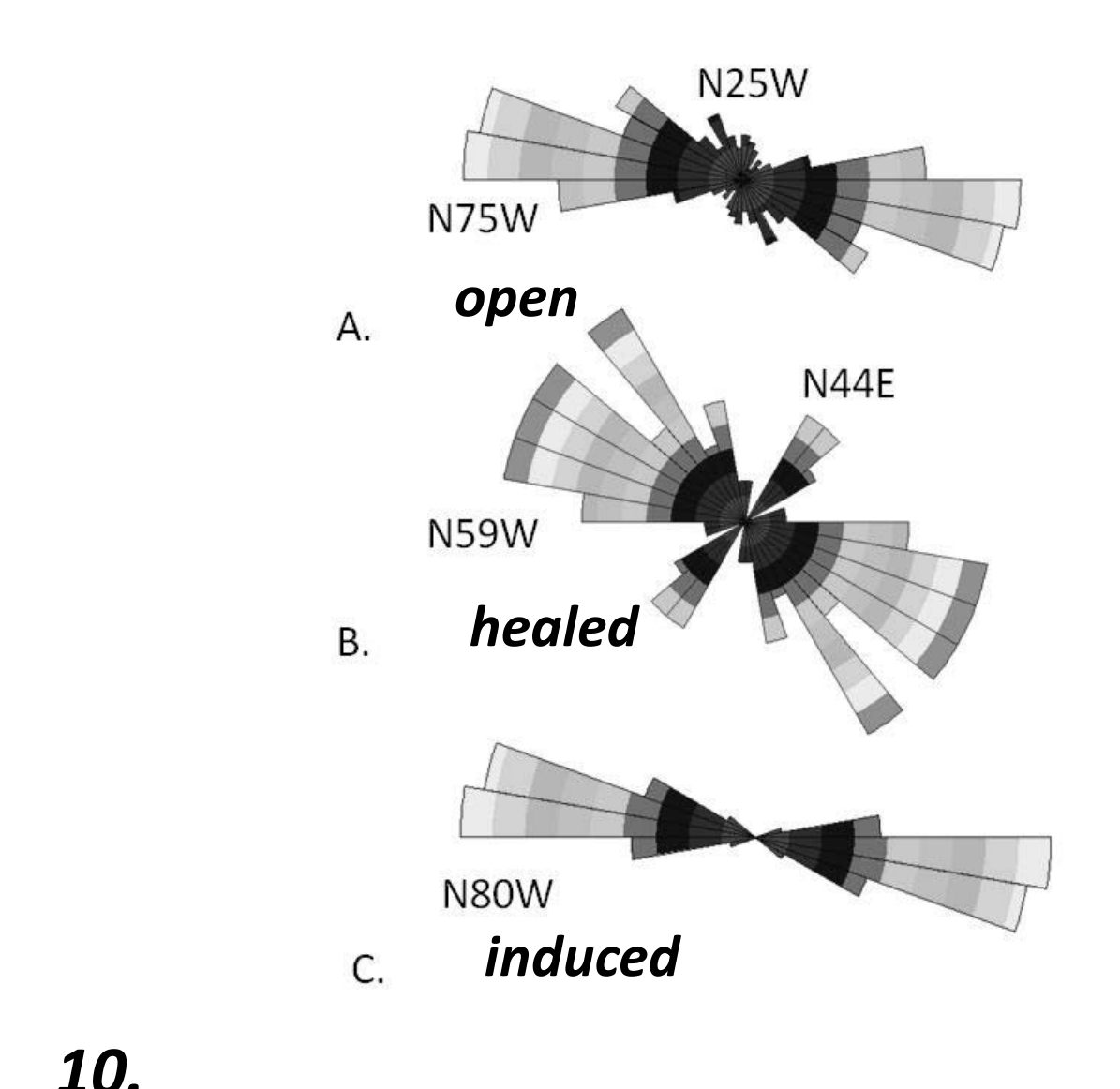
Seismic discontinuities: Teapot Dome, Wy.



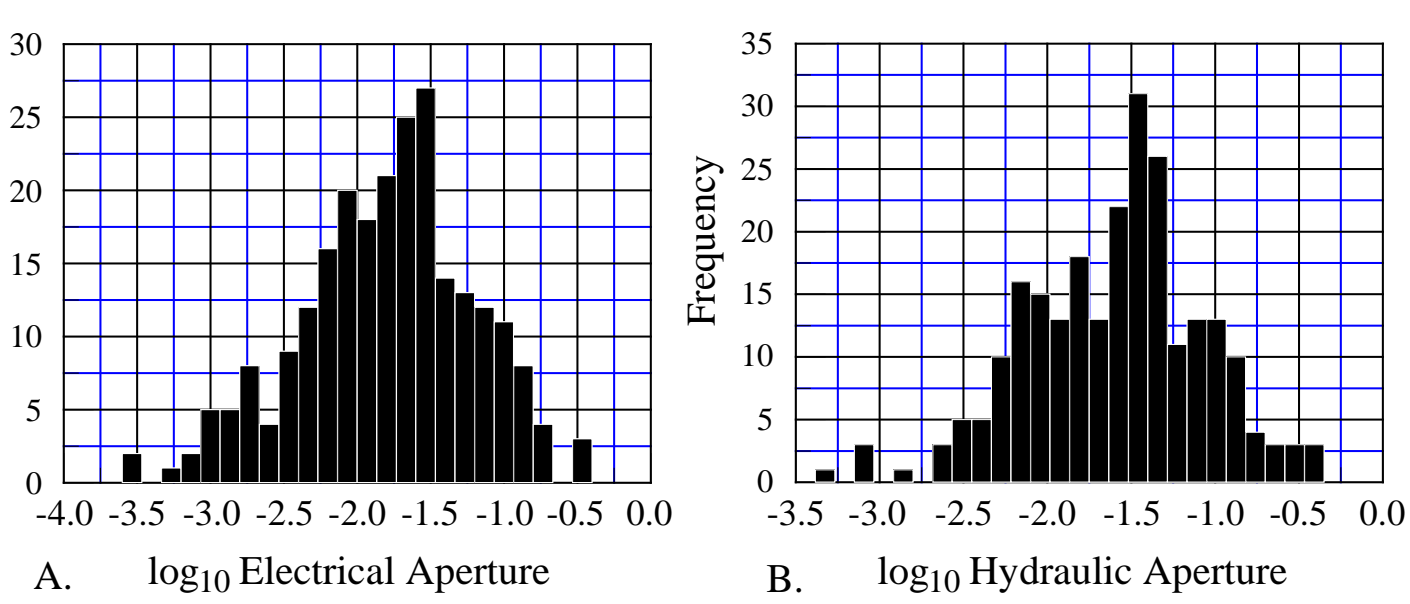
Tensleep open fracture trends by well and in total



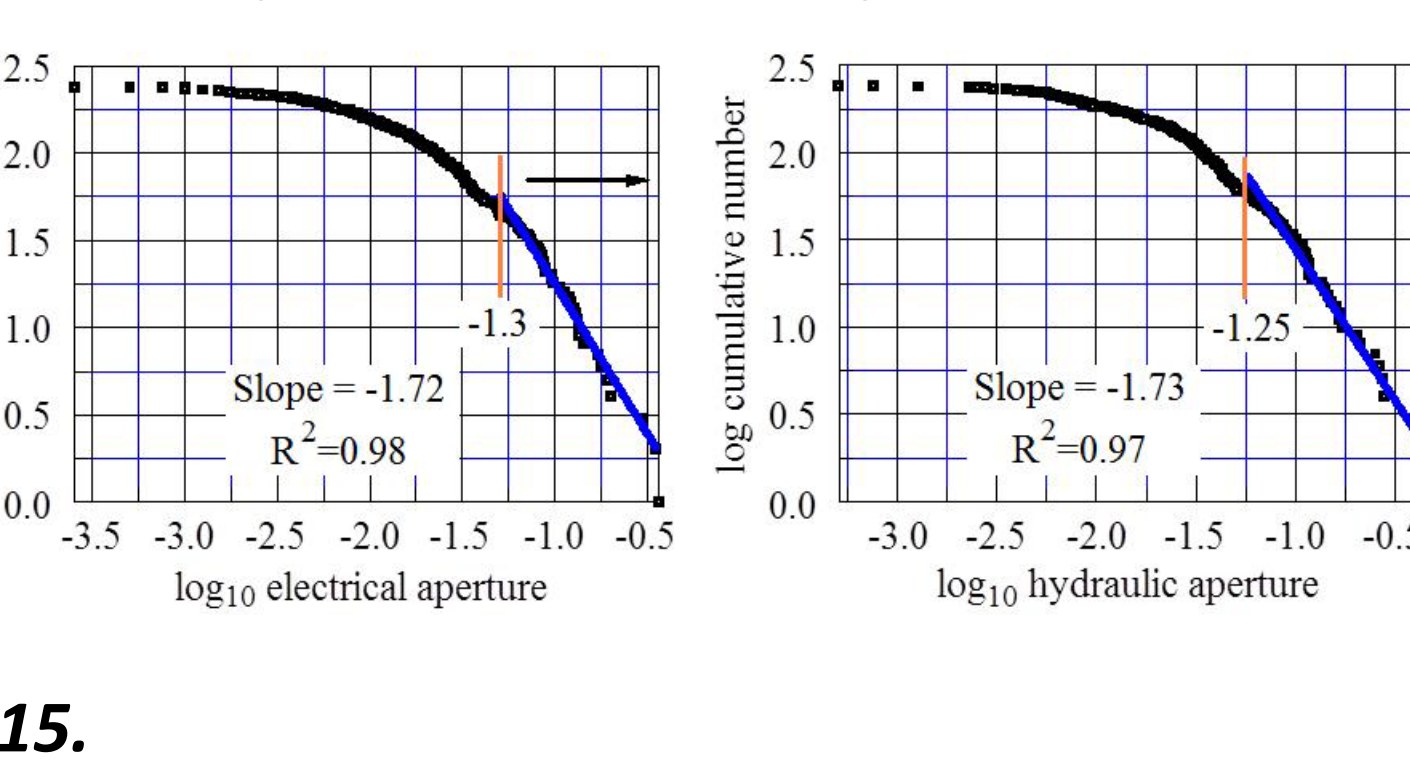
Fracture image log observations; Tensleep Sandstone, Teapot Dome



Aperture distributions – log-normal



Aperture distributions – power-law



Analysis of field observations from Alcova anticline and Freemont Canyon (1-3) provided insights into fracture orientations and fracture height, spacing and length distributions (3, 4, 5 & 10).

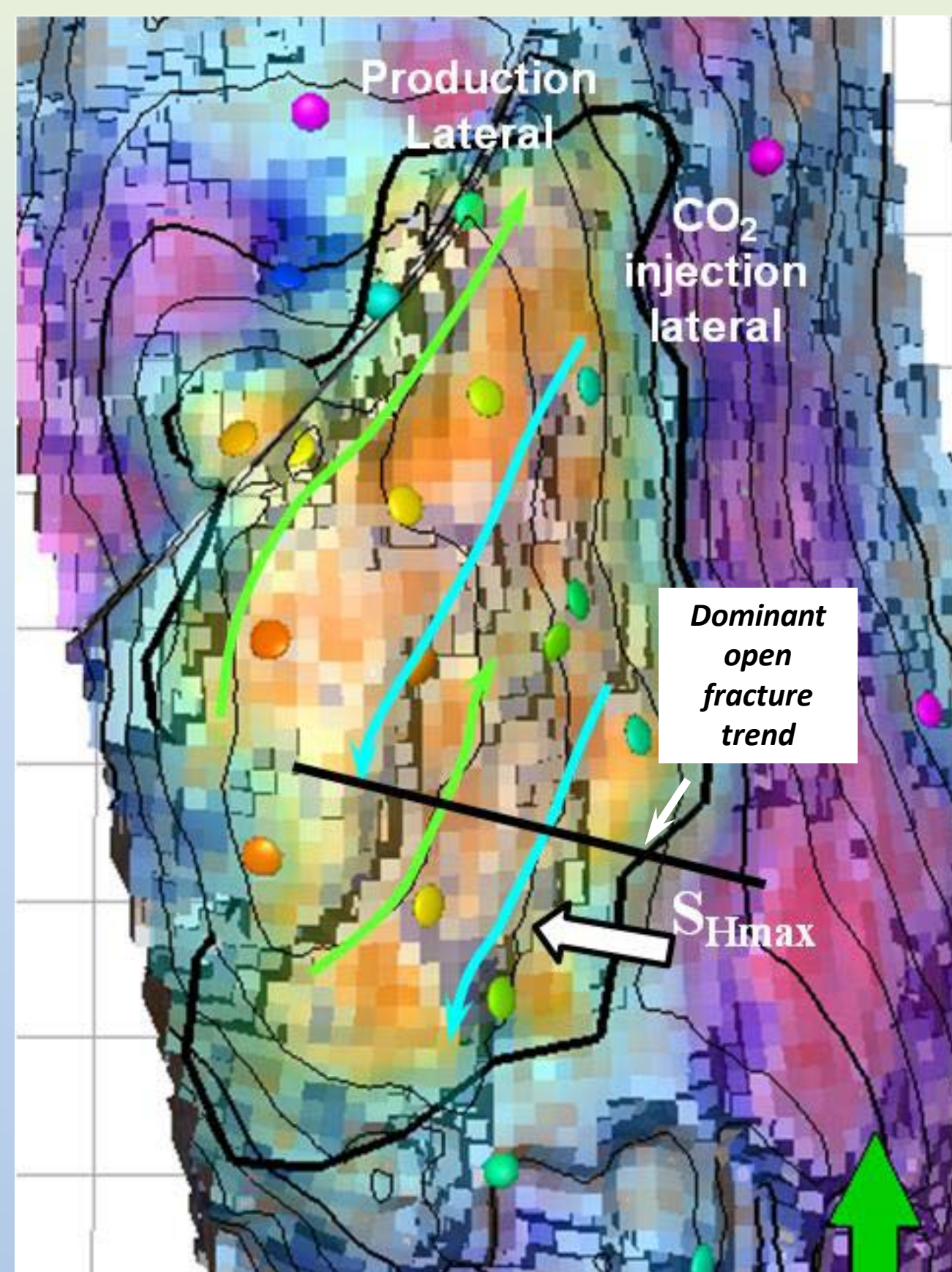
Aspect ratio (reciprocal elongation ratio) was also estimated from the Freemont Canyon length and height measurements. Fracture aspect ratio is the ratio of fracture height to length. Gilbertson (2006) estimated fracture aspect ratio for the Tensleep Sandstone using a value for mean fracture length of 50 meters reported by LaPointe et al. (2002). Gilbertson (2006) reported a geometric mean fracture height of 17.53 m and used LaPointe et al.'s (2002) mean length to obtain an aspect ratio of 0.35. In this study, we estimate aspect ratio using mean height (3.04 m) and mean length (9.1m) to obtain an aspect ratio 0.33. We also used the geometric mean height (2.54m) and length (7.4m) to obtain an aspect ratio of 0.34. Both of these are in good agreement with Gilbertson's (2006) estimate. In our model studies, we use an elongation ratio of 3 or aspect ratio of 0.33.

Reservoir fracture sets and aperture distributions were derived from image log observations (3, 4, 7, 10 and 15).

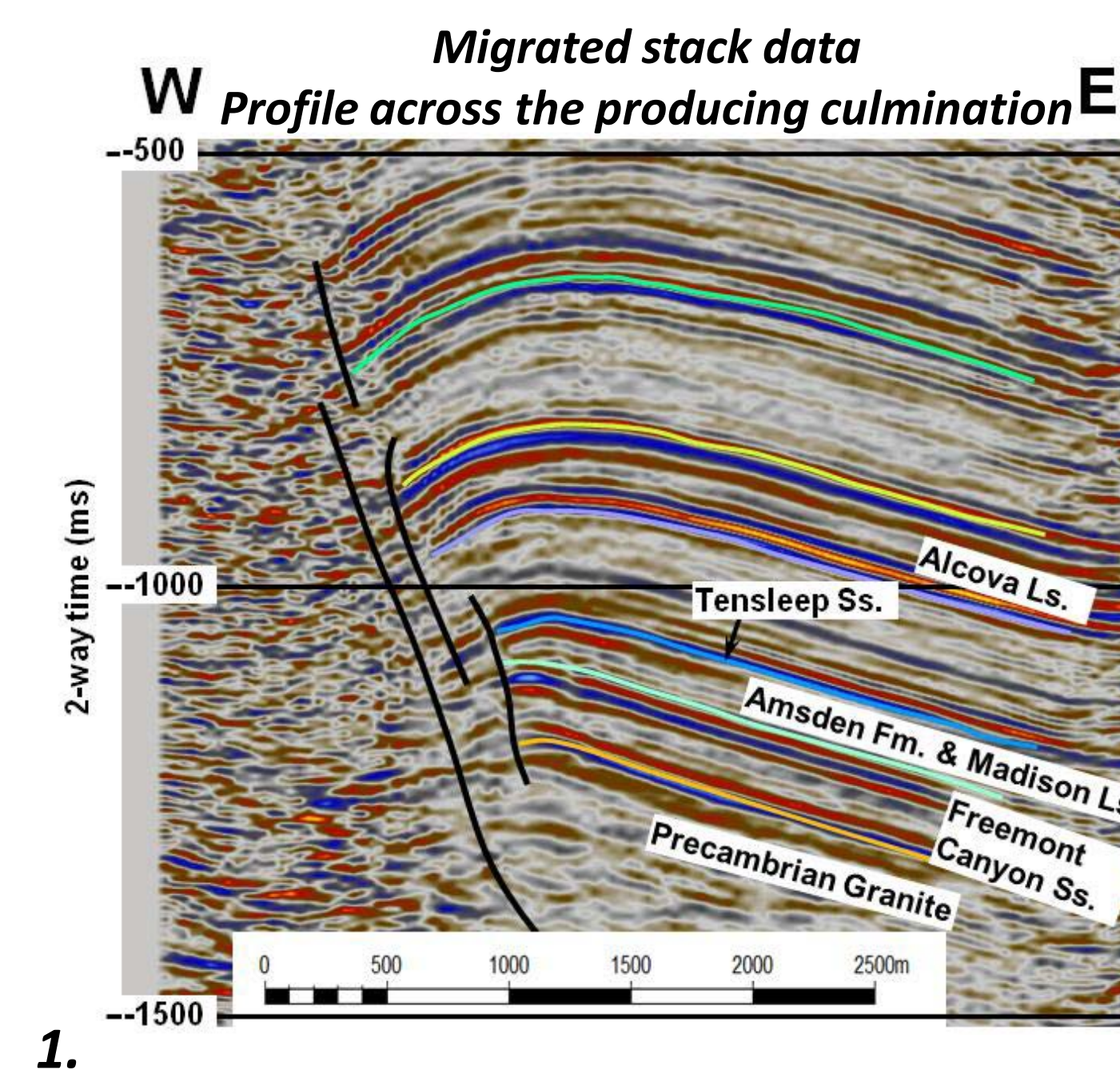
Fracture and discontinuity length distributions tend to follow a power law (12, 13 & 14). However, we note that over the range of scales extending from outcrop to field (seismic) scale, the power becomes increasingly negative. Power law spacing distribution is similarly range-limited and best described as log-normal. The χ^2 goodness of fit test shows that the Freemont Canyon spacing data (for spacings greater than 4m) do have log-normal distribution. The p-value in this case suggested there was only a 40% probability that deviations from normalcy are not due to chance alone. We suspect that fracture lengths, likewise, follow the log-normal distribution over the meter to kilometer scale.

Teapot Dome is a relatively simple forced fold (1 & 2) of Laramide age located near the southwest margin of the Powder River Basin in northeastern Wyoming. Open fracture rose diagrams reveal pervasive NW hinge oblique fractures extending through the entire section in the Tensleep (4, panels 1 and 2).

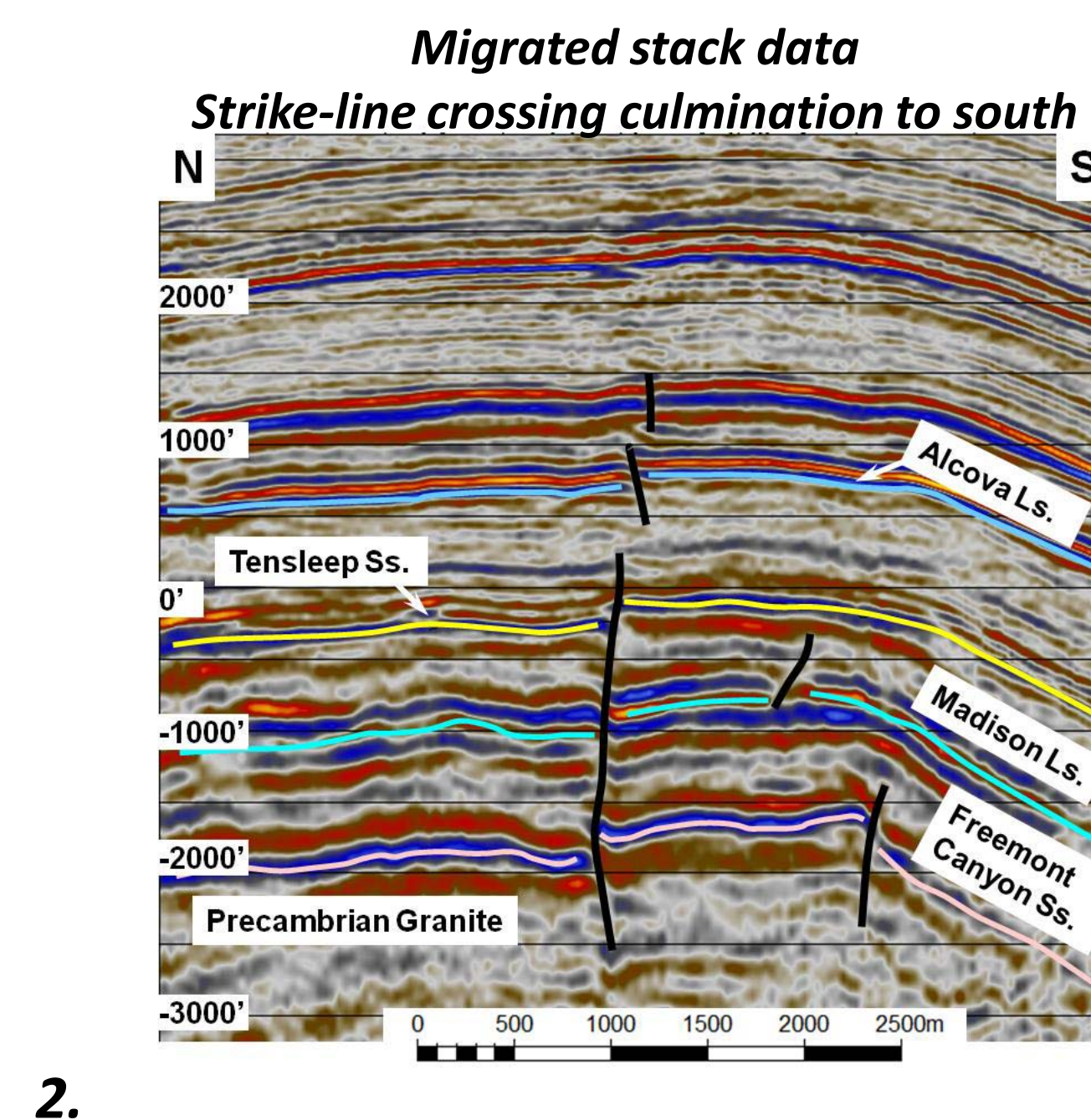
Seismic discontinuities and directional curvature are combined to form a fracture intensity driver (5-8).



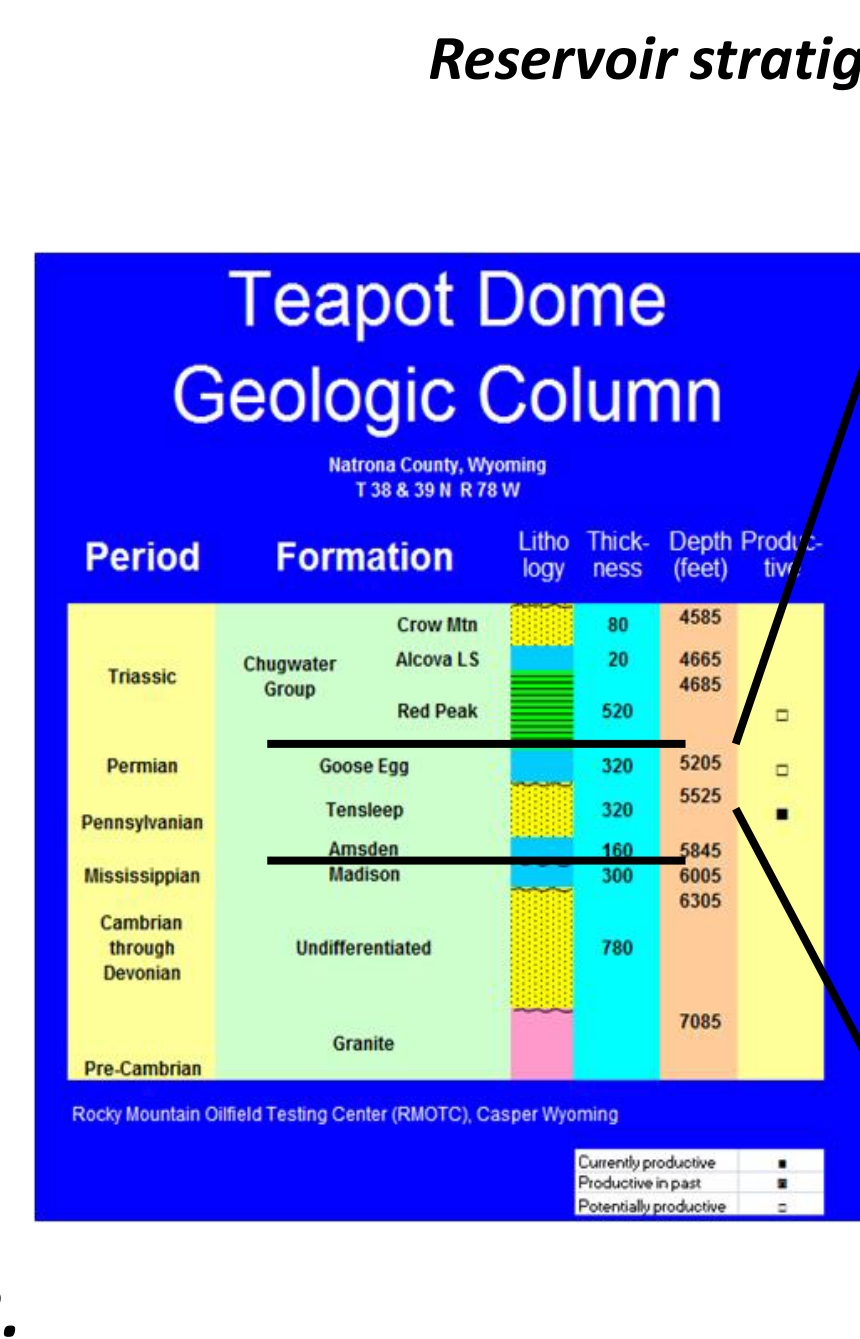
Upscaled driver (9) controls fracture intensity in all model fracture sets (10 & 11). Porosity and permeability computed from the fracture model share properties of the driver (9 & 13). Reservoir compartmentalization is inferred from spatial properties of the driver, computed porosity and permeability, and production distribution (12-14).



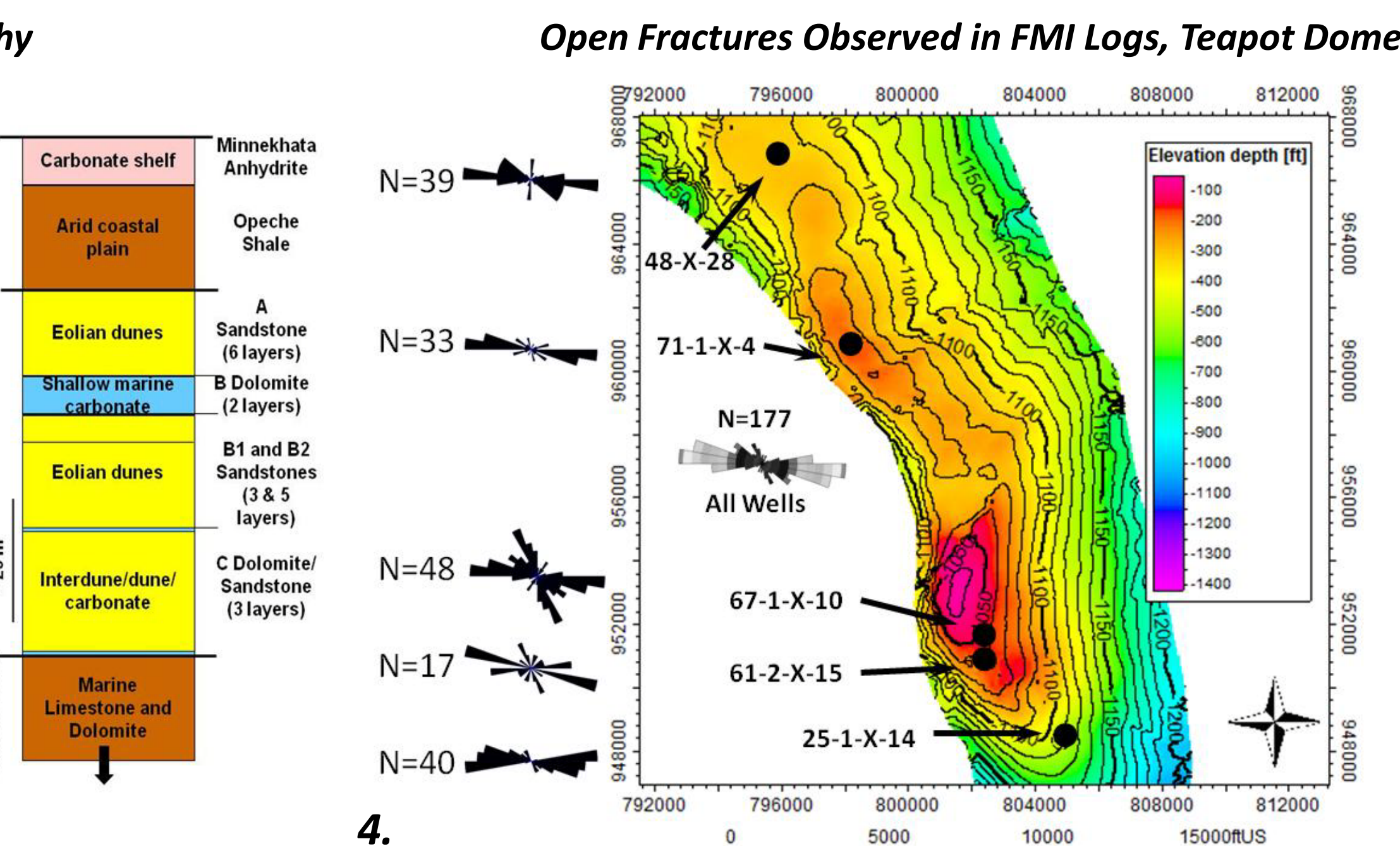
1.



2.

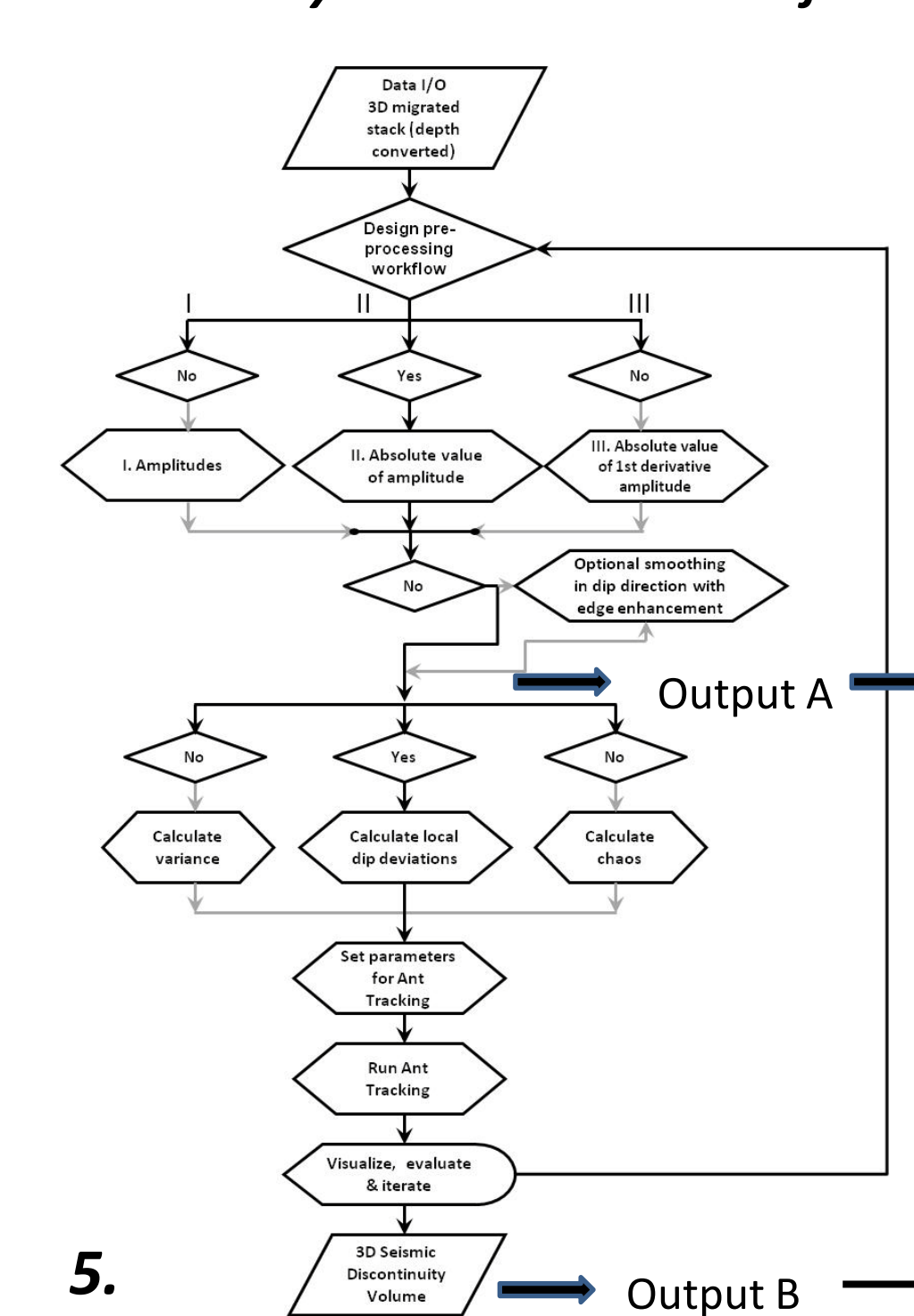


3.



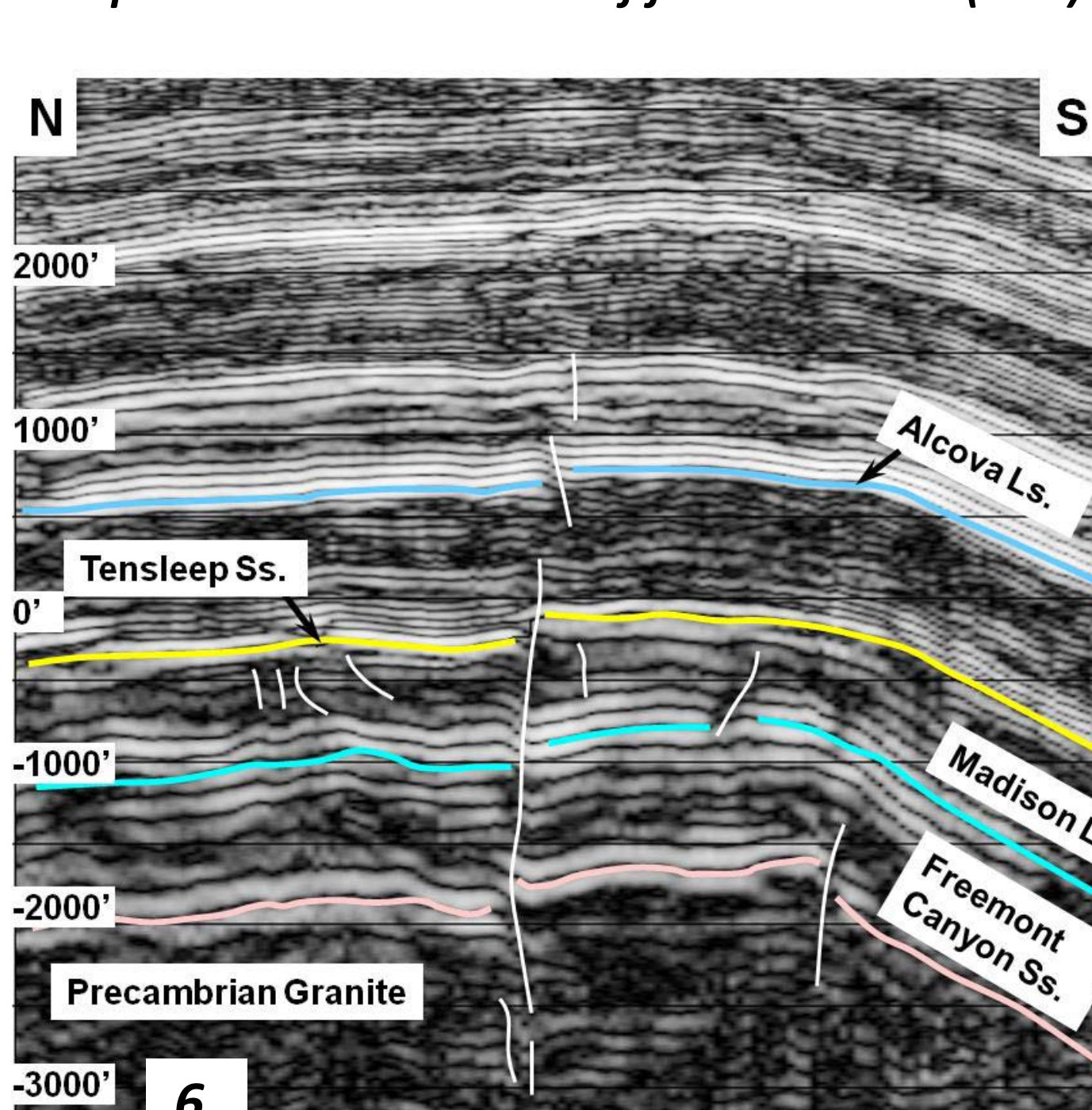
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Discontinuity enhancement workflow



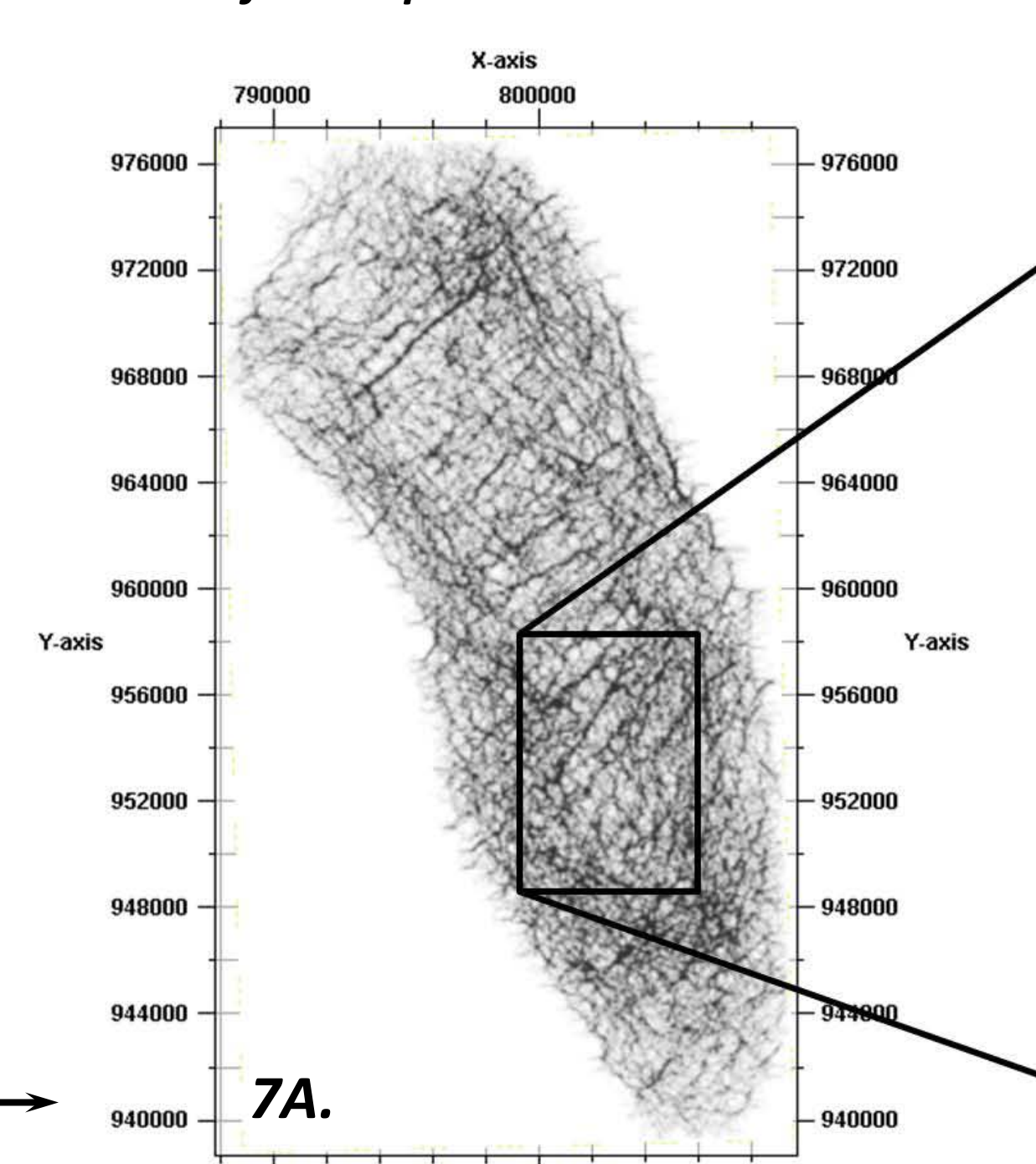
5.

Output A > Absolute value of first derivative (AFD)



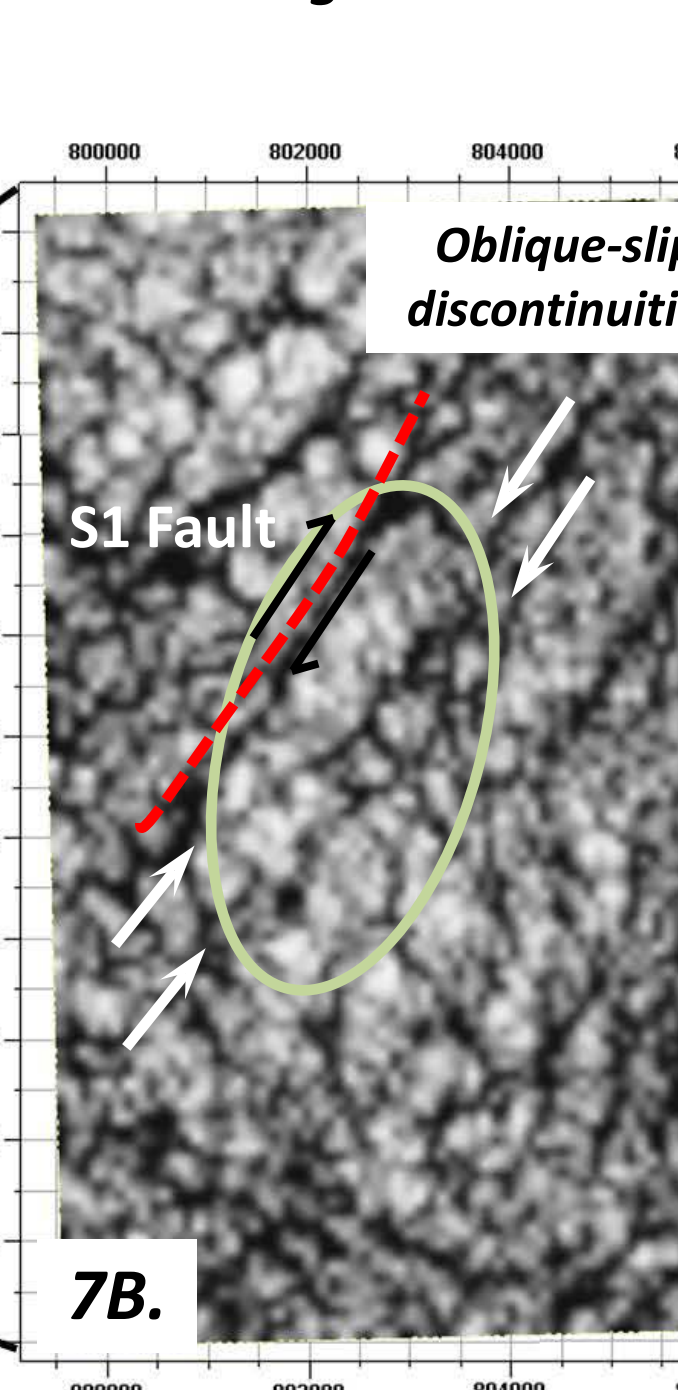
6.

Output B > Ant Track discontinuities extracted from dip deviation on AFD



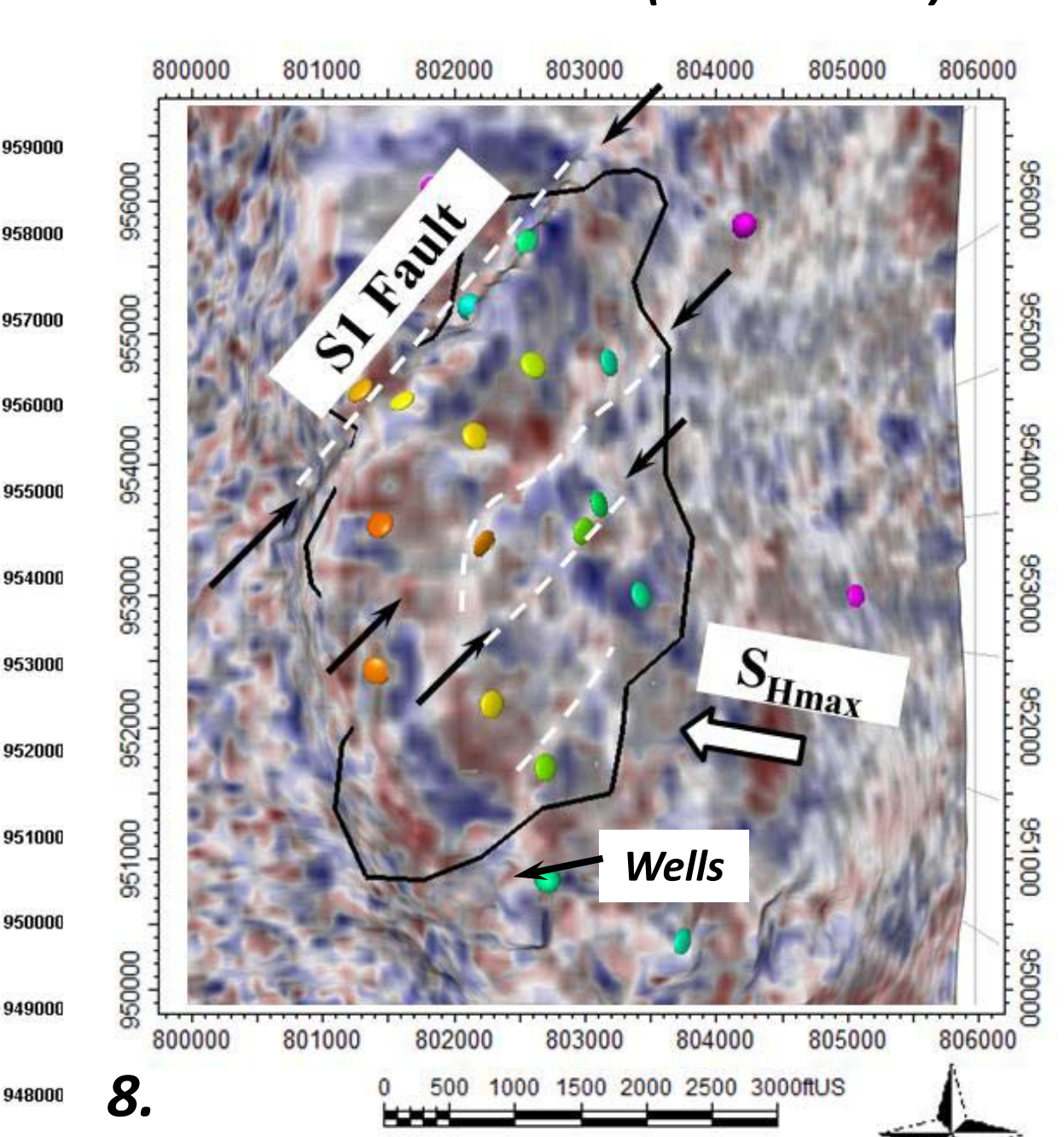
7A.

Producing Culmination



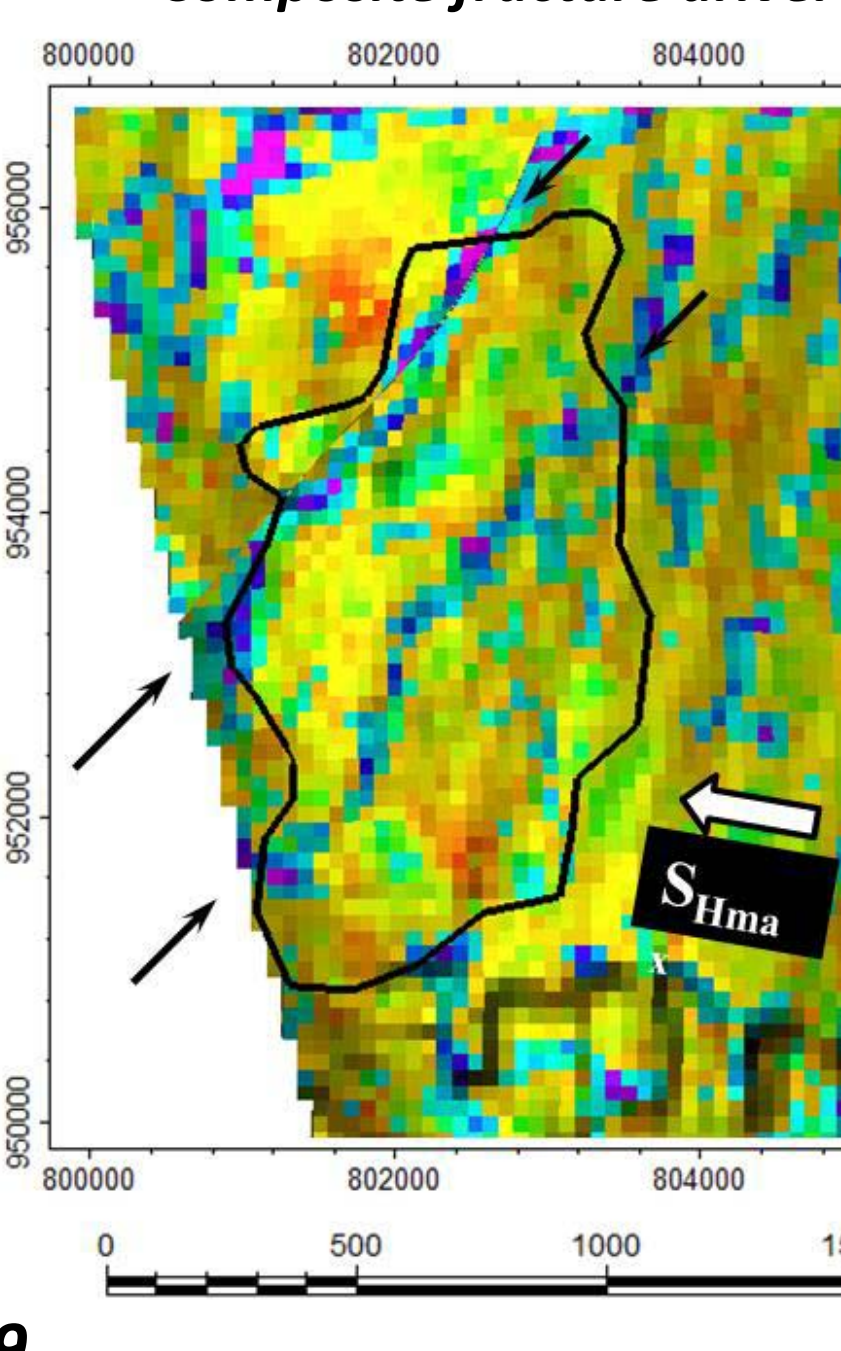
7B.

Surface probe (Tensleep top) shows color blend of discontinuities (whites & grays) and directional curvature (reds & blues)



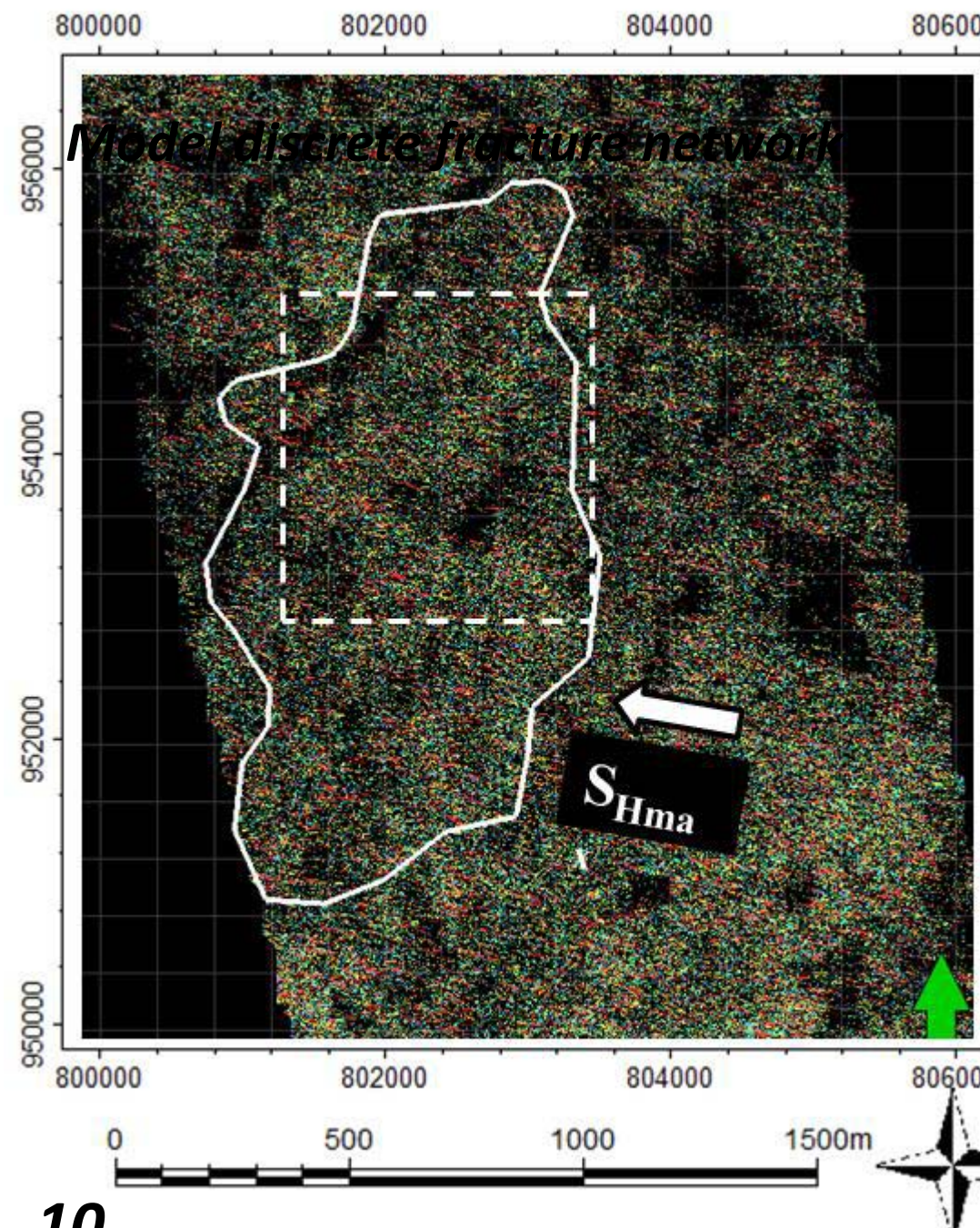
8.

Composite fracture driver



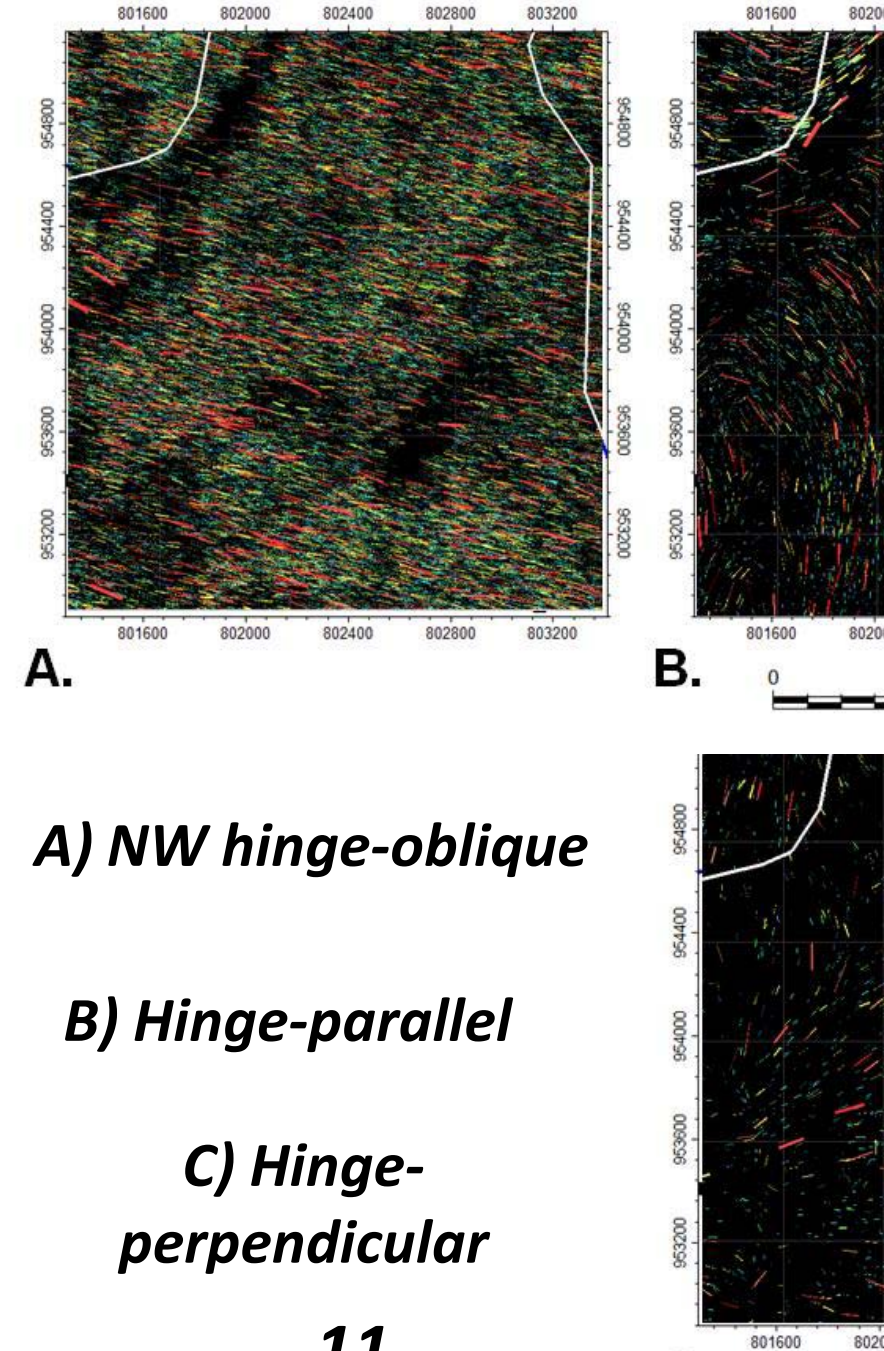
9.

Fracture sets in the DFN



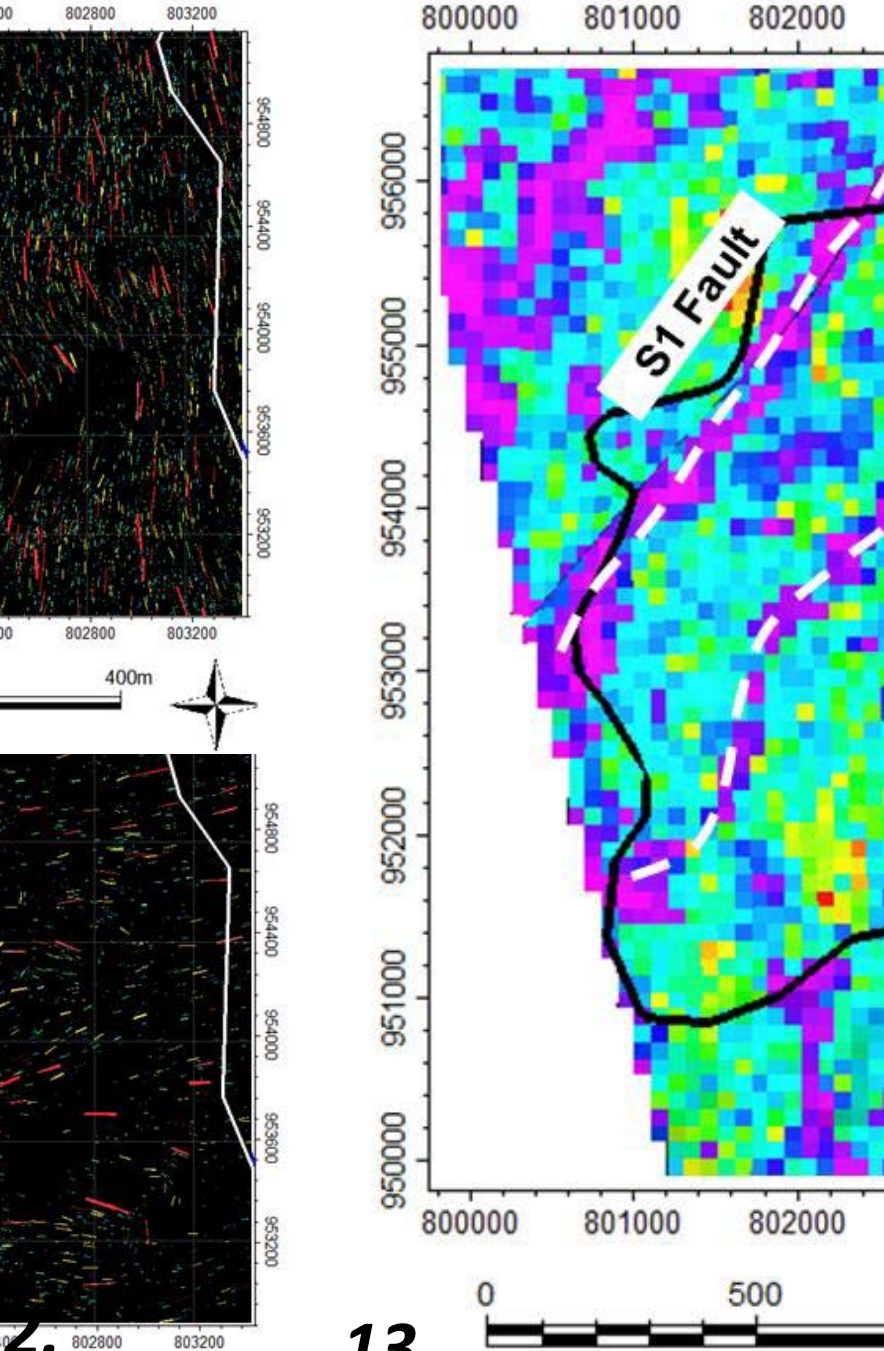
10.

Grid cell porosity distribution



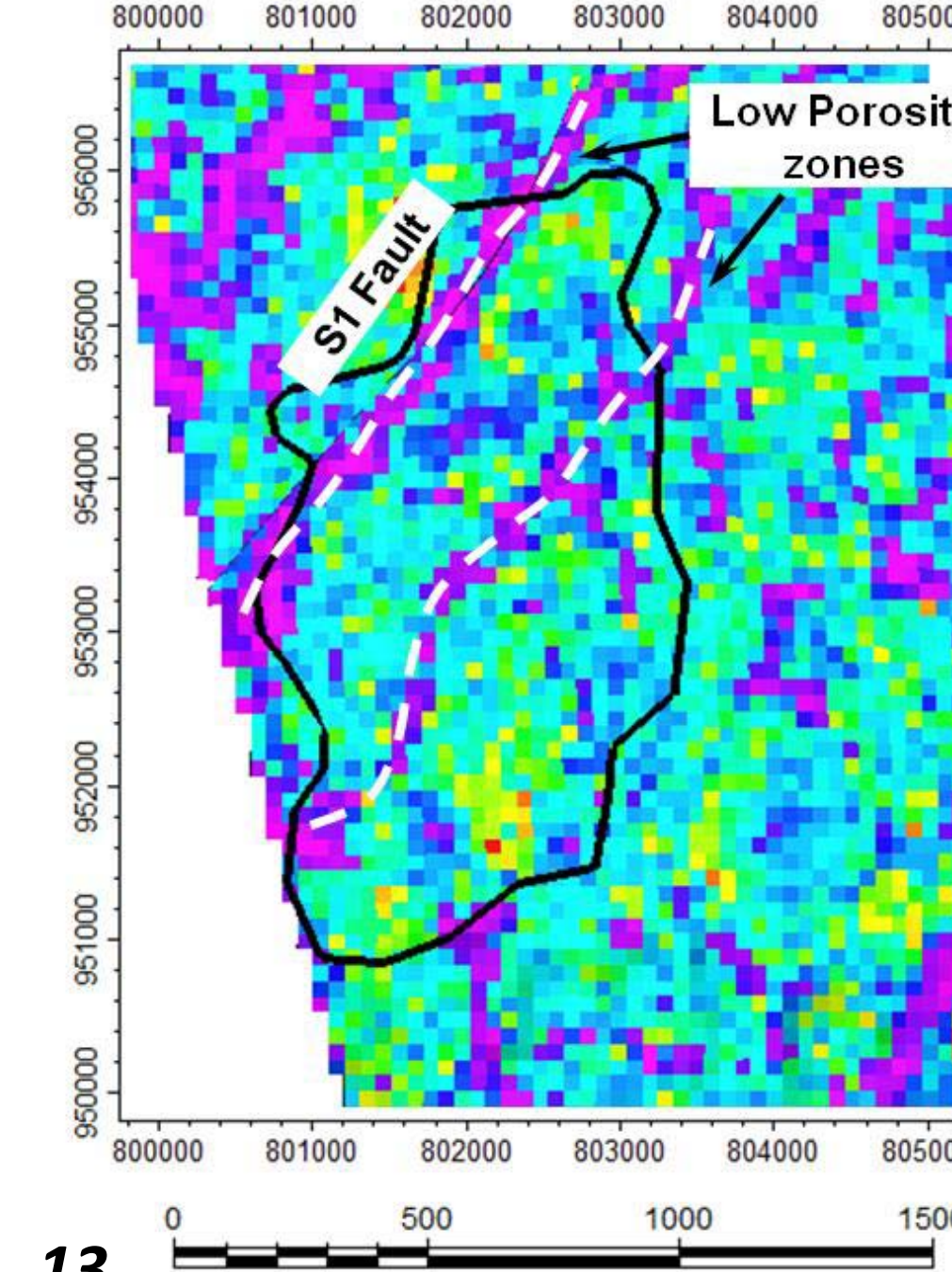
11.

Low Porosity zones



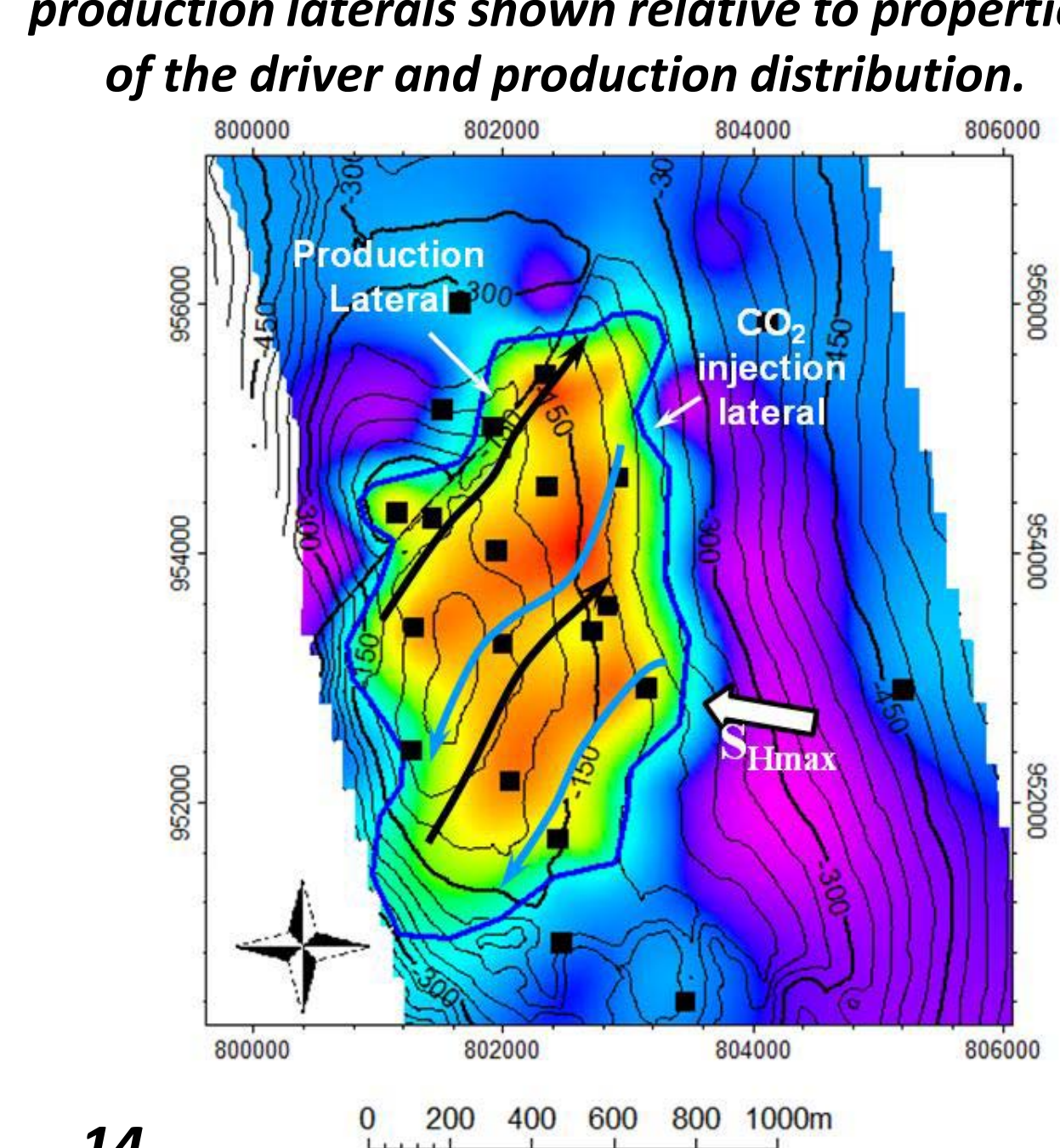
12.

Suggested arrangement of CO2 injection and production laterals shown relative to properties of the driver and production distribution.



13.

Production Lateral



14.

Table 1: Fracture parameter distributions and relative intensities used to generate the model DFN.

Fracture Set	Strike	Length distribution	Height distribution	Aperture distribution	Intensity (relative)
Hinge Oblique	N76W	Power-law	Power-law	Log-normal	1
Hinge-parallel	Orientation parallel to strike of local structure	Power-law	Power-law	Log-normal	0.16
Hinge-perpendicular	Orientation perpendicular to strike of local structure	Power-law	Power-law	Log-normal	0.04

Table 2: Distribution parameters for length, height and aperture applied to all sets.

Length distribution	Height distribution	Aperture range
Power = -2	Estimated from lengths using aspect ratio of 0.33	Mean log aperture (mm) of -1.81
Minimum length of 5m	Minimum height of 1.7m	Standard deviation log aperture (mm) of 0.59
Maximum length limited to 150m	Maximum length limited to 51m	Range 2.1x10 ⁻⁵ mm to 0.3048mm

References

Gilbertson, 2006, 3D geologic modeling and fracture interpretation of the Tensleep Sandstone, Alcova anticline, Wyoming; M. S. Thesis, Colorado School of Mines, 265p.
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Also see -
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Acknowledgements

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