Regional Tectonics and Their Thermal Influence on Sedimentary Basins: Denver Basin

BROKAW, CASEY P., Graduate Student (Geophysics), Southern Methodist University, Roy M. Huffington Department of Earth Sciences

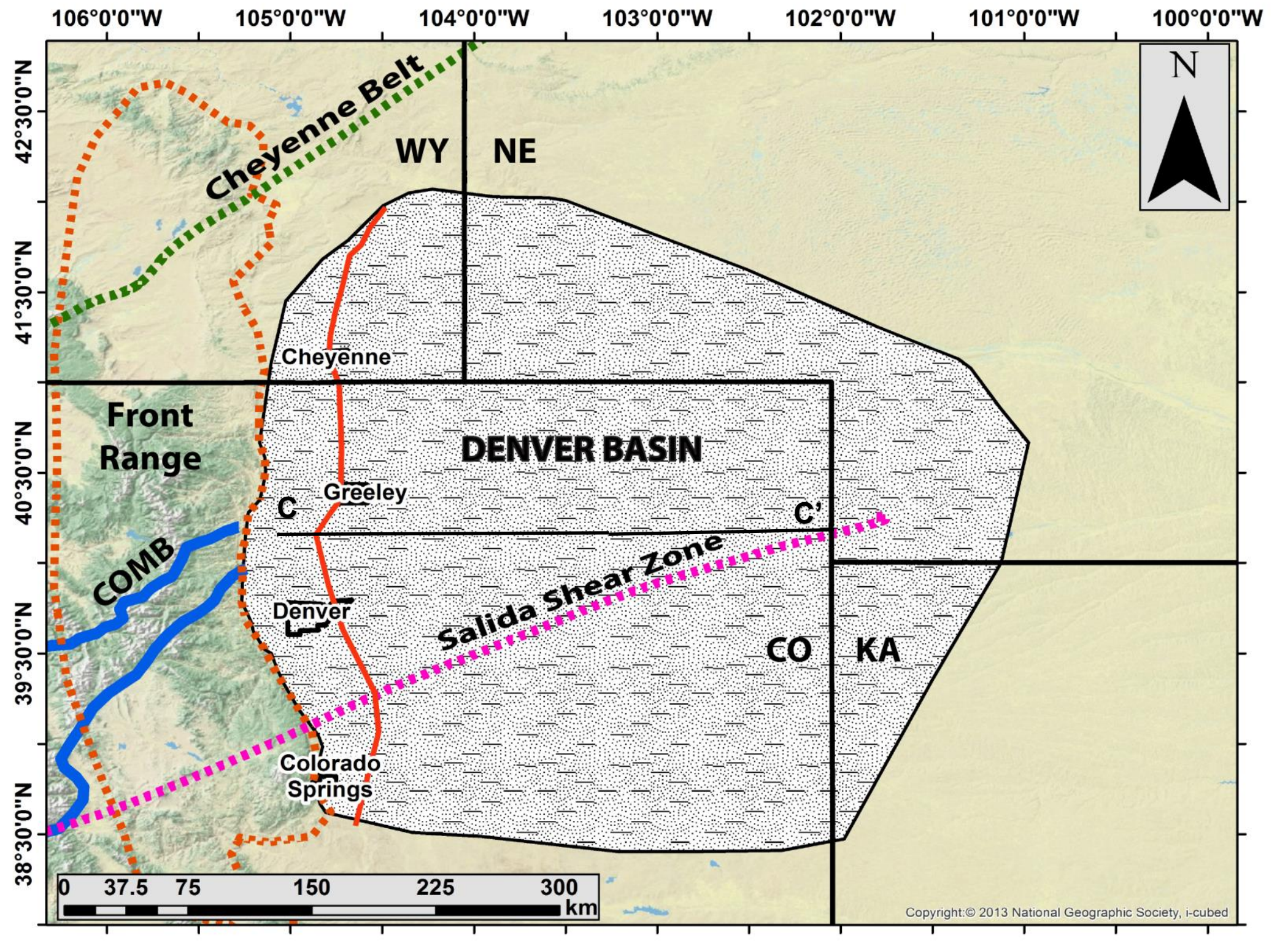
Purpose

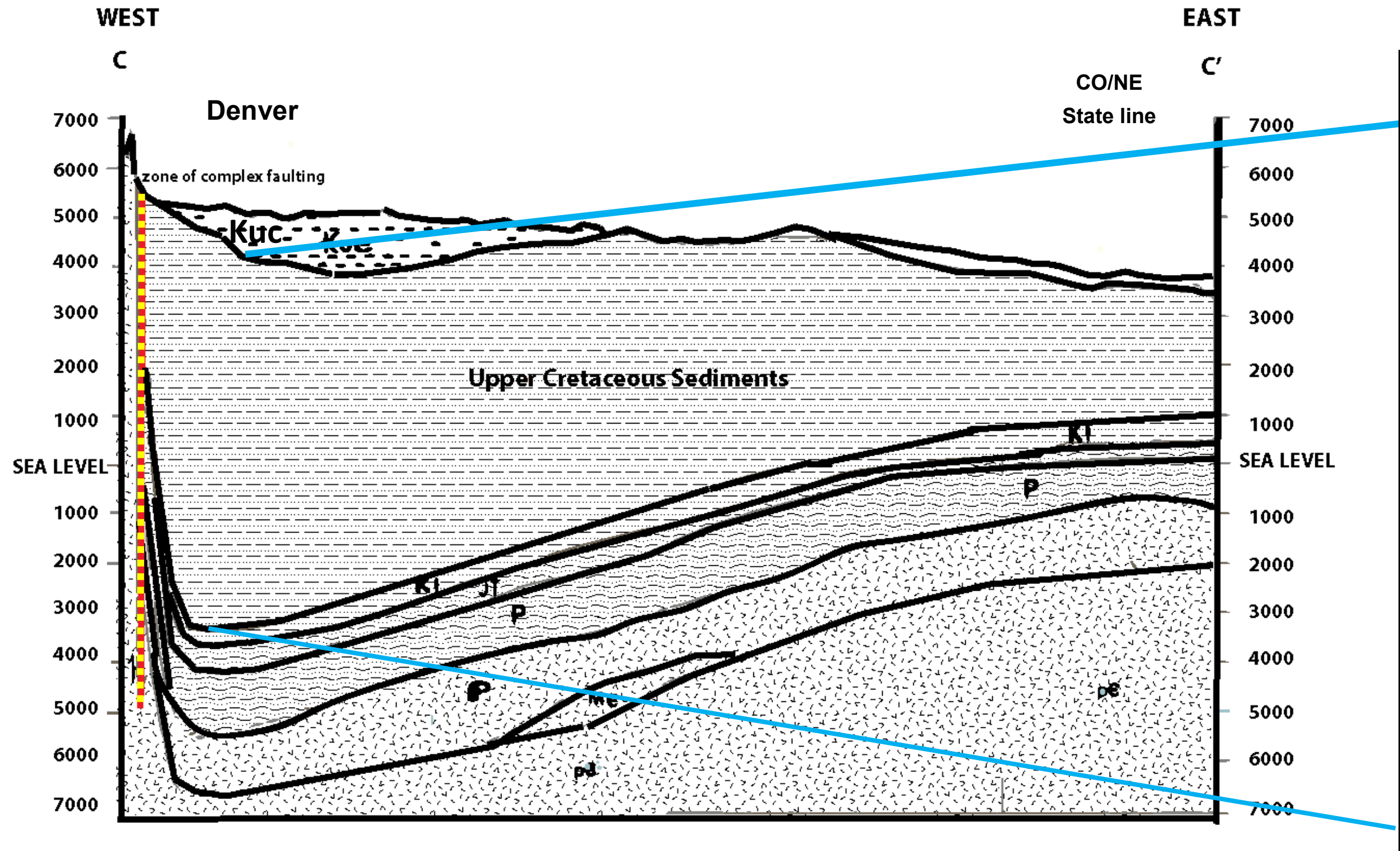
The purpose of this project is to analyze the heat flow regime within the sedimentary Denver Basin and assess its variability. Thermal conductivity measurements were made on Cretaceous sedimentary core samples provided by Anadarko Petroleum Corp. and the United States Geological Survey Core Research Center (USGS CRC). Measured thermal conductivity values were used to calibrate and constrain heat flow within the basin. Two equilibrium logs along with the newly measured thermal conductivity were used to calculate site specific heat flow. These new data points help constrain the observed variation in heat flow along the basin's western syncline. Methods for the analytics of causation of basin thermal variability will follow outlines similar to those of Blackwell & Steele, 1989 (see Table 1 for thermal effects).

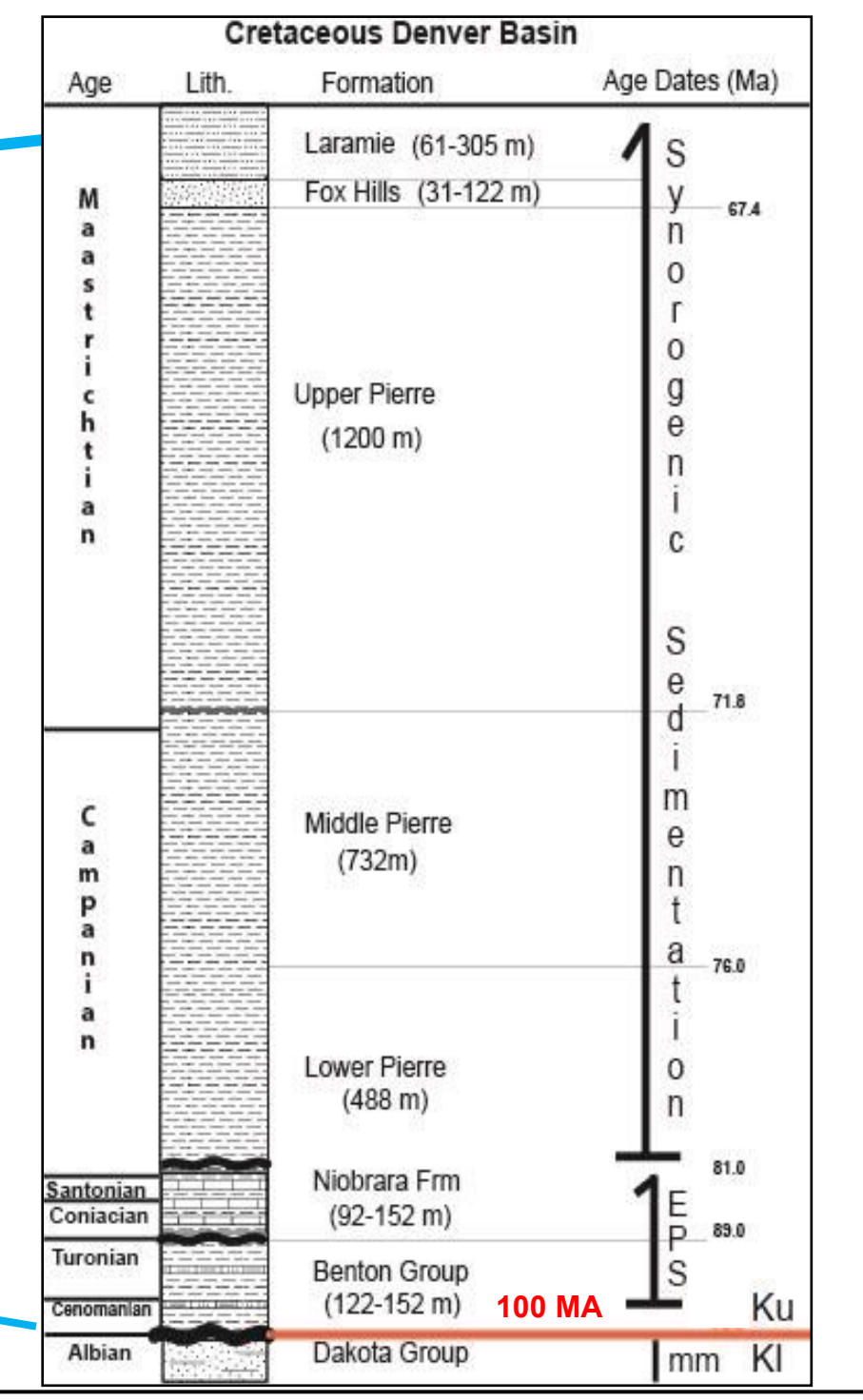
Description/Event	Scale of Effect
Initial thermal event (e.g. rifting)	10-20%
Transient external thermal event (climate)	5-10%
Radioactive heat production (U, Th, K)	20-50%
Fluid flow	50-100%
Thermal properties of sediments	50-100%
Internal thermal events (e.g. magmatic intrusion)	**Very Large**

Table 1. From Blackwell and Steele's study Thermal Conductivity of Sedimentary Rocks: Measurement and Significance. It Illustrates the variables and their scale of effect that can effect the thermal regimes within sedimentary basins.

Study Area





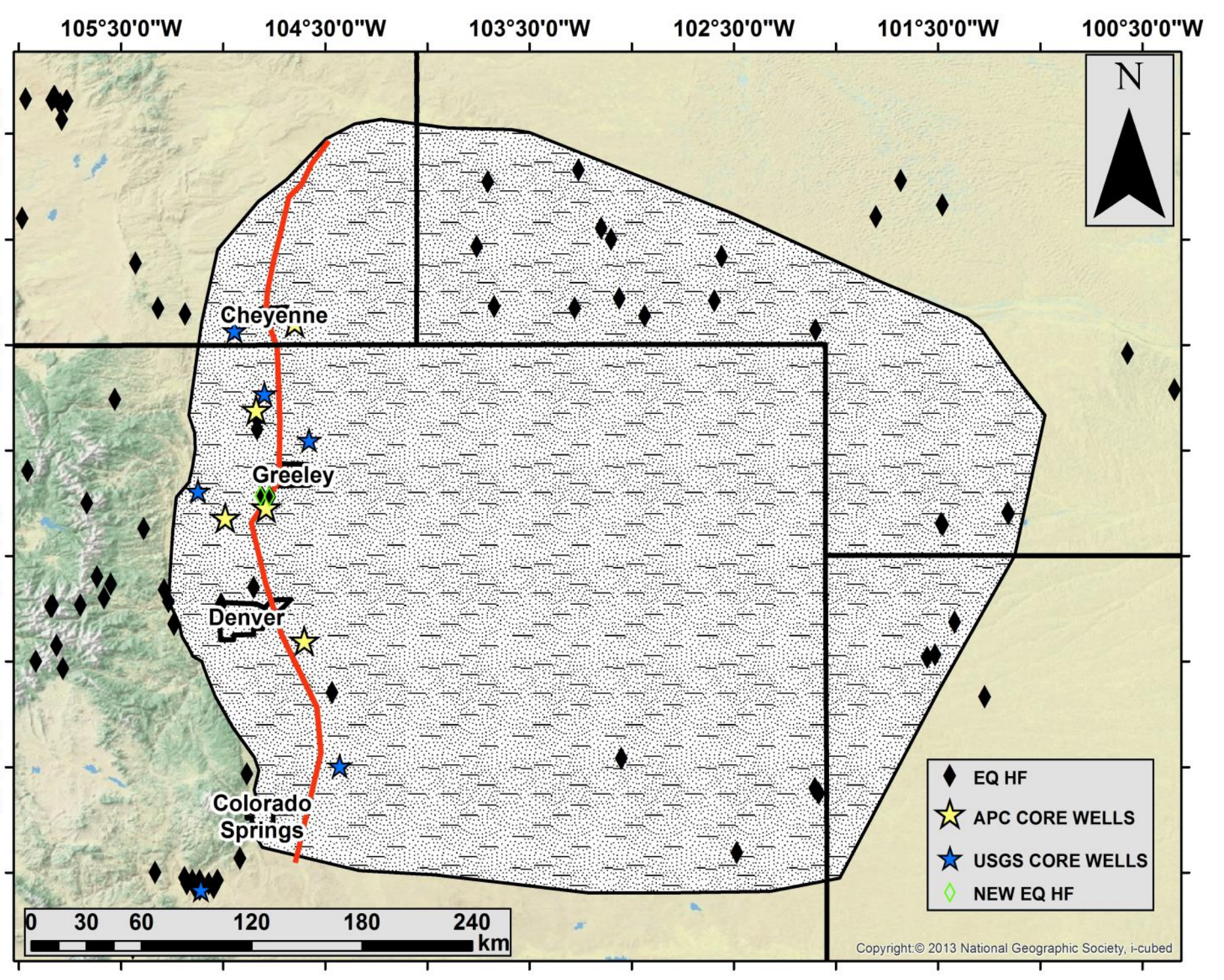


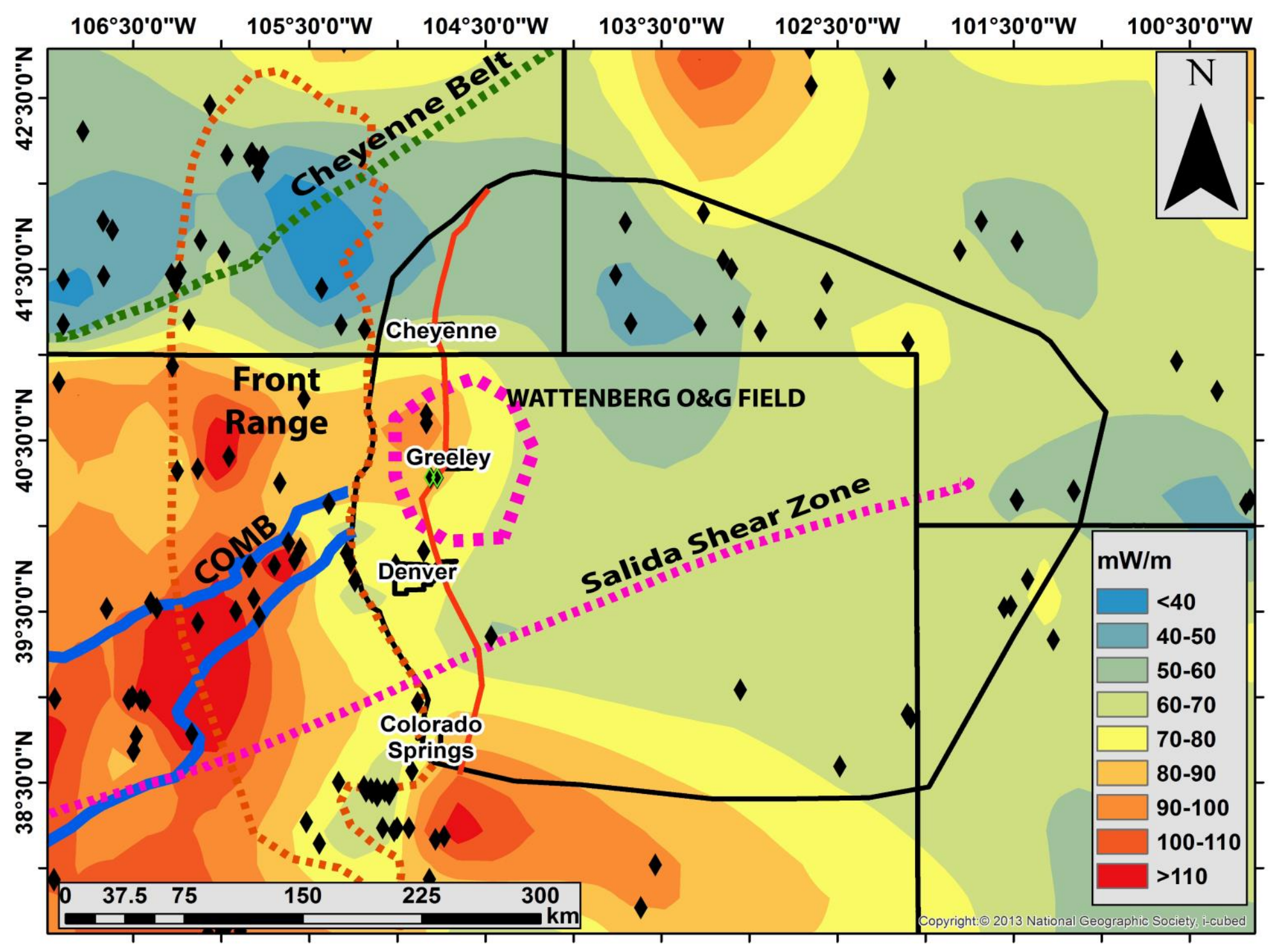
- The **Denver Basin** spans portions of Colorado, Wyoming, Nebraska, and Kansas. Structurally, a foreland basin that was subjected to massive amounts of deformation and sedimentation during the Laramide Orogeny (Kauffman, 1977).
- Pre Laramide sedimentation was the result of the Western interior Seaway that inundated the basin from the Albian to Maastrichtian, with a highstand occurring during the Turonian (~90 MA) with paleo sea levels more than 250 meters above present (Kauffman, 1977), (see stratigraphic column to right).
- The basin sits atop old Precambrian shear zones (**Cheyenne Belt, Salida Shear Zone)** that generally strike to the northeast, and are thought to be the conduit of the Cenozoic emplacement of dikes and sills, which are referred to as the Colorado Mineral Belt (**COMB)** (Tweto et al., 1963).
- **Cheyenne Belt, Salida Shear Zone outline from Karlstrom et al., 2005**

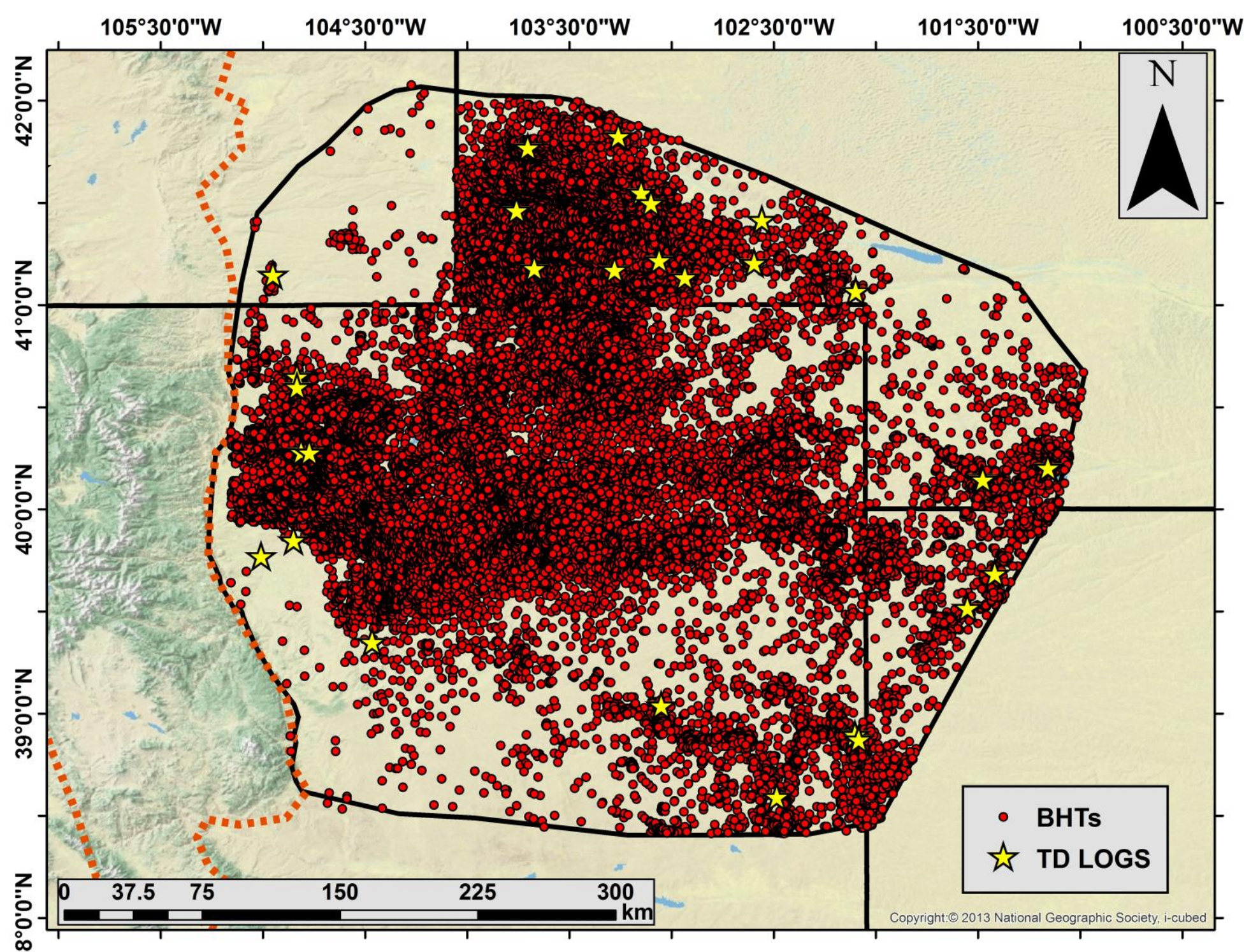
- Structure profile of line C to C' (figure left) showing foreland thickening of sediments from east to west, (modified from Robson & Banta, 1987).
- The Pierre Shale (Upper Cretaceous) as seen in the stratigraphic column (figure right) is by far the thickest formation within the basin, and in turn exerts the most thermal control on the basin thermal regime related to the basin sediment thermal properties, which have a Scale of Effect of 50-100% (table 1).

- Stratigraphic column of Cretaceous sediments along the western syncline, modified from Weimer et al., 1986.
- Radiometric age dates (far right) from Obradovich et al., 1993.
- Onset of synorogenic sedimentation derived from DeCelles, 2004.
- **EPS**: Epeiric shelf sedimentation, Western Interior Seaway (WIS) associated sediments
- **mm:** Marginal/variable marine sedimentation (e.g. near shore, shore, deltaic front).

Regional Heat Flow & Well Locations







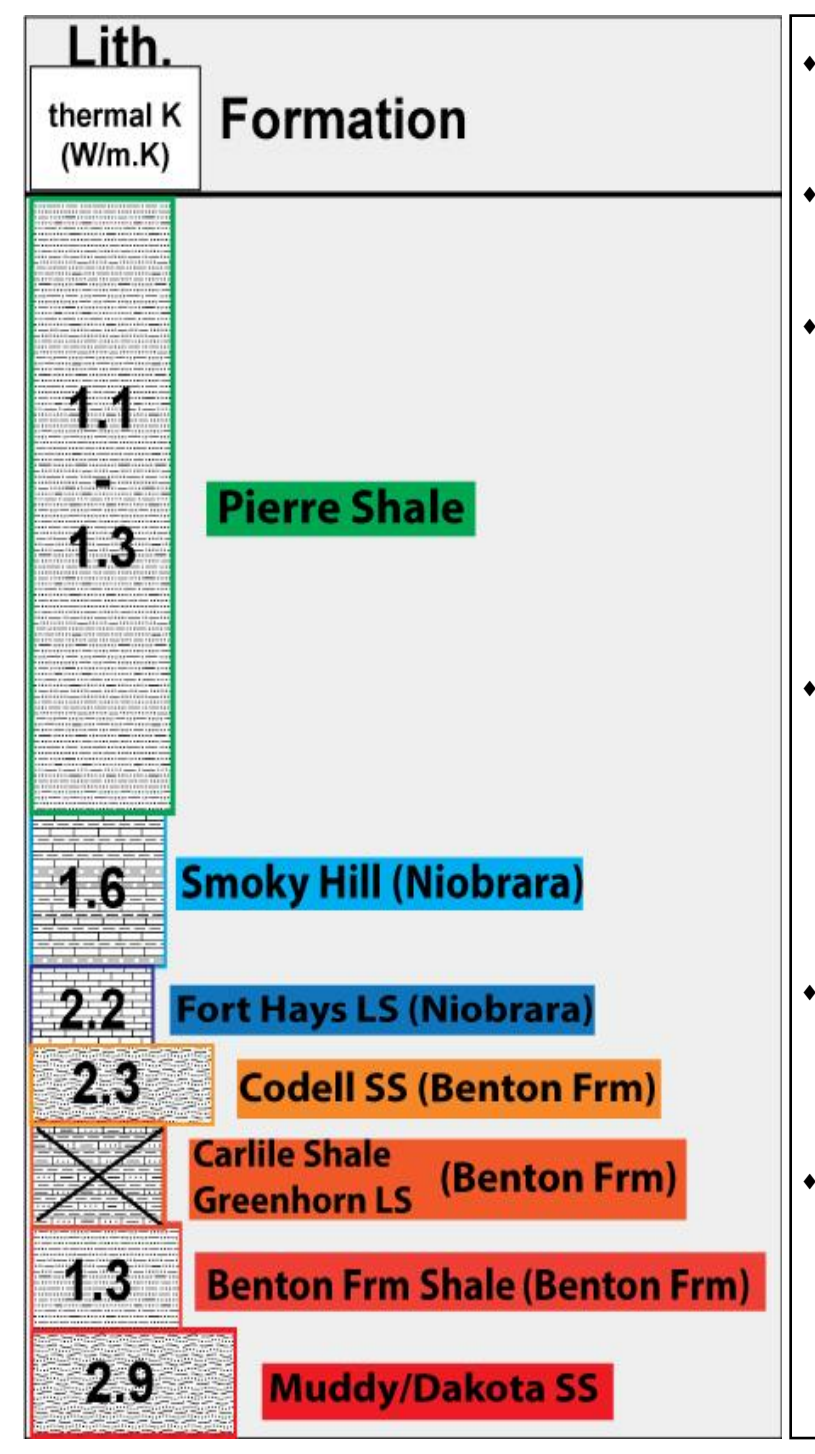
- Equilibrium heat flow data points were gathered from the National Geothermal Database and Geothermal Map of North America (Blackwell and Richards, 2004)
- Core samples from Anadarko Petroleum Corporation and the USGS CRC were provided to calculate and catalog thermal conductivities for Cretaceous sediments

- Regional heat flow interpolation map between equilibrium heat flow points. A natural neighbor interpolation model was used to assess variations in heat flow.
- Two new data points were calculated from thermal conductivity values measured for this study and were added to existing EQ HF Points

- Denver Basin bottom hole temperatures (BHTs) were extracted from the National Geothermal Database
- BHTs were compared to existing equilibrium temperature at depth logs to assess their validity in predicting temperature at depth.

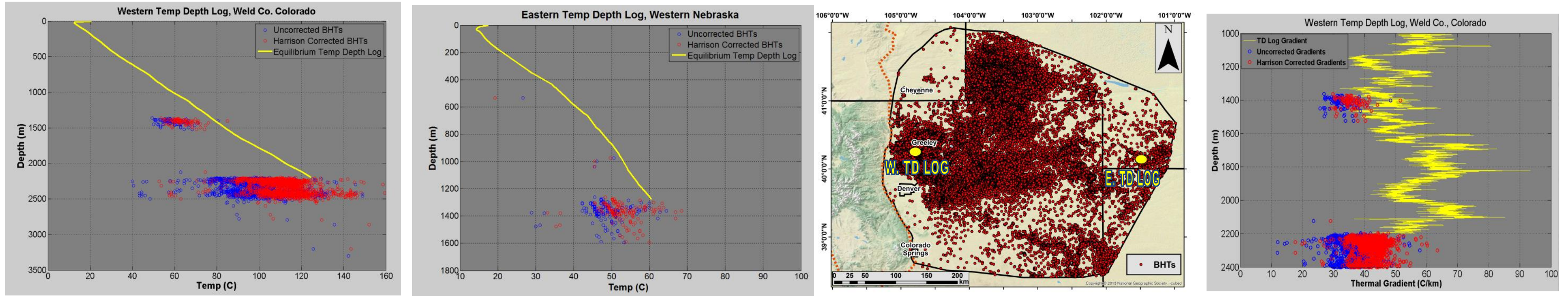
Observations & Analysis

Thermal Conductivity of Basin Sediments



- Average thermal conductivity values by formation.
- Formations are scaled for thickness and grain size.
- Thermal conductivity measurements were made on core samples utilizing the divided bar apparatus and methods outlined by Blackwell & Spafford, 1987.
- Generally sediments showed a decrease in thermal conductivity value with an increase in shale/clay content.
- Core samples were provided by Anadarko Petroleum Corp. and the USGS CRC.
- Thermal K values are corrected for in-situ wellbore temps by correction provided by Sekiguchi, 1984.

Bottom Hole Temperature Data



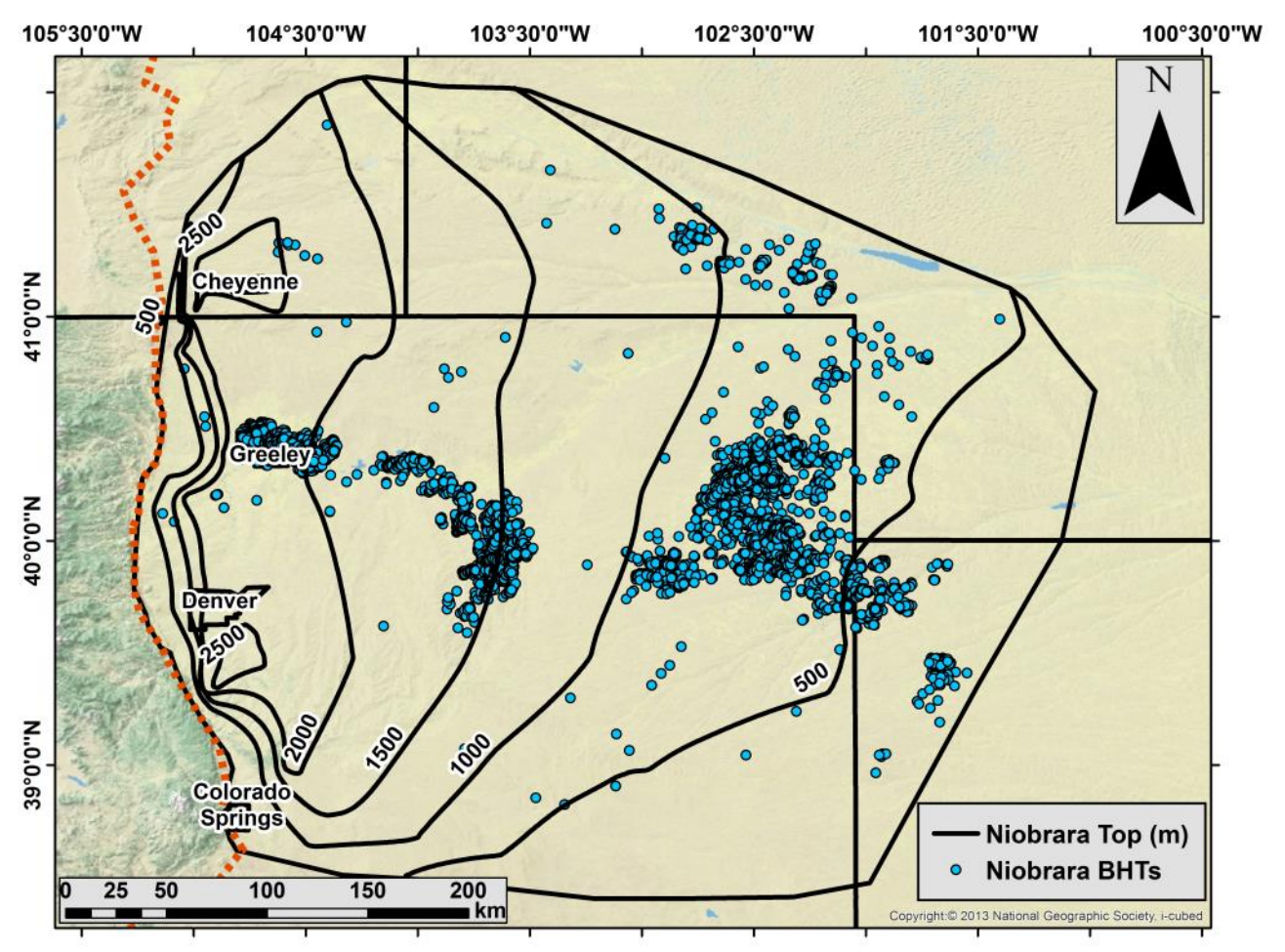
- Uncorrected BHTS were extracted utilizing a spatial extraction (10 km radius from Eq. log well site) based on the sedimentary formations they were measured within.
- BHTs were then corrected for temperature at depth utilizing the Harrison Correction:

$$T = -16.5 + 0.018 * depth - 2.35 * 10^{-6} * depth^2$$

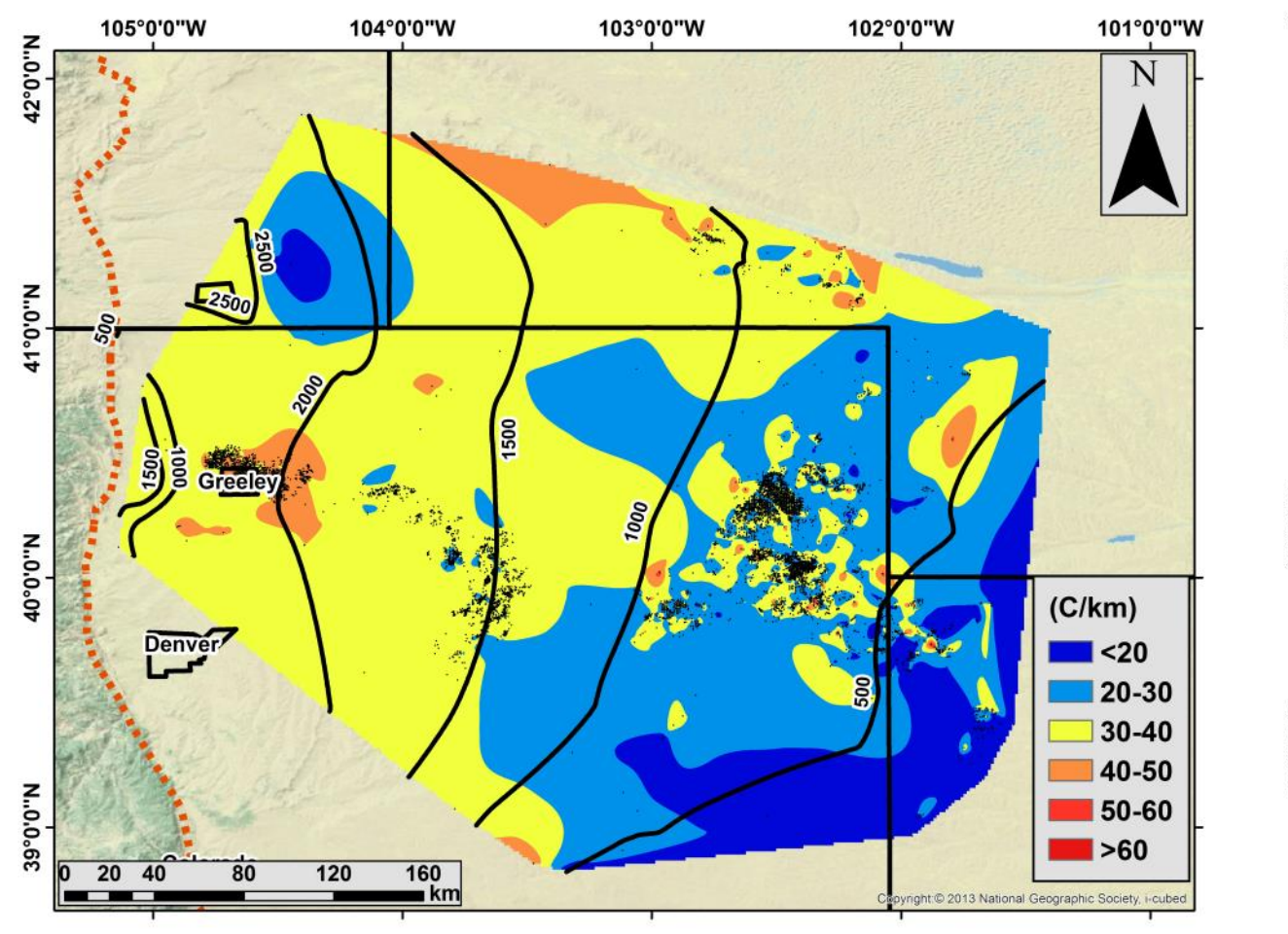
(Harrison et al., 1983)

- Formation tops were derived from oil and gas petrophysical logs throughout the basin.
- The BHTs are then measured for geothermal gradient based upon average annual surface temp. derived from NOAA and the corrected BHT.
- The Harrison corrected BHTs still appear to be colder than in-situ temperature at depth. Validation by more equilibrium well sites is needed.
- Future work will determine a more accurate BHT temperature at depth for portions of the DB based upon proximal equilibrium temp logs.

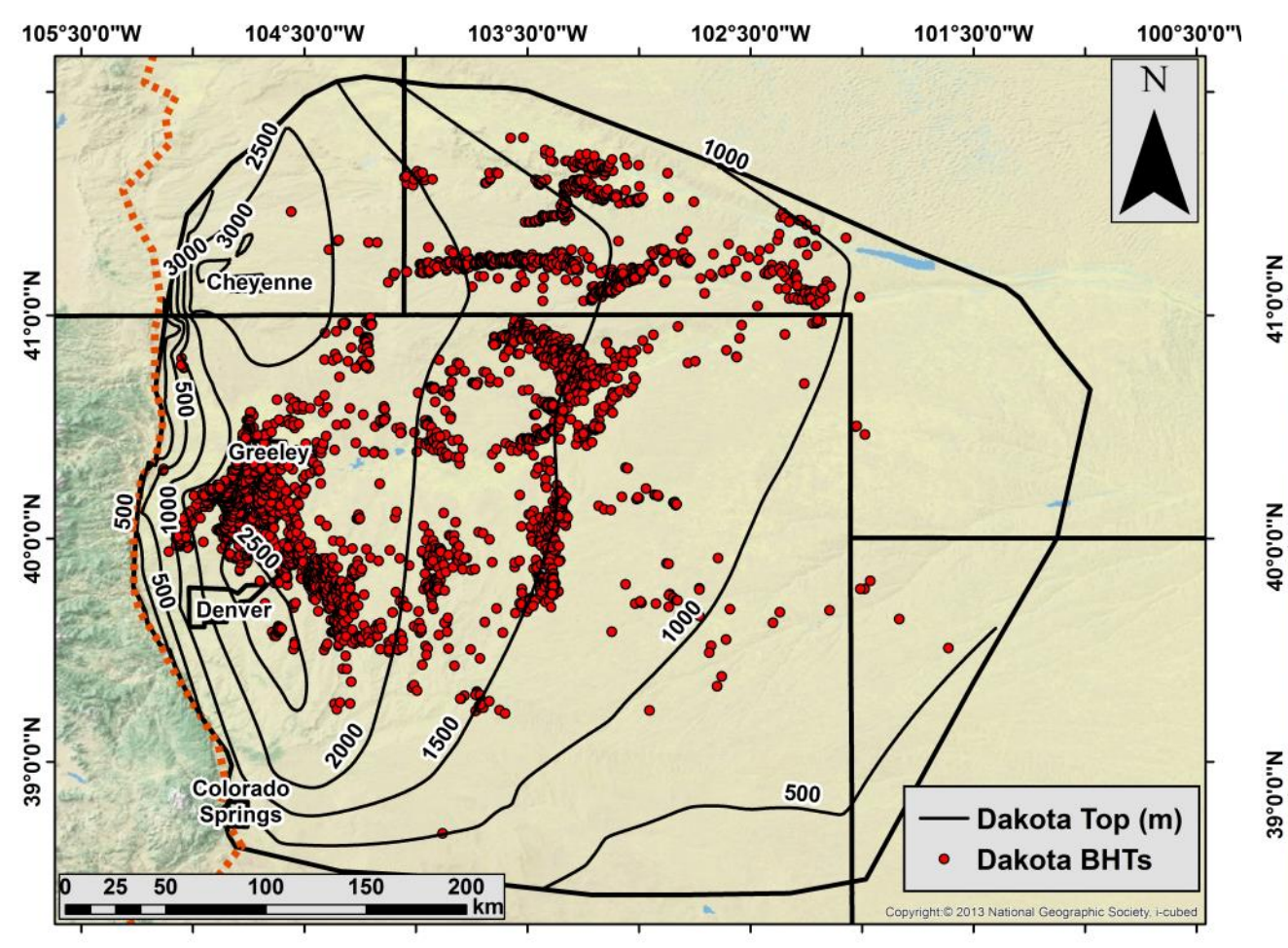
Corrected Niobrara BHTs



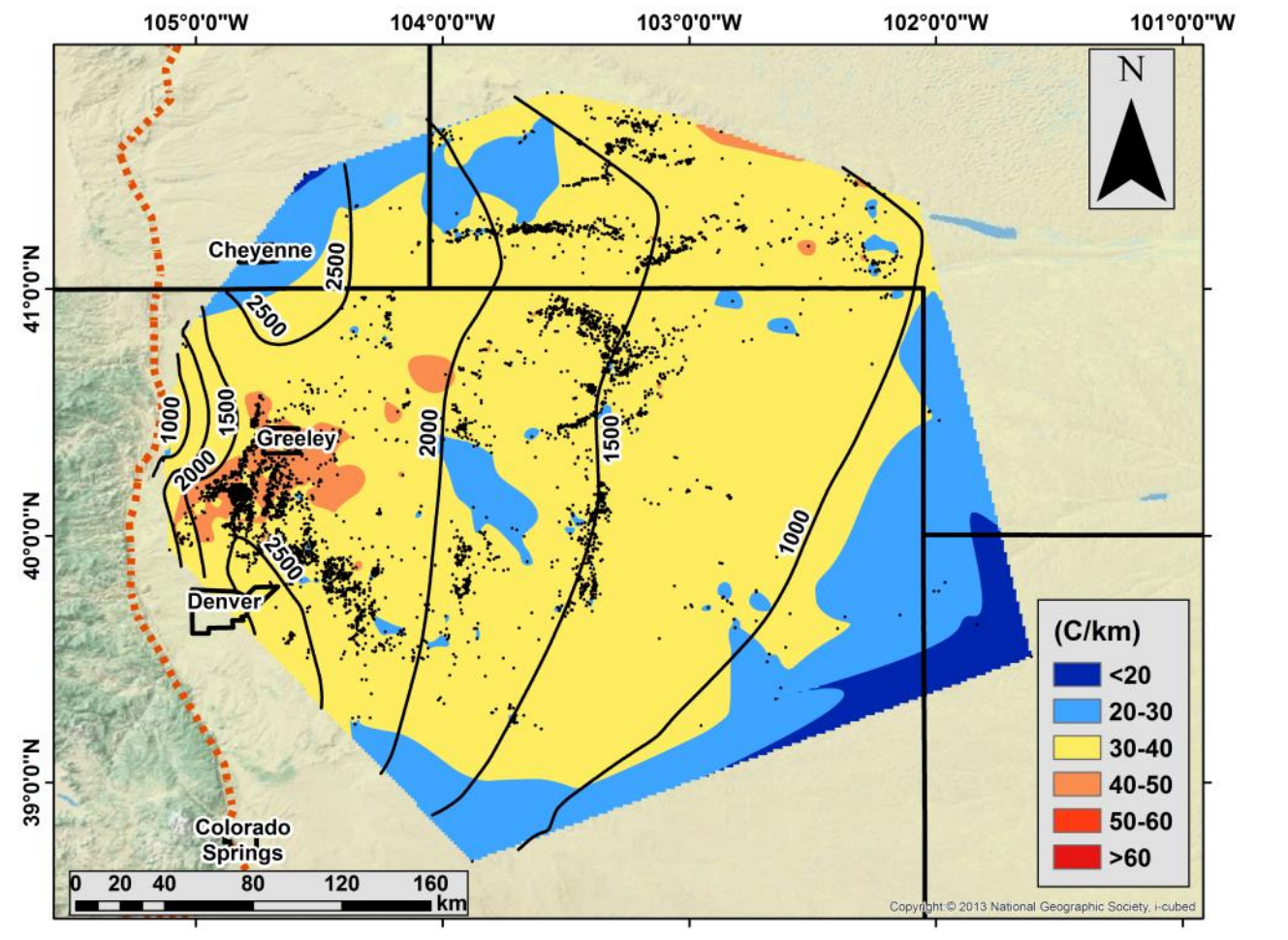
Corrected Niobrara Gradients



Corrected Dakota SS BHTs



Corrected Dakota Gradients

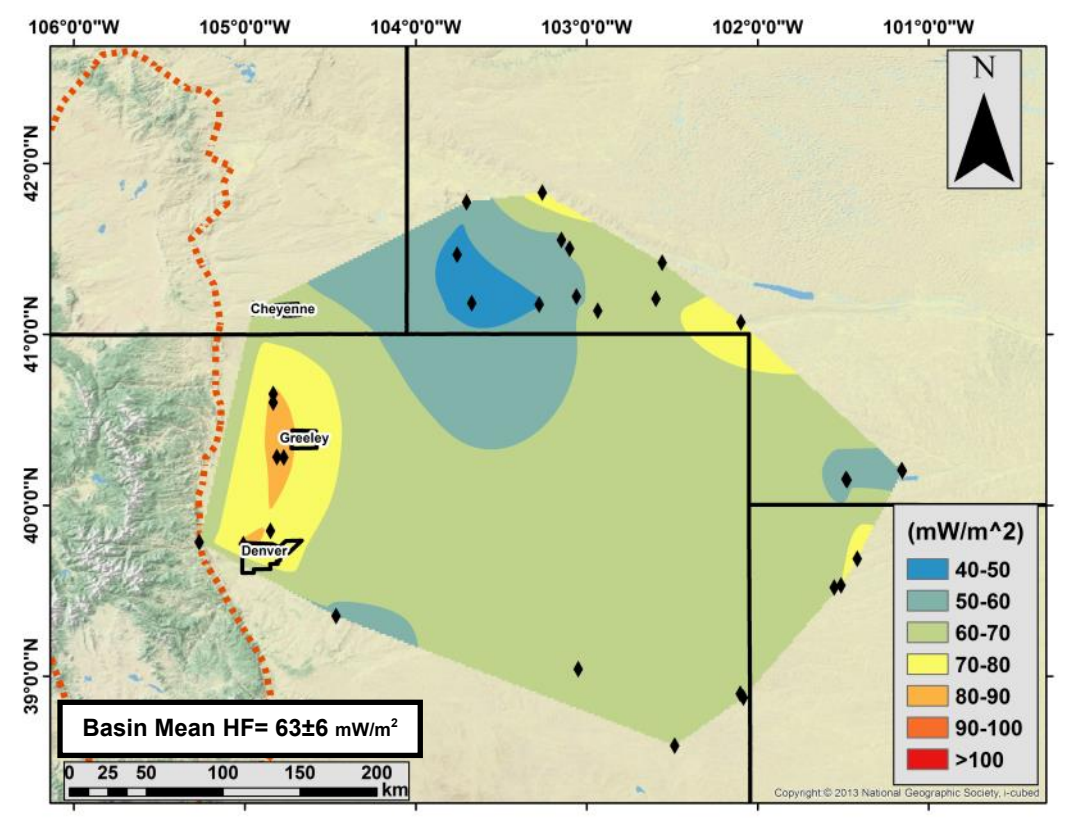


- Harrison corrected BHTs were extracted by their measurement based on formation top picks of sedimentary formations.
- The BHTs were then calculated for their geothermal gradient based upon the mean annual surface temperature from NOAA and their corrected temperature along with measurement depth:

$$Thermal\ Gradient = \left(\frac{measurement\ temp - mean\ annual\ surface\ temp}{measurement\ depth}\right)$$

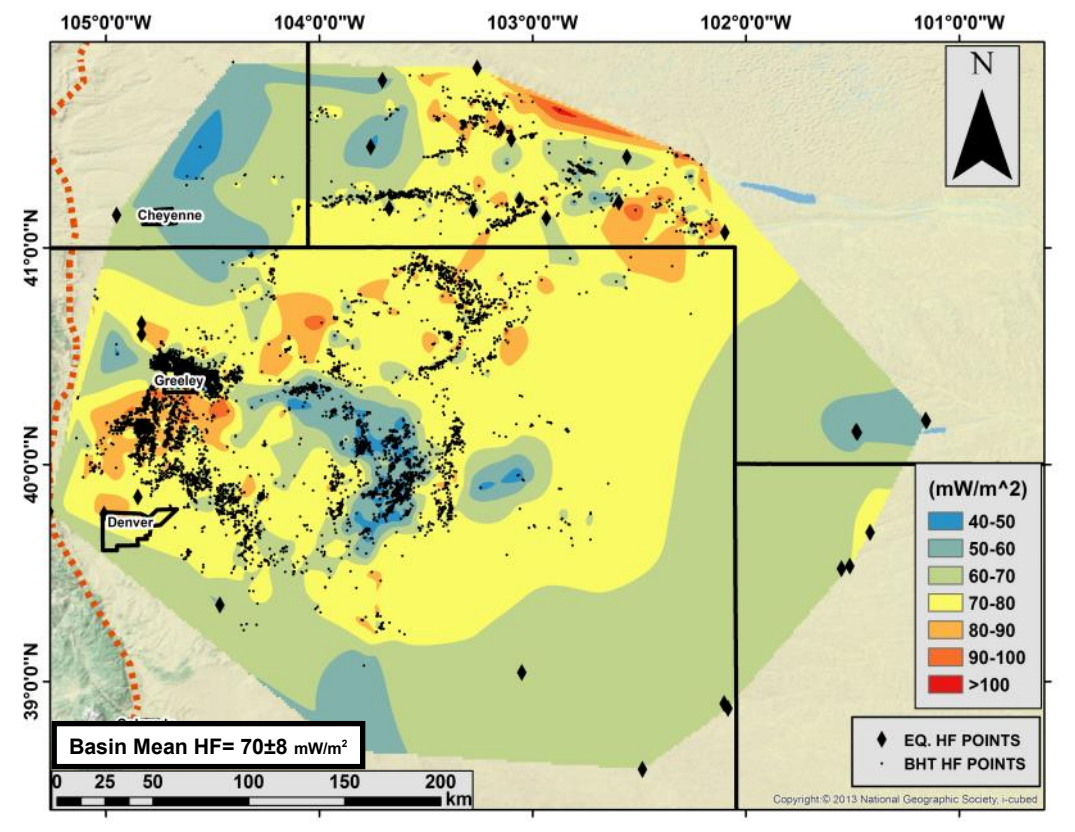
- These points were then calculated for heat flow based upon their corrected thermal gradient and the measured thermal conductivity of the formations in which the wells penetrate

Equilibrium Heat Flow



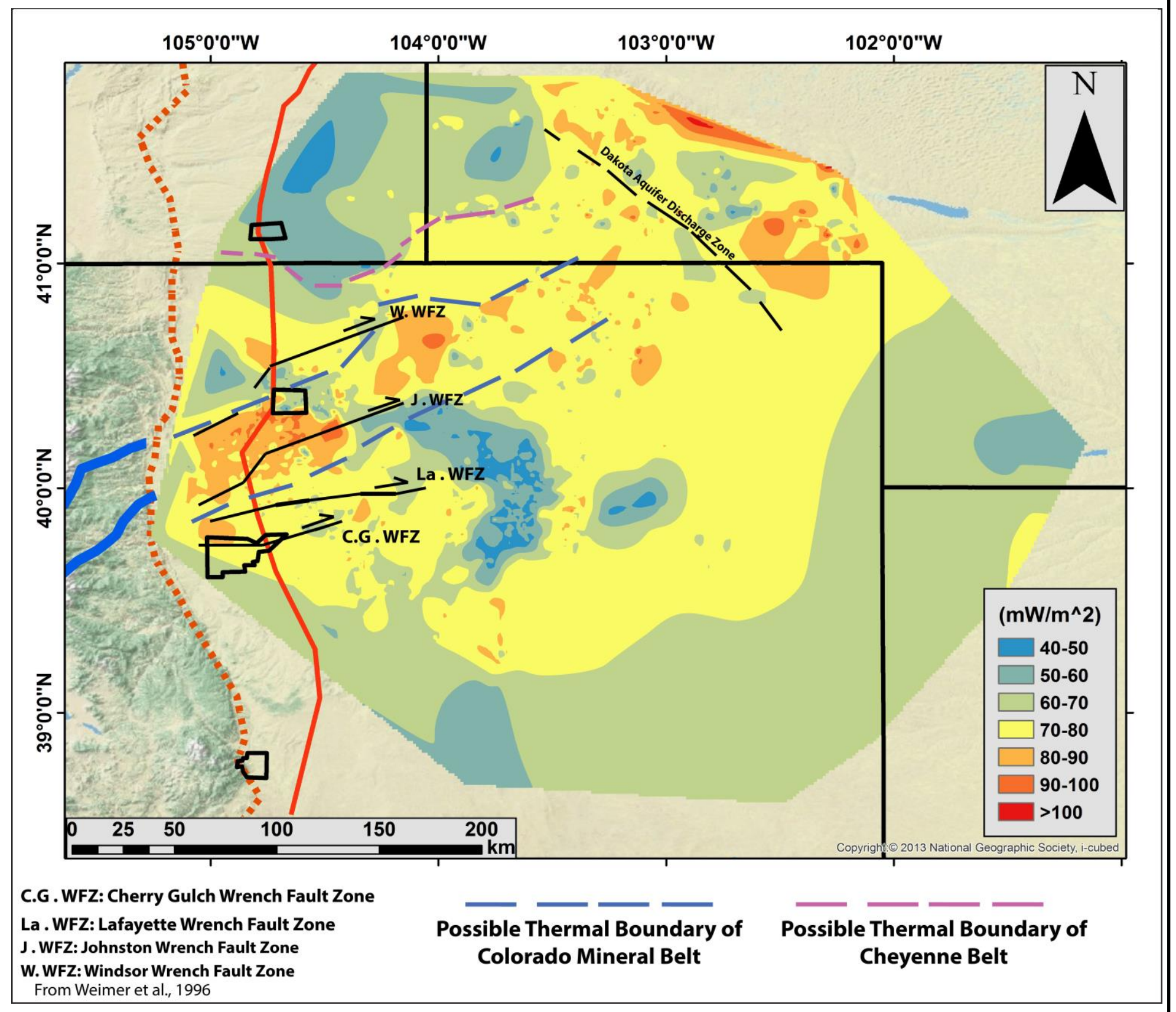
- Natural neighbor interpolation of equilibrium heat data points (Geothermal Map N.A., 2004) within the Denver Basin.
- Model performed on ArcGIS
- Lack of data within the central portion of the basin makes interpreting thermal trends in the basin spurious at best.

Eq. Heat Flow + Corrected BHT Heat Flow



- Natural neighbor interpolation model of the merged equilibrium heat flow data plus the heat flow calibrated BHT data points.
- Model performed on ArcGIS
- By utilizing heat flow it allows a basin-wide normalization of gradient and thermal conductivity; allowing a more in depth look at basin thermal trends.

Discussion



C.G . WFZ: Cherry Gulch Wrench Fault Zone
La . WFZ: Lafayette Wrench Fault Zone
J . WFZ: Johnston Wrench Fault Zone
W. WFZ: Windsor Wrench Fault Zone
From Weimer et al., 1996

- Transecting the basin syncline is a thermal hotspot zone that appears to be related to basement emplacement of the Colorado Mineral Belt, which would have added sub-basinal magmas and highly conductive metals during the Late Cretaceous to Middle Cenozoic (~70-40 Ma).
- Basinal wrench faults also orientated in a northeast trend (activated during the Laramide Orogeny, Weimer et al., 1996) seem to be the transport mechanism for the heat generated by the emplacement and cooling of the COMB.
- Due to its NE transection of the syncline, and its mean of 85 mW/m^2 the COMB induced hotspot can not be explained just from sediment thickness variability (Fig above, areas near Cheyenne and Denver are the thickest portions of the Foreland, which should increase thermal gradient). Shale thickness along syncline is ± ~ 500 m. Sedimentary Formations are generally consistent in thickness within the rest of the basin.
- SE trending zone of elevated heat flow in W. Nebraska is thought to be related to advective transport of heat from upward moving Dakota SS Aquifer zone modeled by Gosnold, 1985.
- Cheyenne Belt is the boundary zone separating the older & thicker Archean Cratonic Crust in Wyoming and the younger & thinner Proterozoic Crust to the south. The thicker crustal root of the Archean is generally thought to be the cause of heat flow changes N/S of this trend, see Birch, 1950.

Acknowledgements

Many thanks are owed to Anadarko Petroleum Corporation, namely Peter Kubik and Keith Mahon for suggesting , funding, acknowledging the importance of this project and providing help along the way. Much thanks is also owed to Matt Hornbach, Maria Richards, David Blackwell, as well as the whole SMU Geothermal Lab team for their advisement and constant help/feedback. Thanks is also owed to the staff at the United States Geological Survey Core Research Facility for maintaining and helping with core samples in their vast library of publicly available core samples.

References

Birch, F. (1950). Flow of heat in the Front Range, Colorado. *Geological Society of America Bulletin*, *61*(6), 567-630.

Bird, P. (1984). Laramide crustal thickening event in the Rocky Mountain foreland and Great Plains. *Tectonics*, *3*(7), 741-758.

Blackwell, D. D., & Steele, J. L. (1989). Thermal conductivity of sedimentary rocks: measurement and significance. In *Thermal history of sedimentary basins* (pp. 13-36). Springer New York.

Blackwell, D. D., & Richards, M. (2004, June). Calibration of the AAPG geothermal survey of North America BHT data base. In *AAPG Annual Meeting, Dallas, TX, paper* (Vol. 87616, p. 2004).

Blackwell, D., & Richards, M. C. (2004). The 2004 geothermal map of North America, explanation of resources and applications. *Geothermal Resource Council Transactions*, *28*, 317-320.

Blackwell, D. D., & Spafford, R. E. (1987). 14. Experimental Methods in Continental Heat Flow. *Methods of experimental physics*, *24*, 189-226.

DeCelles, P. G. (2004). Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA. *American Journal of Science*, *304*(2), 105-168.

Gosnold, W. D. (1985). Heat flow and ground water flow in the Great Plains of the United States. *Journal of Geodynamics*, *4*(1-4), 247-264

Harrison, WE., Luza, KV., Prater, M.L., and Cheung, PK., (1983). Geothermal resource assessment in Oklahoma, Oklahoma Geological Survey Special Publication SP 83-1, 42 p.

Haq, B. U., Hardenbol, J., & Vail, P. R. (1987). Chronology of fluctuating sea levels since the Triassic. *Science*, *235*(4793), 1156-1167.

Karlstrom, K. E., Whitmeyer, S. J., Dueker, K., Williams, M. L., Bowring, S. A., Levander, A. R., ... & CD□ROM Working Group. (2005). Synthesis of Results from the Cd□Rom Experiment: 4□D Image of the Lithosphere Beneath the Rocky Mountains and Implications for Understanding the Evolution of Continental Lithosphere. *The Rocky Mountain Region: An Evolving Lithosphere Tectonics, Geochemistry, and Geophysics*, 421-441.

Kauffman, E. G. (1977). Geological and biological overview: Western Interior Cretaceous basin. *The Mountain Geologist*.

Obradovich, J., 1993. A Cretaceous time scale, in: Caldwell, W.G.E., Kauffman, E.G., (Eds.), Evolution of the Western Interior Basin. Spec. Pap.-Geol. Assoc. Can. 39, 379–396.

Robson, S. G., & Banta, E. R. (1987). *Geology and hydrology of the deep bedrock aquifers in eastern Colorado* (No. 85-4240).

Tweto, O., & Sims, P. K. (1963). Precambrian ancestry of the Colorado mineral belt. *Geological Society of America Bulletin*, *74*(8), 991-1014.

Weimer, R. J., & Sonnenberg, S. A. (1996). *Guide to the Petroleum Geology and Laramide Orogeny, Denver Basin and Front Range, Colorado* (Vol. 51). Colorado Geological Survey, Department of Natural Resources.

Weimer, R. J., Sonnenberg, S. A., & Young, G. B. (1986). Wattenberg Field, Denver Basin, Colorado.