Timing of the Exhumation Episodes and Burial/Thermal History of Kevin Dome, Northwestern Montana*

Elijah O. Adeniyi[1,2], Colin A. Shaw[1,2], David W. Bowen[1,2], Chuck W. Calavan[1], and Mary S. Hubbard[1]

Search and Discovery Article #42571 (2021)**
Posted June 7, 2021

*Adapted from oral presentation accepted for the 2020 AAPG Annual Convention and Exhibition online meeting, September 29 – October 1, 2020
 DOI: 10.1306/42571Adeniyi2021.

[1]Department of Earth Sciences, Montana State University, Bozeman MT (adeniyi_1@yahoo.com)
[2]Energy Research Institute, Montana State University, Bozeman MT.

Abstract

Kevin Dome is a 320 km long structural culmination along the Sweetgrass Arch in northwestern Montana that produces both oil and gas and has trapped ≈ 85 billion cubic meter (bcm) of CO_2. The Late Devonian Duperow Formation CO_2 reservoir at Kevin Dome traps one of the largest known natural CO_2 resource in the northwestern United States. Despite the economic importance of Kevin Dome's CO_2 resource for Enhanced Oil Recovery (EOR) and Carbon Capture, Utilization and Storage (CCUS) potential in the region as well as hydrocarbon productions, the thermal evolution and exhumation history of the dome has not been constrained and the source and timing of the CO_2 emplacement is uncertain. Several tectonic and structural evolution models have been proposed for the initiation of the Sweetgrass Arch and subsequent development of Kevin Dome. These models were largely based on strata distribution, erosion or non-deposition but are now constrained with new cooling age histories of constituent formations. Here we present preliminary results of lowtemperature thermochronology ((U - Th)/He) analysis on apatite minerals recovered from drill cuttings in five (5) Kevin Dome historic wells. The pilot samples analyzed were selected from Precambrian basement, Three Forks, Bakken, Kootenai and Bow Island Formations at depths of 400-1430 m. The obtained cooling ages range from ≈ 68 to 10 Ma indicating that the dome cooled periodically and mainly during the Tertiary. This clearly show that all units sampled reached temperatures above 70°C (apatite closure T) implying about 3 km of uplift difference and overburden thickness have been removed due to this exhumation since the Late Cretaceous. The cooling ages were further grouped into two exhumation episodes: (1) Paleogene, 68 - 25 Ma (Late Cretaceous – Oligocene), and (2) Neogene, 23 - 10 Ma. The first exhumation episode of Paleogene cooling histories would be consistent with (1) Late Cretaceous-Paleocene emplacement of the Rocky Mountain overthrust, (2) evidence of uniform eastward tilting of the proximal Sweetgrass Hills, Bearpaw Uplift, Little Rockies Mountains and Highwood Mountains similar to the Sweetgrass Arch during Paleocene to early Eocene and (3) post Eocene uplifts related to late Laramide orogeny model. The Neogene cooling ages could also be related to the Pendroy Fault movement during Oligocene-Miocene (or younger ages) which moved a bulge on the Sweetgrass Arch's crest (≈ 48 km) eastward to form the present-day Kevin Dome. The burial and thermal history of Kevin Dome strata and how these thermal conditions drove hydrocarbon generation were also constrained by incorporating cooling age histories with available thermal maturity indices of Kevin Dome strata. This study provides new contexts for understanding how exhumation episodes controlled thermal

evolution, generation and migration of associated hydrocarbons and emplacement of CO_2 at Kevin Dome.

References

Aviles, M.A. and Cheadle, B.A. 2015. Regional study of the thickness of exhumed sediments in the foredeep section of the Western Canada Foreland Basin using the sonic compaction-based technique. GeoConvention 2015: New Horizons

Bowen, D.W., Lageson, D.R., Jackson, F.D., Eby, D., 2009. Kevin Dome, Montana: Reservoir Characterization of a Natural Analog for CO_2 Sequestration and Its Significance for Evaluating Similar Structural Features in Montana. AAPG Search and Discovery Article #90090 ©2009 AAPG Annual Convention and Exhibition, Denver, Colorado, June 7-10, 2009.

Bustin, R.M., 1991. Organic maturity in the western Canada sedimentary basin. International Journal of Coal Geology, 19 (1991) 319-358.

Carrapa, B., DeCelles, P.G., and Romero, M., 2019, Early inception of the Laramide Orogeny in Southwestern Montana and Northern Wyoming: Implications for models of flat-slab subduction: Journal of Geophysical Research. Solid Earth, v. 124, p. 2102–2123, https://doi .org/10.1029/2018JB016888.

Downey, J.S., 1986. Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming. U.S. Geological Survey. Paper 1402-E, p. E1-E87.

Fuentes, F., DeCelles, P.G., Constenius, K.N., and Gehrels, G.E., 2011. Evolution of the Cordilleran foreland basin system in northwestern Montana, U.S.A. GSA Bulletin; March/April 2011; v. 123; no. 3/4; p. 507–533; doi: 10.1130/B30204.1;

Peterson, J.A., 1987. Subsurface Stratigraphy and Depositional History of the Madison Group (Mississippian), U.S. Portion of the Williston Basin and Adjacent Areas, Rocky Mountain Association of Geologists, p. 171-192.

Rukhlov, A.S. and Pawlowicz, J.G. (2012): Eocene potassic magmatism of the Milk River area, southern Alberta (NTS 72E) and Sweet Grass Hills, northern Montana: overview and new data on mineralogy, geochemistry, petrology and economic potential; Energy Resources Conservation Board, ERCB/AGS Open File Report 2012-01, 88 p

Shepard, W., and Bartow, B., 1986. Tectonic history of the Sweetgrass Arch, a key to finding new hydrocarbons, Montana and Alberta

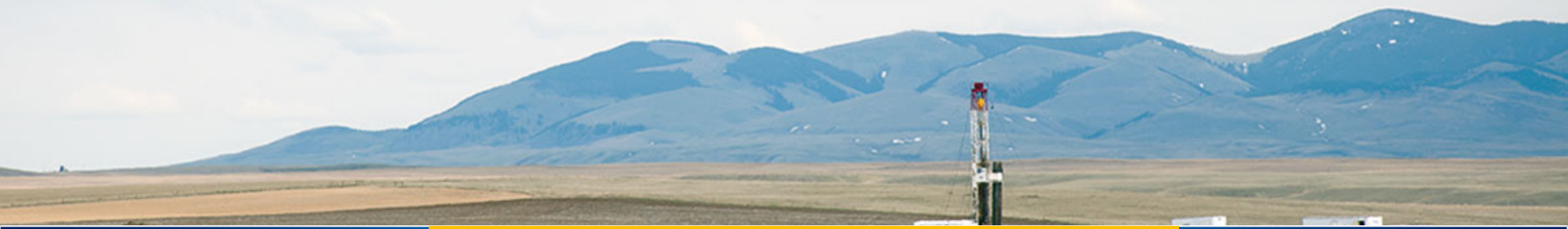
Vermeesch, P., 2012, On the visualisation of detrital age dis¬tributions: Chemical Geology, v. 312–313, p. 190–194, https://doi .org/10.1016/ j.chemgeo.2012.04.021

Vuke, S.M. and others, 2007. Geologic Map of Montana, Montana Bureau of Mines and Geology: Geologic Map 62D.

Timing of the Exhumation Episodes and Burial/Thermal History of Kevin Dome, Northwestern Montana.

ELIJAH O. ADENIYI [*a, b], Colin A. Shaw [a, b], David W. Bowen [a, b]

Chuck W. Calavan [a] and Mary S. Hubbard [a]

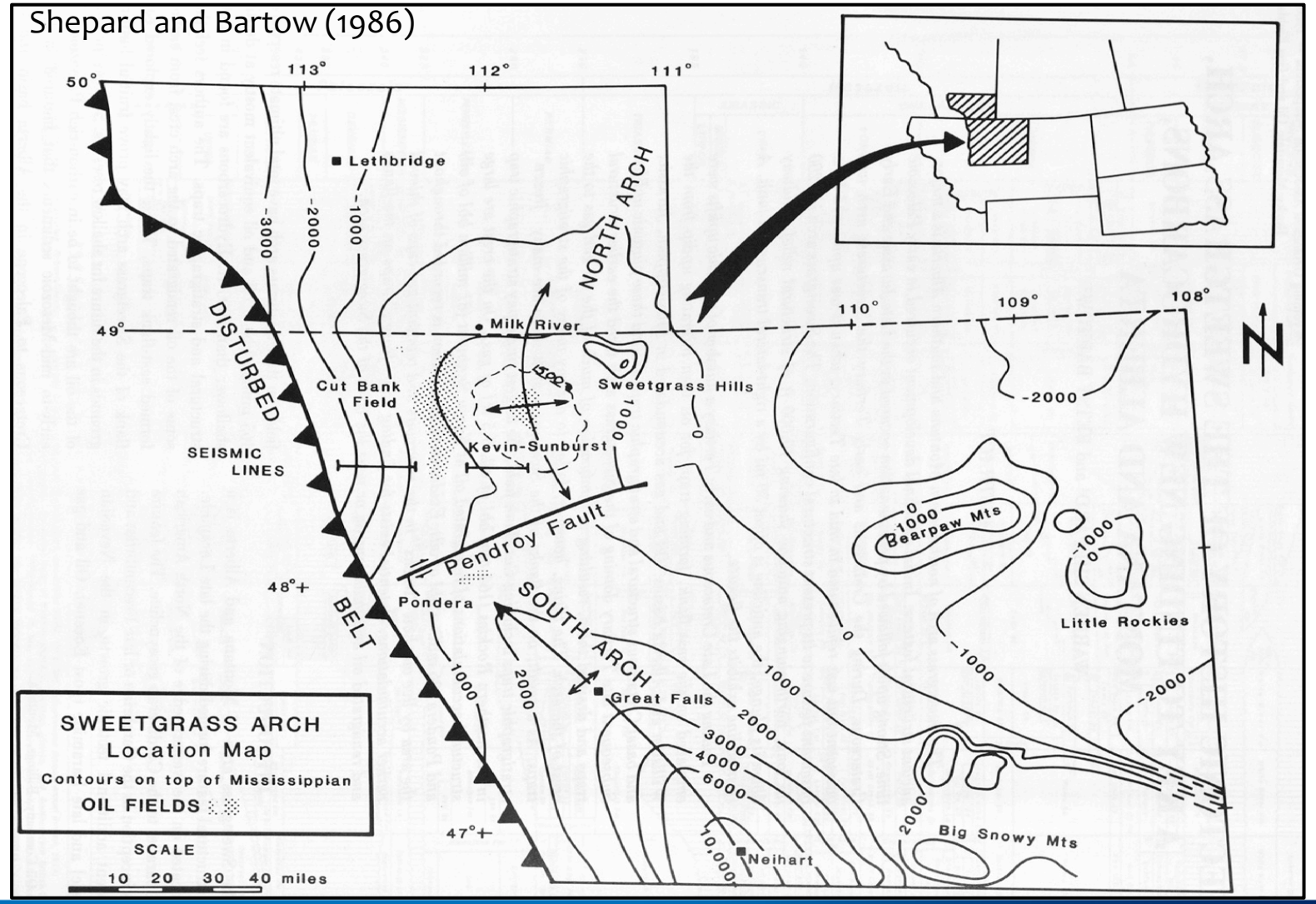


MONTANA STATE UNIVERSITY

a. Department of Earth Sciences, Montana State University, Bozeman MT.
b. Energy Research Institute, Montana State University, Bozeman MT.
** Corresponding author: adeniyi_1@yahoo.com*

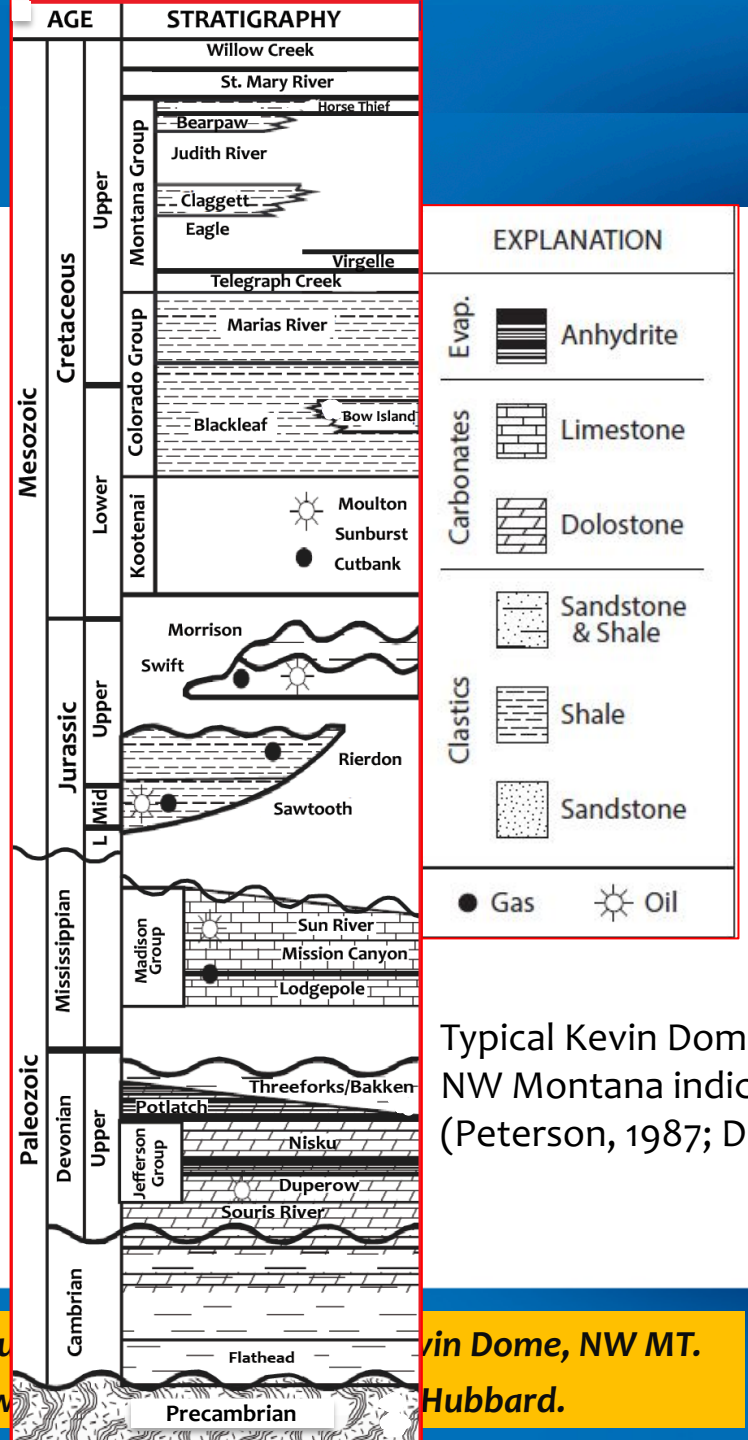
Research Background.

Kevin Dome is a 320-km long, north plunging structural culmination along the Sweetgrass Arch in Northwest Montana hosting ~85 bcm natural CO2 resource and is an historic oil and gas producer in the region.



Research Background.

Existing tectonic and structural evolution models for the Sweetgrass Arch development and/or Kevin Dome exhumation were based on strata distribution, thermal maturity data, erosional surfaces or non-deposition evidence; however, they are poorly constrained on timing.

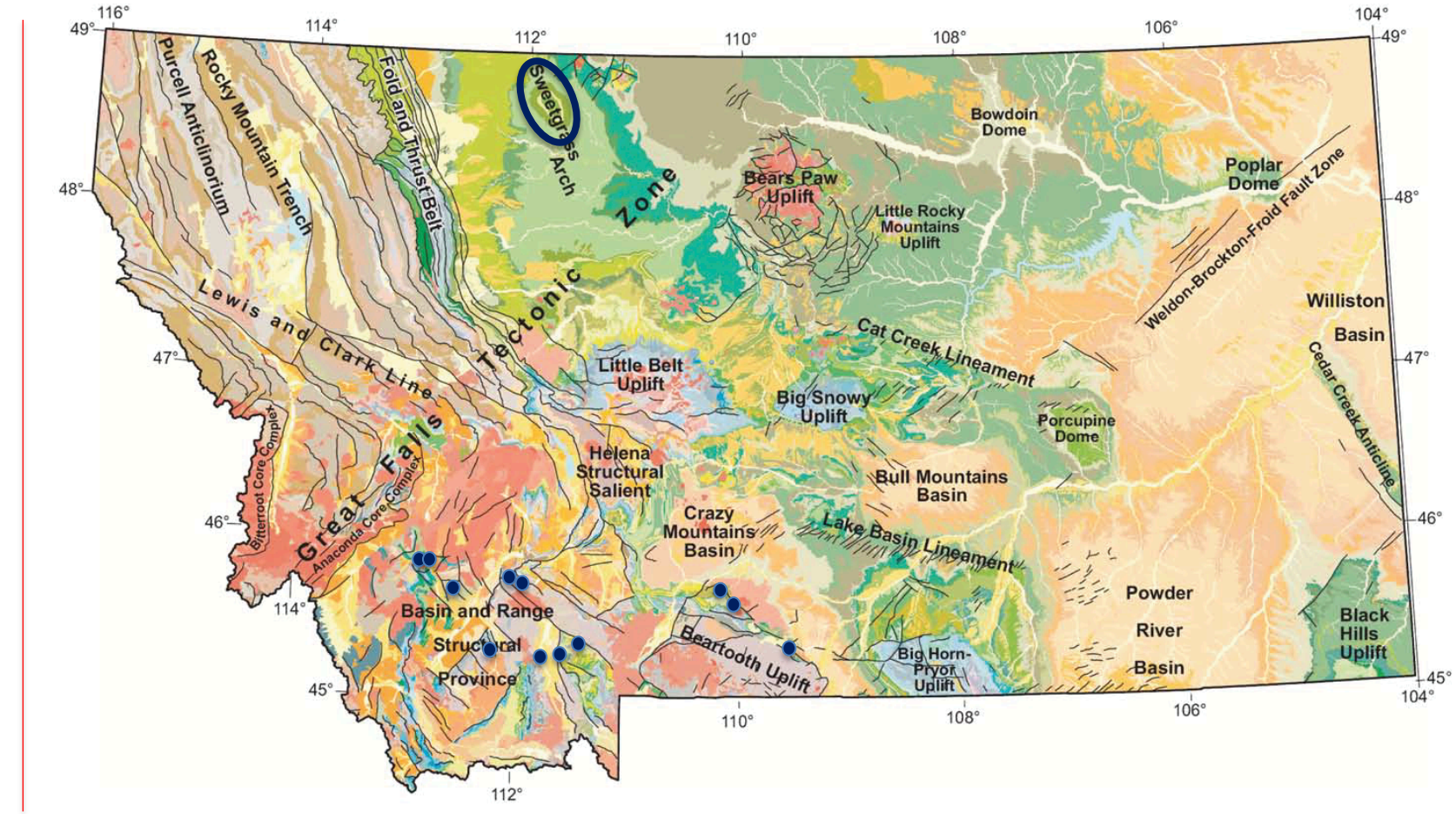


Typical Kevin Dome Stratigraphy
NW Montana indicating the producing Fms
(Peterson, 1987; Downey, 1986).

Current Study

1. Using time-temperature technique (low-temperature thermochronology) to constrain the thermal evolution and exhumation episodes at Kevin Dome

2. First thermochronological approach on Kevin Dome and NW MT with subsurface sampling only

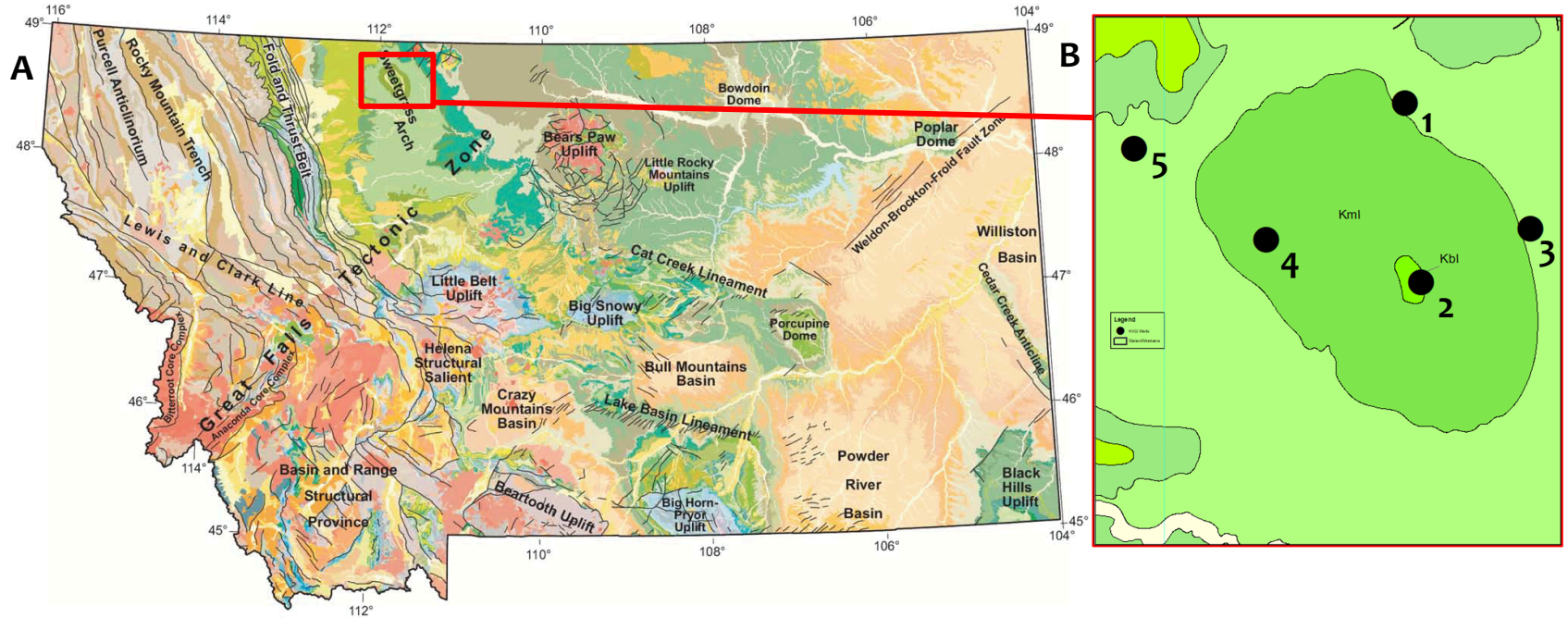


Geologic Map of Montana showing major tectonic features, structures & faults (Vuke et al. 2007)

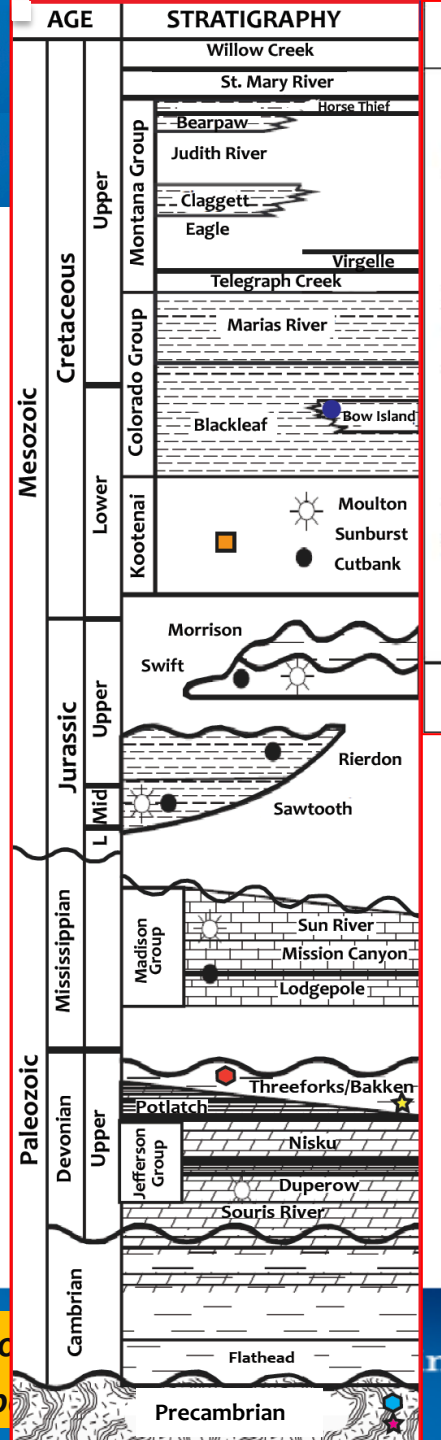
● Nearest/Recent Carrapa et al. (2019) study areas in SW Montana using low-temp thermochronology.

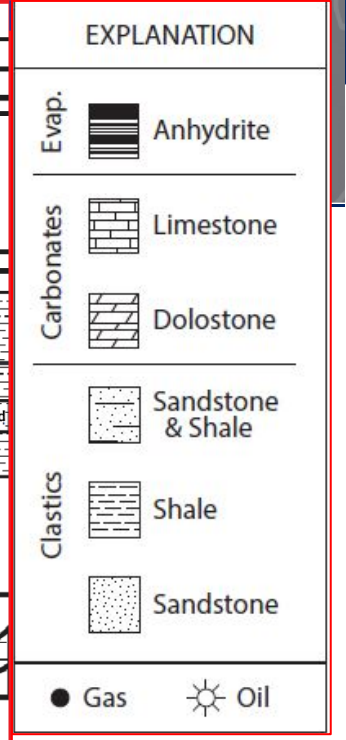
Methodology

1. **Core cuttings** from five (5) Kevin Dome wells; provided by the Montana Bureau of Oil and Gas Commission (MBOGC) Billings, MT.



A. Geologic Map of Montana showing major tectonic features, structures & faults (Vuke et al. 2007)
B. Surface Geology of Kevin Dome showing locations of selected wells





Typical Kevin Dome Stratigraphy, NW Montana (Peterson, 1987; Downey, 1986).

Showing sampled points

Methodology

2. **Minerals separation:** Crushing and sieving, followed by magnetic and density separations procedures at GEOSEPS, Moscow, ID.

Methodology

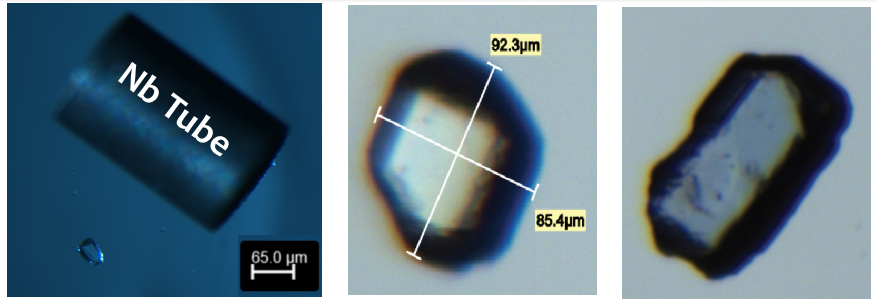
3. **Apatite (U-Th)/He Thermochronology:**
Performed on apatite minerals grains from six (6) samples at CU Boulder TRaIL Lab by:

a. Petrographic mineral examination
b. Extracting and measuring He (by heating in a vacuum),
c. Determining U, Th and Sm isotopic compositions in spiked solutions (using ICPMS), and
d. Calculating the measured He ages

ASI Alphachron

ICP-MS

Photomicrographs from petrographic examination of apatite minerals selected.

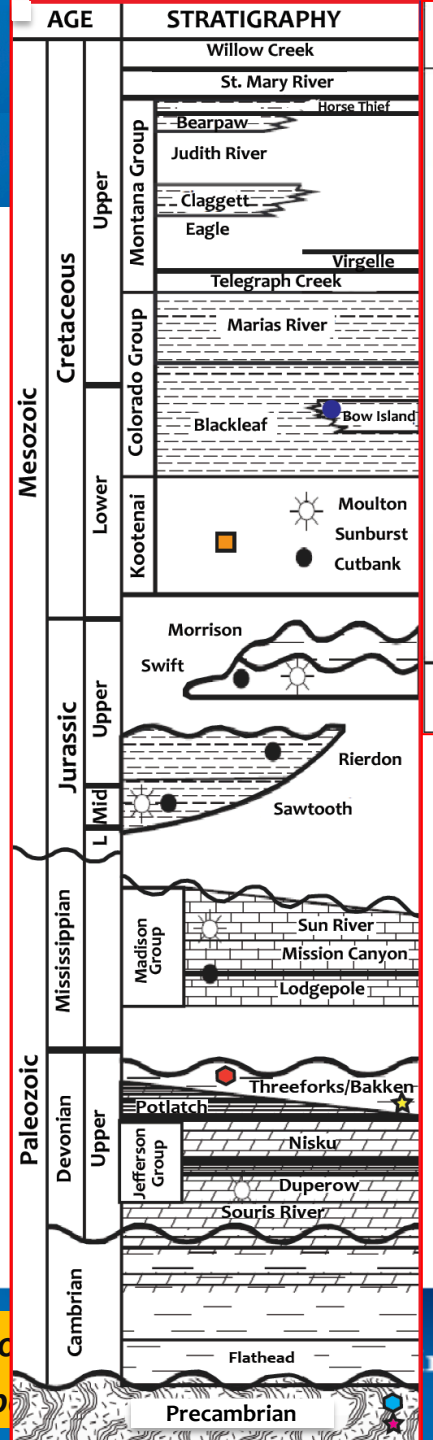


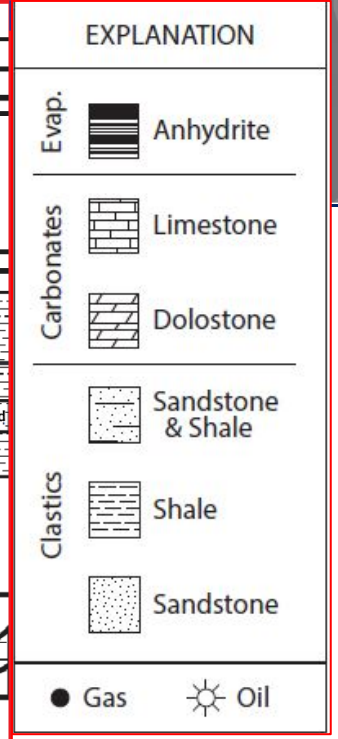
Results and Interpretations.

1. AHe-ages (18) were obtained from:

a. Precambrian basement (7)
b. Three Forks Formation (2)
c. Bakken Formation (2)
d. Kootenai Formation (4)
e. Bow Island Formation (3)

All strata recorded younger AHe-ages compared to depositional ages.





Typical Kevin Dome Stratigraphy, NW Montana (Peterson, 1987; Downey, 1986).

Showing sampled points

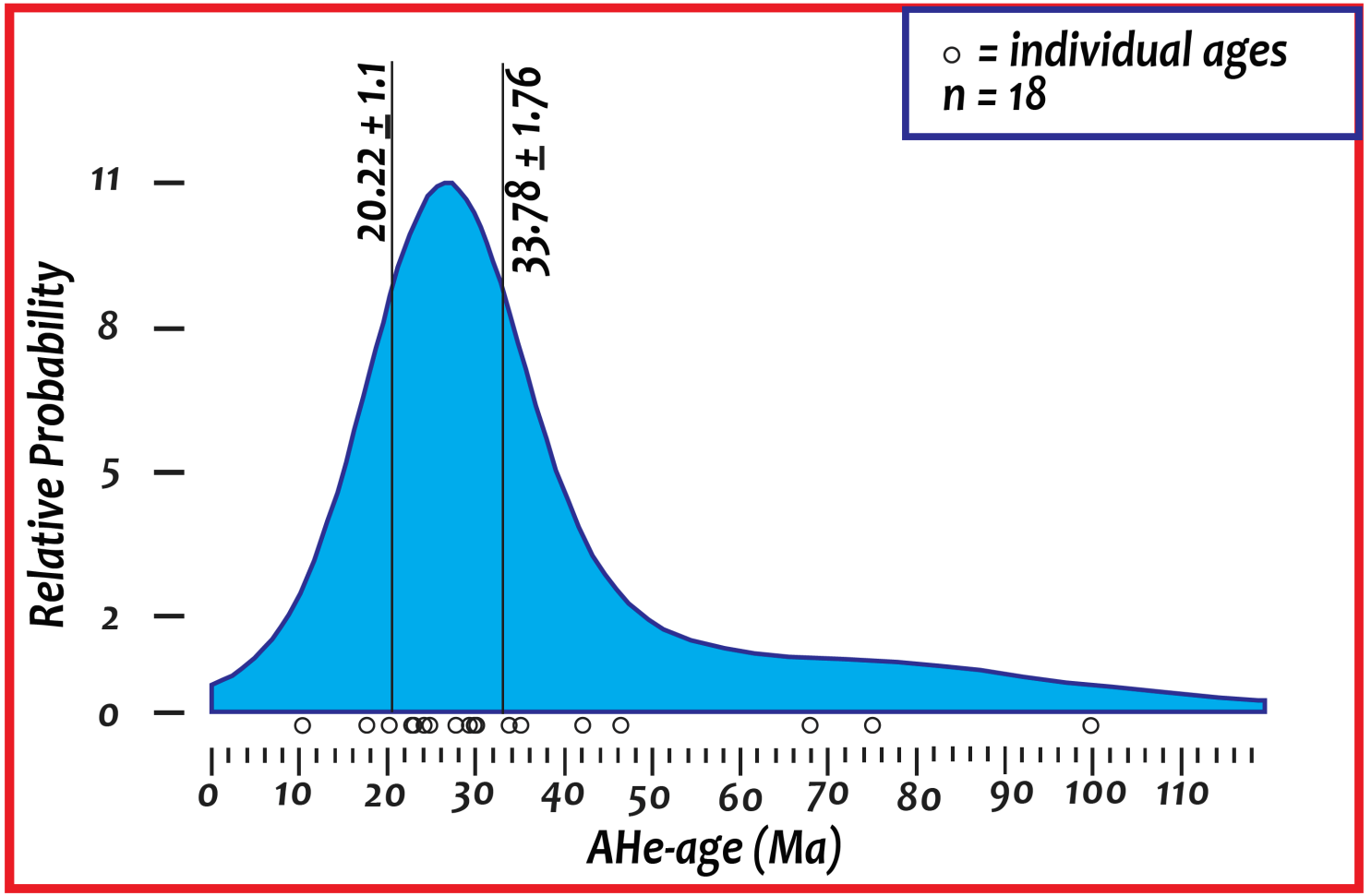
Results and Interpretations.

2. Age Distribution

Cooling ages range from ≈ 68 to 10 Ma.

*except for two outliers (≈ 75 and 99Ma) in the Bakken and Three Forks Fms respectively.

Age probability distribution shows a prominent Oligocene to Miocene exhumation or thermal event



Density kernel functions of Kevin Dome AHe-ages. Vertical lines and ages represent populations calculated in automated mode using Density Plotter (Vermeesch, 2012).

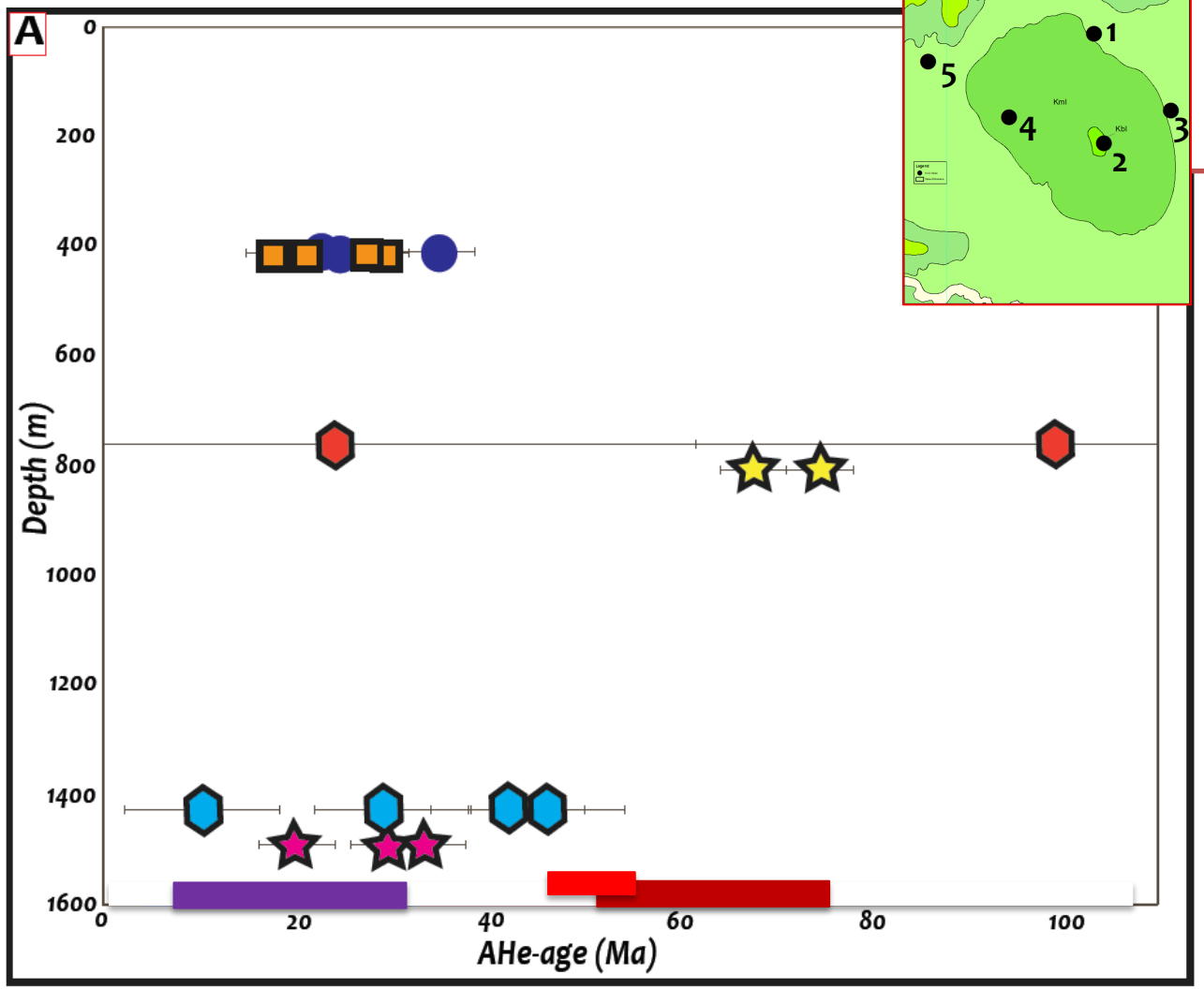
Results and Interpretations.

3. Depth versus AHe-ages: Kevin Dome:

W2 and **W4** (near the center of the dome), **W3** and **W5** at the margins of the dome showed similar cooling history respectively.

W2 maybe problematic due to wide age gap in Three Forks Fm

Fuentes et al (2011); Rukhlov and Pawlowicz (2012); Shepard and Bartow (1986).



Surface Geology of Kevin Dome showing locations of selected 5 wells

LEGENDS

Kevin Dome

- Well 2 Threeforks Fm
- Precambrian
- Well 3 Kootenai Fm
- Well 4 Bakken Fm
- Precambrian
- Well 5 Bow Island

- Pendroy Fault Movement
- Rocky Mtn Eocene Pluton Emplacement
- Laramide Orogeny

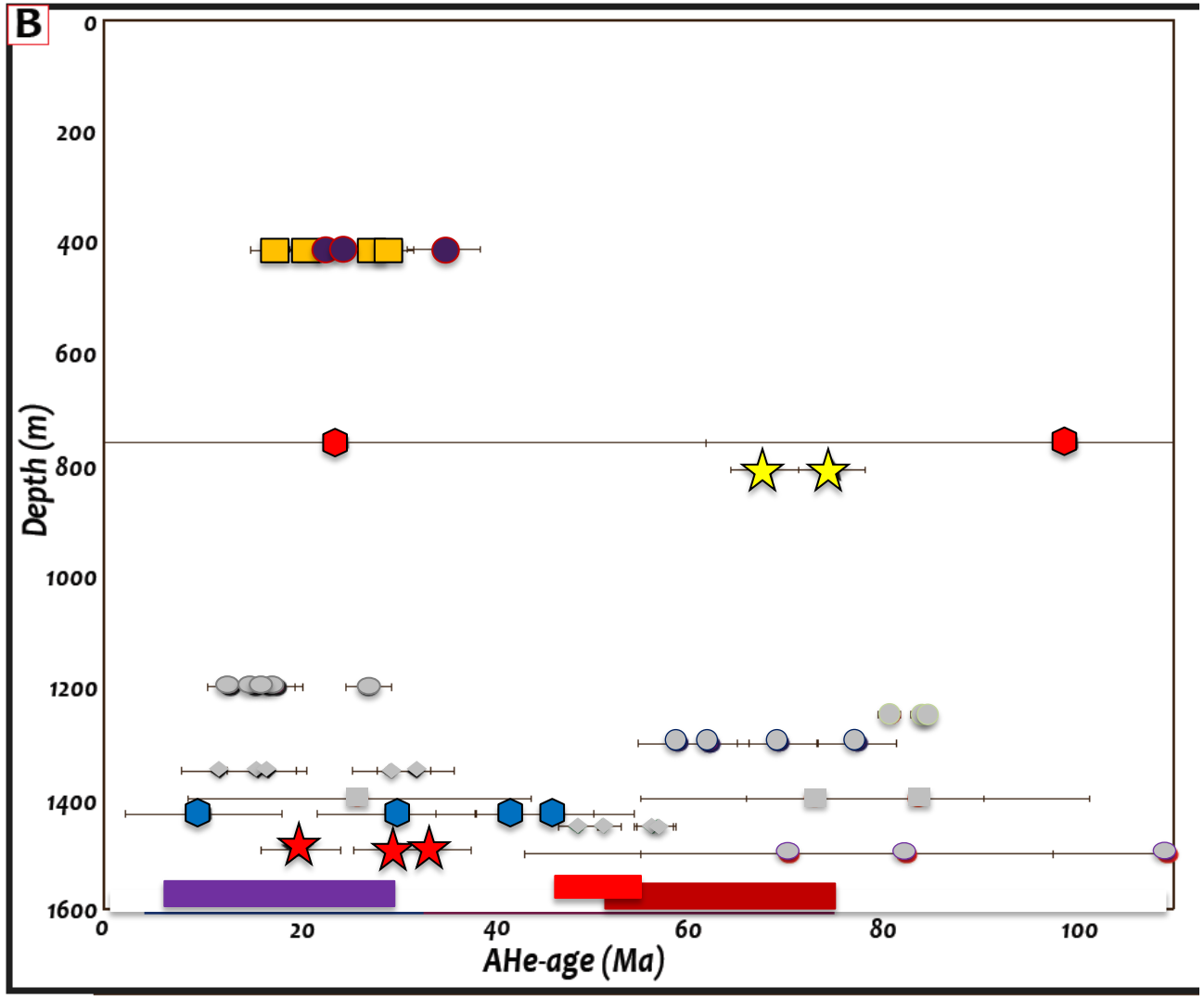
* Depth of AHe-age inferred

Results and Interpretations.

4. Depth versus AHe-ages: Kevin Dome and others

The data was also compared with six Laramide ranges in Southwest Montana (AHe-age data) by Carrapa et al (2019) for a regional context of the cooling history.

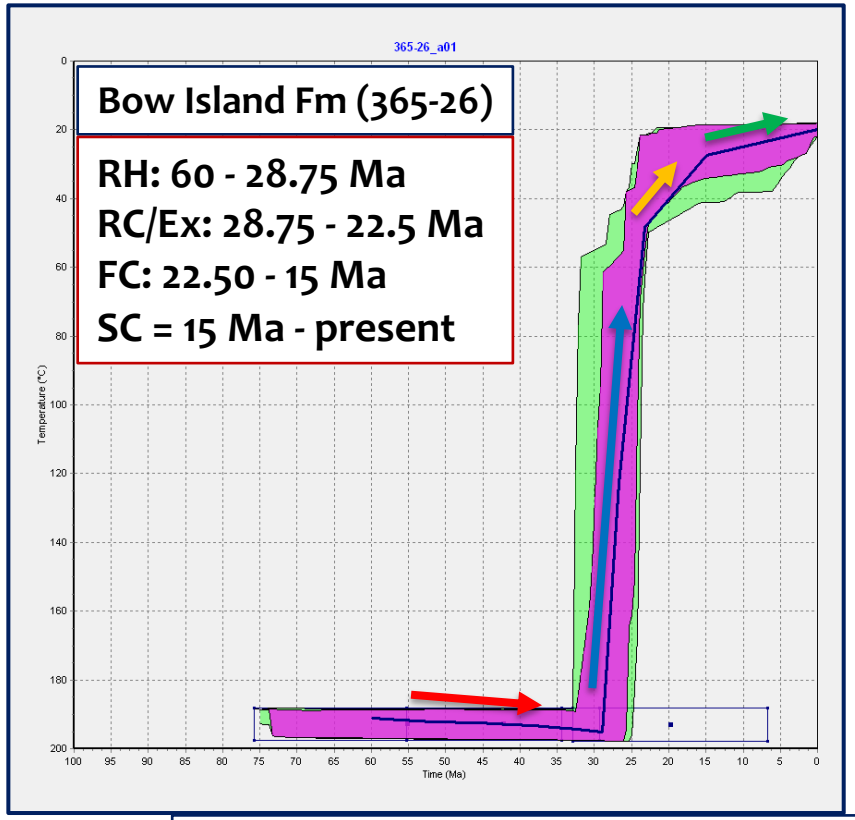
Fuentes et al (2011); Rukhlov and Pawlowicz (2012); Shepard and Bartow (1986).

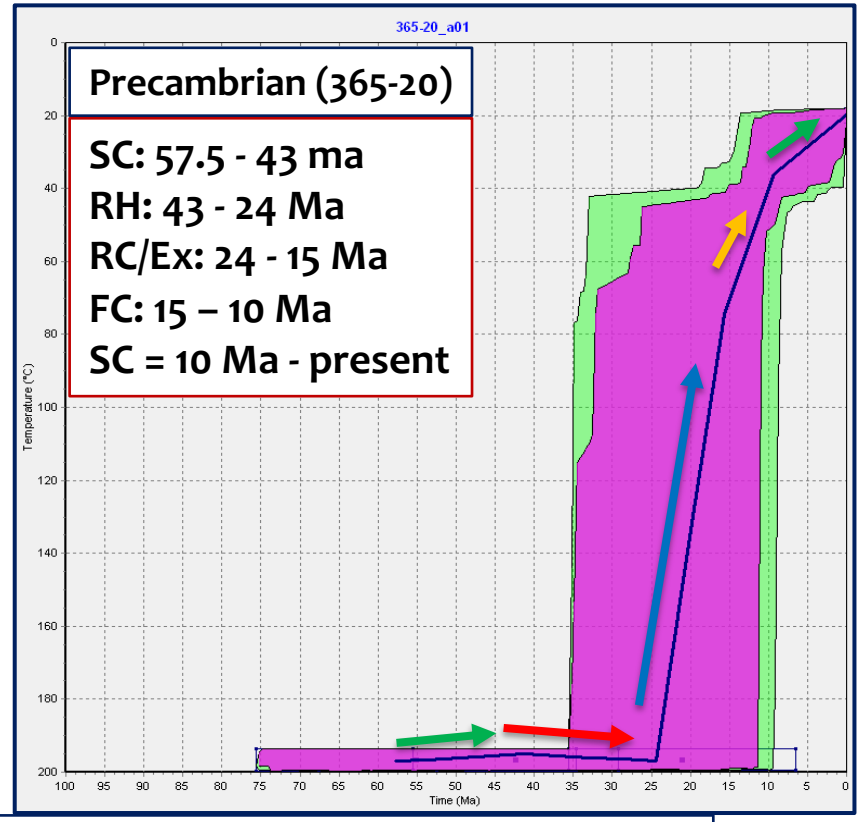


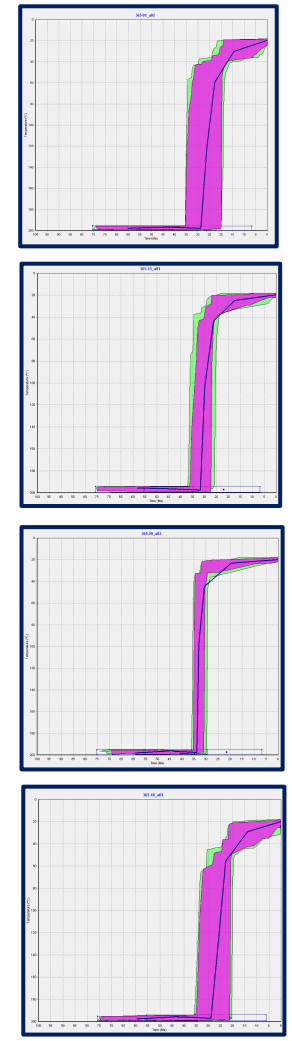
Results and Interpretations.

5. Thermal History Modeling: HeFTy

Models show the weighted mean path of a reconstructed thermal histories of the sample.







Thermal History Paths: Good Acceptable Weighted Mean

Thermal history Trends: Reheating (RH). Rapid Cooling/Exhumation (RC). Fast Cooling(FC). Slow Cooling (SC)

Conclusions

1. All units sampled reached temperatures above 70° C (apatite closure T), implying ≈ 3 km of uplift difference and overburden thickness have been removed due to exhumation since the Late Cretaceous.

2. Based on obtained cooling ages (≈ 68 to 10Ma), Kevin Dome cooled periodically and mainly during the Tertiary.

3. AHe-age probability distribution predominantly shows a post Eocene (Oligocene to Miocene) exhumation/thermal event, while the Kevin Dome thermal histories modeling reveals a major exhumation between ≈ **30 to 15 Ma** in the Paleozoic, Mesozoic and Basement units.

4. The post Eocene exhumation event observed at Kevin Dome, Northwestern Montana is significant in contrast to the (much older) Early to mid-Cretaceous exhumation recorded from six Laramide ranges in Southwestern Montana (Carrapa et al 2019).

Conclusions

5. Our new data supports previous regional exhumation stories (further north) in the proximal Western Canadian Sedimentary Basin (e.g. Buston, 1991; Aviles and Cheadle 2015) and is the first data set to constrain the timing.

6. We think that the Sweetgrass Arch and Kevin Dome are structural elements related to Laramide Orogeny (e.g. Shepard and Bartow, 1986; Fuentes et al. 2012; Carrapa et al. 2019), but our data revealed a younger exhumation episode that requires further research.

7. Additional low-temperature thermochronology, thermal maturity data input and thermal history modelling for Kevin Dome and distal-to-proximal strata are needed to constrain the timing of its post-Eocene exhumation(s); either to a localized tectonic evolution, erosional exhumation or a regional epeirogenic event.

THANK YOU.

Acknowledgements:

This research was funded by the U.S. Department of Energy and the National Energy Technology Laboratory through award number: DE-FC26-05NT42587 to the Energy Research Institute and Big Sky Carbon Sequestration Partnership at Montana State University.

References

1. Aviles, M.A. and Cheadle, B.A. 2015. Regional study of the thickness of exhumed sediments in the foredeep section of the Western Canada Foreland Basin using the sonic compaction-based technique. GeoConvention 2015: New Horizons
2. Bowen, D.W., Lageson, D.R., Jackson, F.D., Eby, D., 2009. Kevin Dome, Montana: Reservoir Characterization of a Natural Analog for CO2 Sequestration and Its Significance for Evaluating Similar Structural Features in Montana. AAPG Search and Discovery Article #90090 ©2009 AAPG Annual Convention and Exhibition, Denver, Colorado, June 7-10, 2009.
3. Bustin, R.M., 1991. Organic maturity in the western Canada sedimentary basin. International Journal of Coal Geology, 19 (1991) 319-358.
4. Carrapa, B., DeCelles, P.G., and Romero, M., 2019, Early inception of the Laramide Orogeny in Southwestern Montana and Northern Wyoming: Implications for models of flat-slab subduction: Journal of Geophysical Research. Solid Earth, v. 124, p. 2102–2123, https://doi .org/10.1029/2018JB016888.
5. Downey, J.S., 1986. Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming. U.S. Geological Survey. Paper 1402-E, p. E1-E87.
6. Fuentes, F., DeCelles, P.G., Constenius, K.N., and Gehrels, G.E., 2011. Evolution of the Cordilleran foreland basin system in northwestern Montana, U.S.A. GSA Bulletin; March/April 2011; v. 123; no. 3/4; p. 507–533; doi: 10.1130/B30204.1;
7. Peterson, J.A., 1987. Subsurface Stratigraphy and Depositional History of the Madison Group (Mississippian), U.S. Portion of the Williston Basin and Adjacent Areas, Rocky Mountain Association of Geologists, p. 171-192.
8. Rukhlov, A.S. and Pawlowicz, J.G. (2012): Eocene potassic magmatism of the Milk River area, southern Alberta (NTS 72E) and Sweet Grass Hills, northern Montana: overview and new data on mineralogy, geochemistry, petrology and economic potential; Energy Resources Conservation Board, ERCB/AGS Open File Report 2012-01, 88 p
9. Shepard, W., and Bartow, B., 1986. Tectonic history of the Sweetgrass Arch, a key to finding new hydrocarbons, Montana and Alberta
10. Vermeesch, P., 2012, On the visualisation of detrital age distributions: Chemical Geology, v. 312–313, p. 190–194, https://doi .org/10.1016/ j.chemgeo.2012.04.021
11. Vuke, S.M. and others, 2007. Geologic Map of Montana, Montana Bureau of Mines and Geology: Geologic Map 62D.