Producing Practical and Useful State Geothermal Maps*

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Abstract

Geothermal maps have many uses including geothermal and petroleum exploration, planning subsurface mining operations, and understanding volcanic and earthquake hazards. The display of relevant information on geothermal maps is not simple, however, as the mode of heat transport may change from conduction to convection both laterally and vertically, the geothermal gradient typically varies vertically and laterally in areas with both mountains and basins, and measureable heat is generated by decay of unstable isotopes of uranium, thorium and potassium in silicic crystalline rocks. For example, traditionally geothermal maps are presented as geothermal gradient maps or heat flow maps. A geothermal gradient map is given in units of °F/100 feet or °C/km, and would be useful if the values on the map could be taken to calculate temperatures at depth. Assuming a surface temperature of 50°F, a geothermal gradient of 2.0°F/100 feet suggests a temperature of 70°F at 1,000 feet, 90°F at 2,000 feet, etc. However, as lithology generally changes with depth, including rock thermal conductivity, the geothermal gradient changes with depth. If the change were from a higher thermal conductivity sandstone to a low thermal conductivity shale at 1,000 feet, the geothermal gradient could double to 4.0°F/100 feet and the temperature at 2,000 feet would be 110°F. Thus, a geothermal gradient map without a contour map of thermal conductivity structure cannot be used to calculate temperatures at depth. Assuming that lateral changes are gentle relative to vertical changes, heat flow is constant with depth. However, heat flow can only be converted to temperature with a knowledge of thermal conductivity. Thus, a heat flow map also requires a contour map of thermal conductivity structure to calculate temperatures at depth. Both heat flow and geothermal gradient determinations require temperature measurements at depth – as temperature is typically the primary quantity of interest, it may be represented as contours of depth to isotherms (lines of constant temperature). Only areas and depths where temperatures are measured are shown definitively on the map. In sedimentary basins there may be thousands of corrected bottom-hole temperature

measurements and detailed temperature information. In mountains, detailed temperature logs may be relatively sparse, but rock thermal conductivities more homogeneous. Revisions of geothermal maps from Colorado will be demonstrated.

Producing Practical and Useful State Geothermal Maps

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for the
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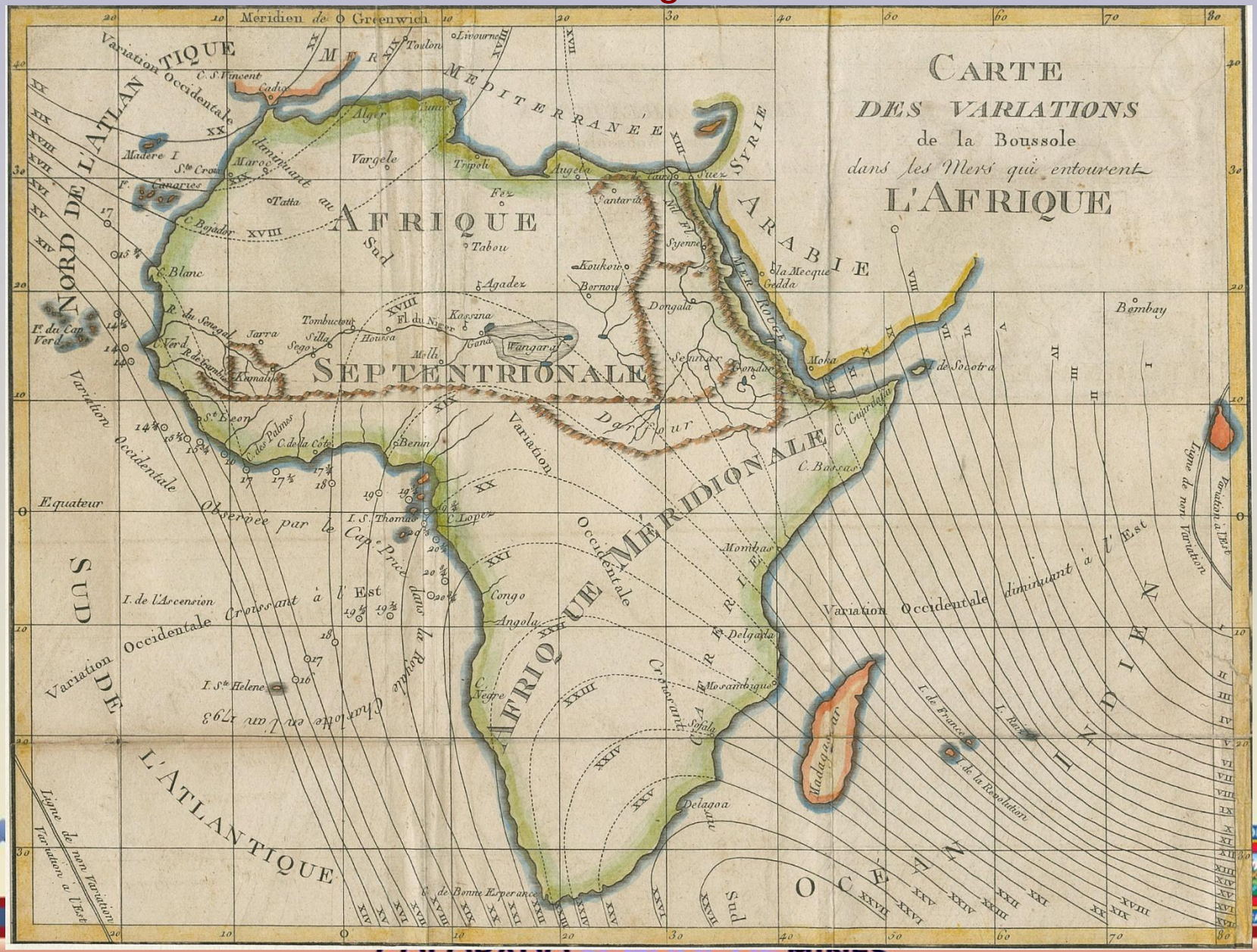
COLORADO GEOLOGICAL SURVEY

COLORADO SCHOOL OF MINES

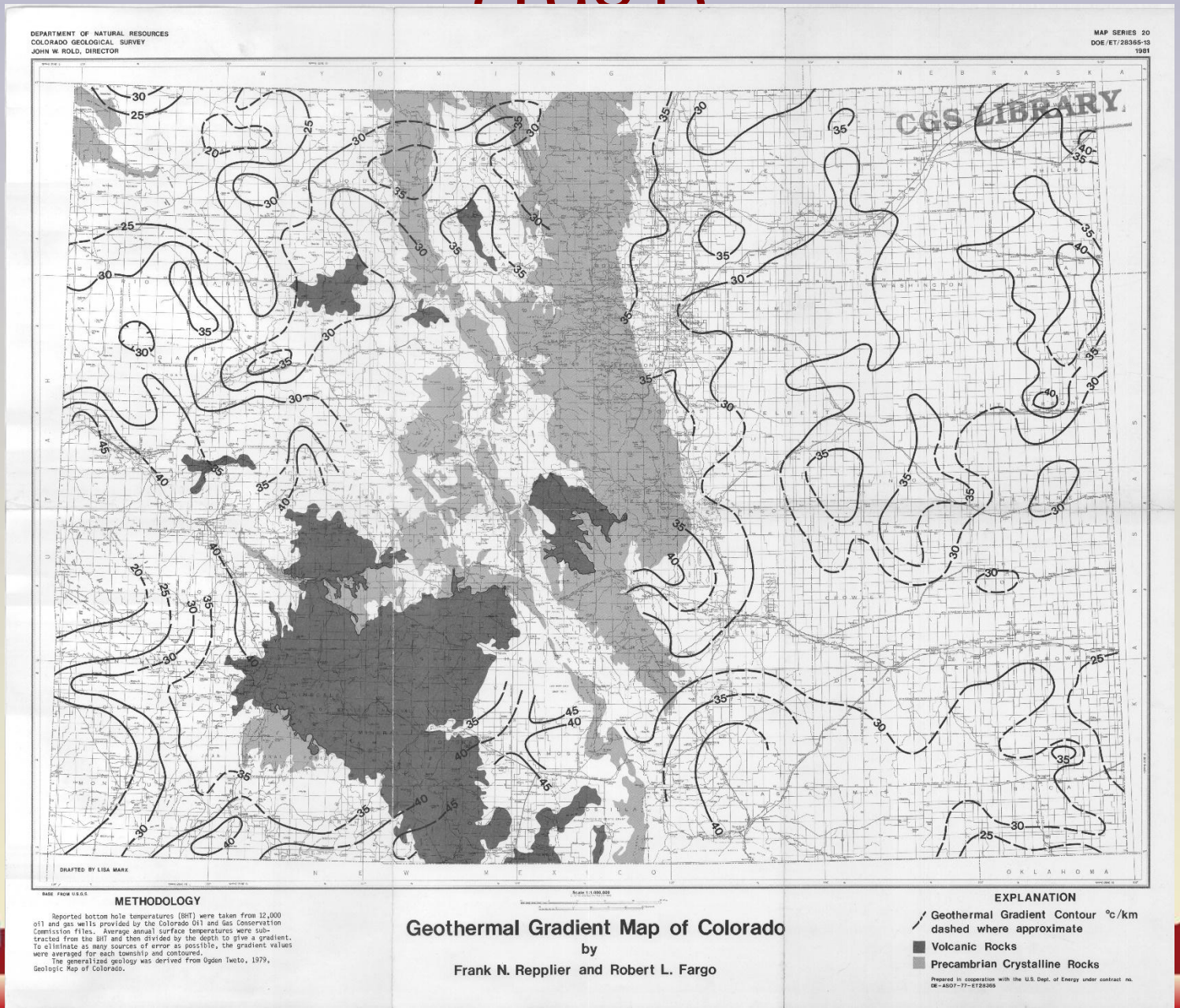
From Static Art to Dynamic Data

- All maps are interpretive:
  - The mapper decides what to put on the map and in how much detail:
    - often controlled by the density and quality of data available;
    - and sometimes limited by the scale of the map and the limitations of the 2-D surface of a map.
  - The data interpreter and/or draftsperson may further modify the original map:
    - smoothing contours, reconciling contours or other features of the map with other data, or adding other information to the map.
  - The user typically has a specific purpose for reading the map:
    - This purpose may not be the same as the original function for which the map was made.

(1793) Map of Variations of Magnetic Declination in the Seas Surrounding Africa



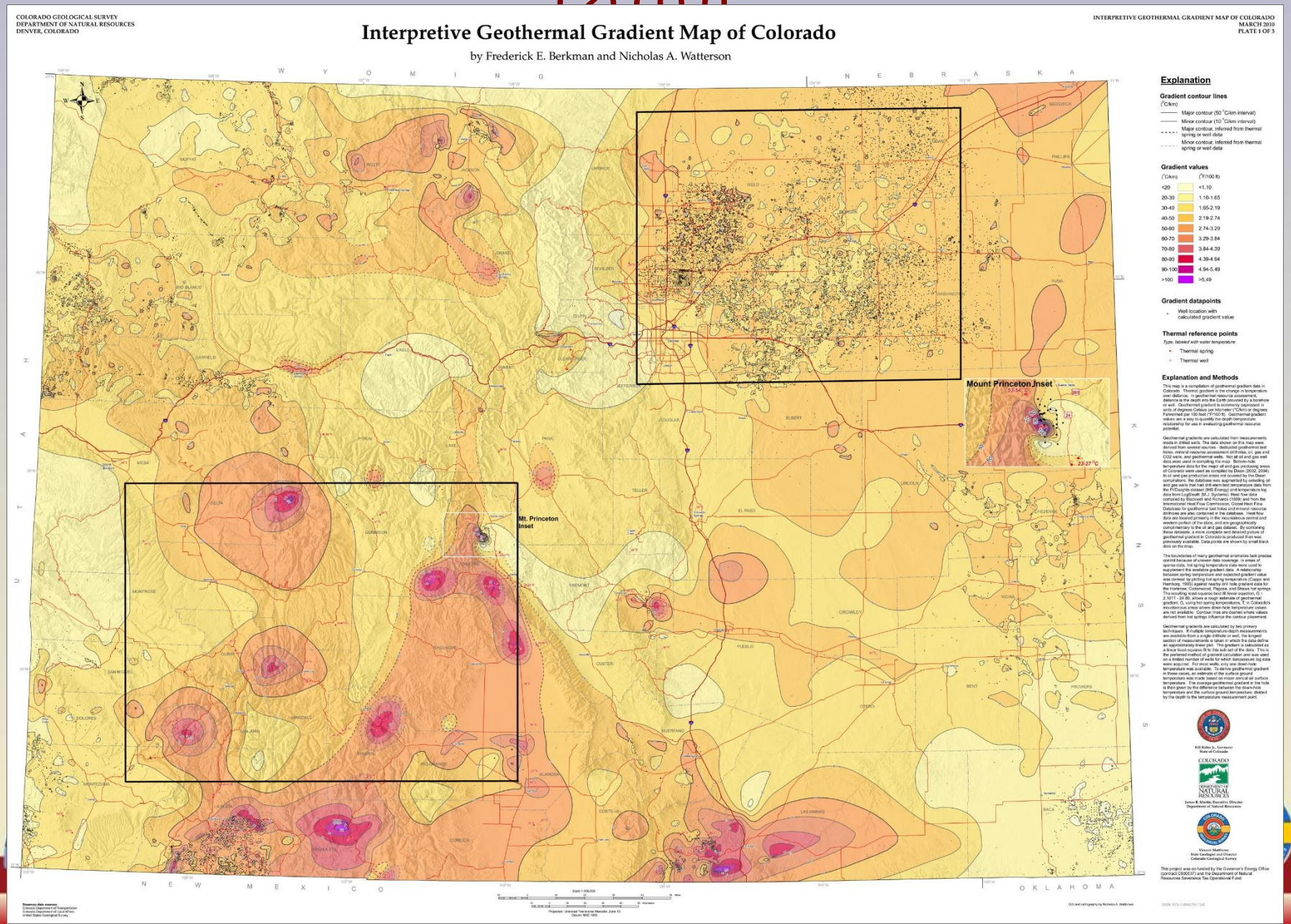
Colorado's First 'Geothermal' Map (1981)



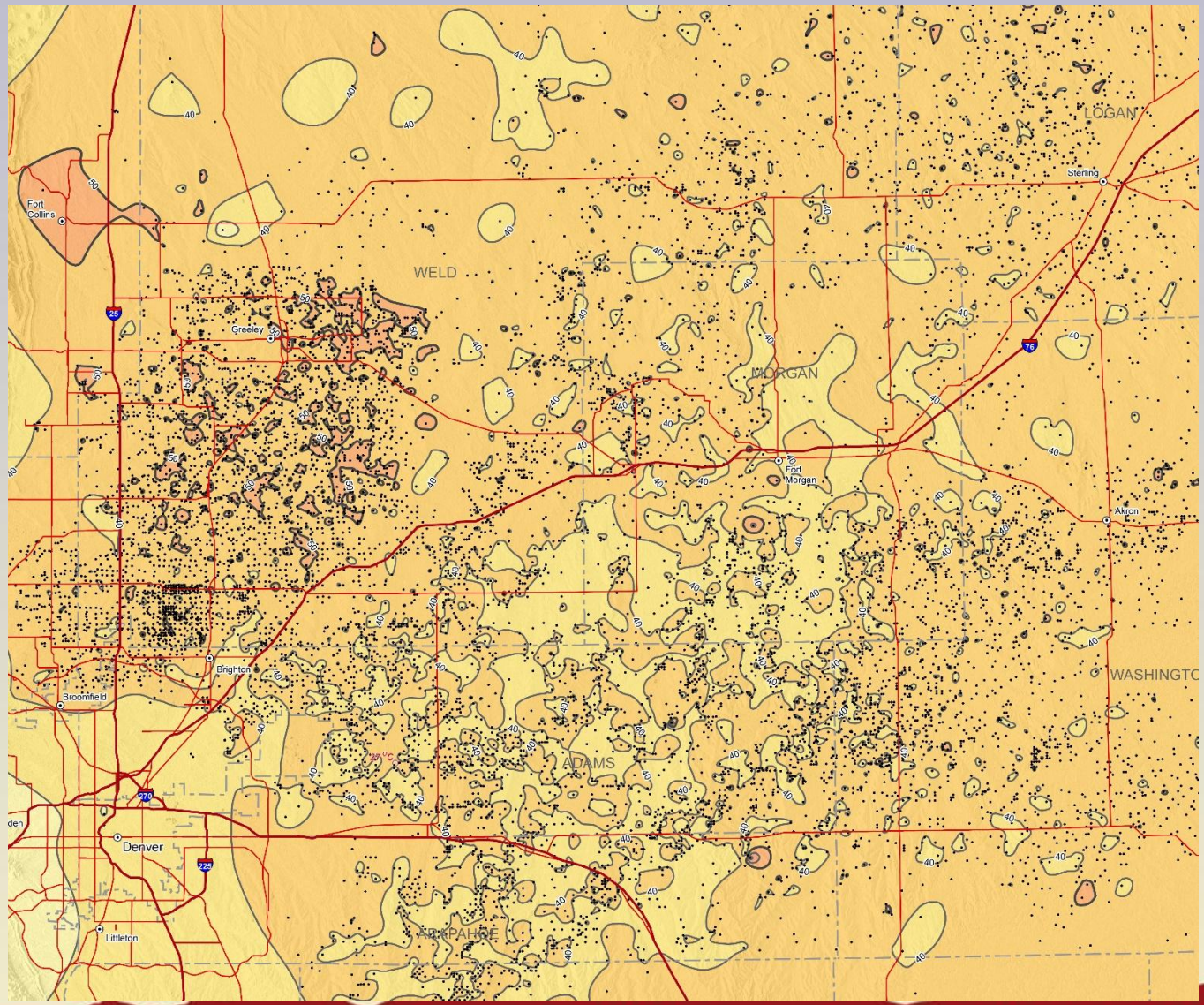
Features of First 'Geothermal' Map

- Map generated toward the end of a period of high geothermal exploration activity in the western US (1974-1985).
- Contours in °C/km over about 2/3 of the state at 5°C/km intervals, based on oil and gas well bottom-hole temperatures (BHTs), averaged over each township (~6 mi by ~6 mi areas), uncorrected for drilling disturbances.
- No indication of depth of BHTs: how deep could gradients be extrapolated?
- No data in areas of outcrops volcanic rocks or crystalline basement which host most of the thermal springs in the Colorado.

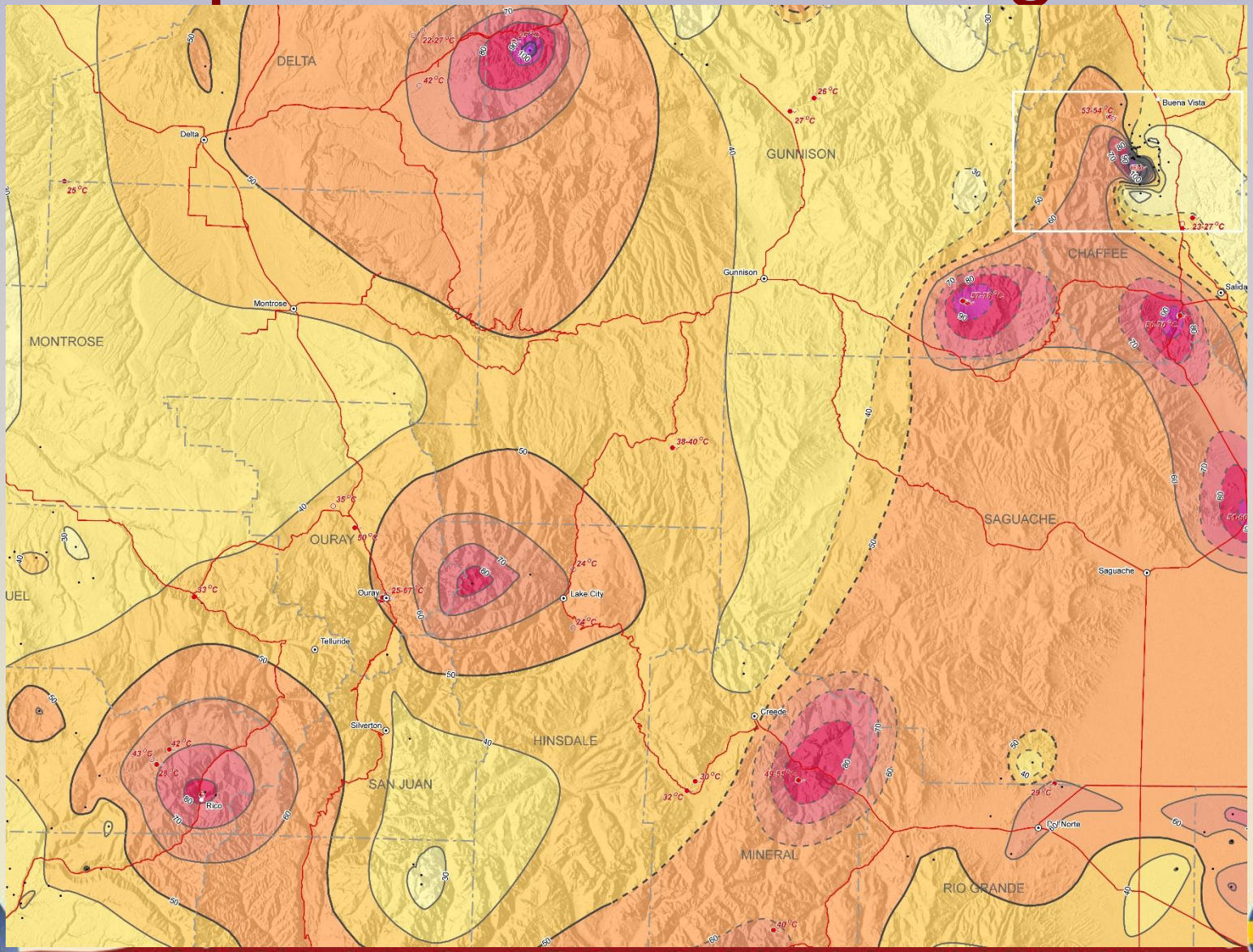
Colorado Geothermal Gradient Map Mk. II (2010)



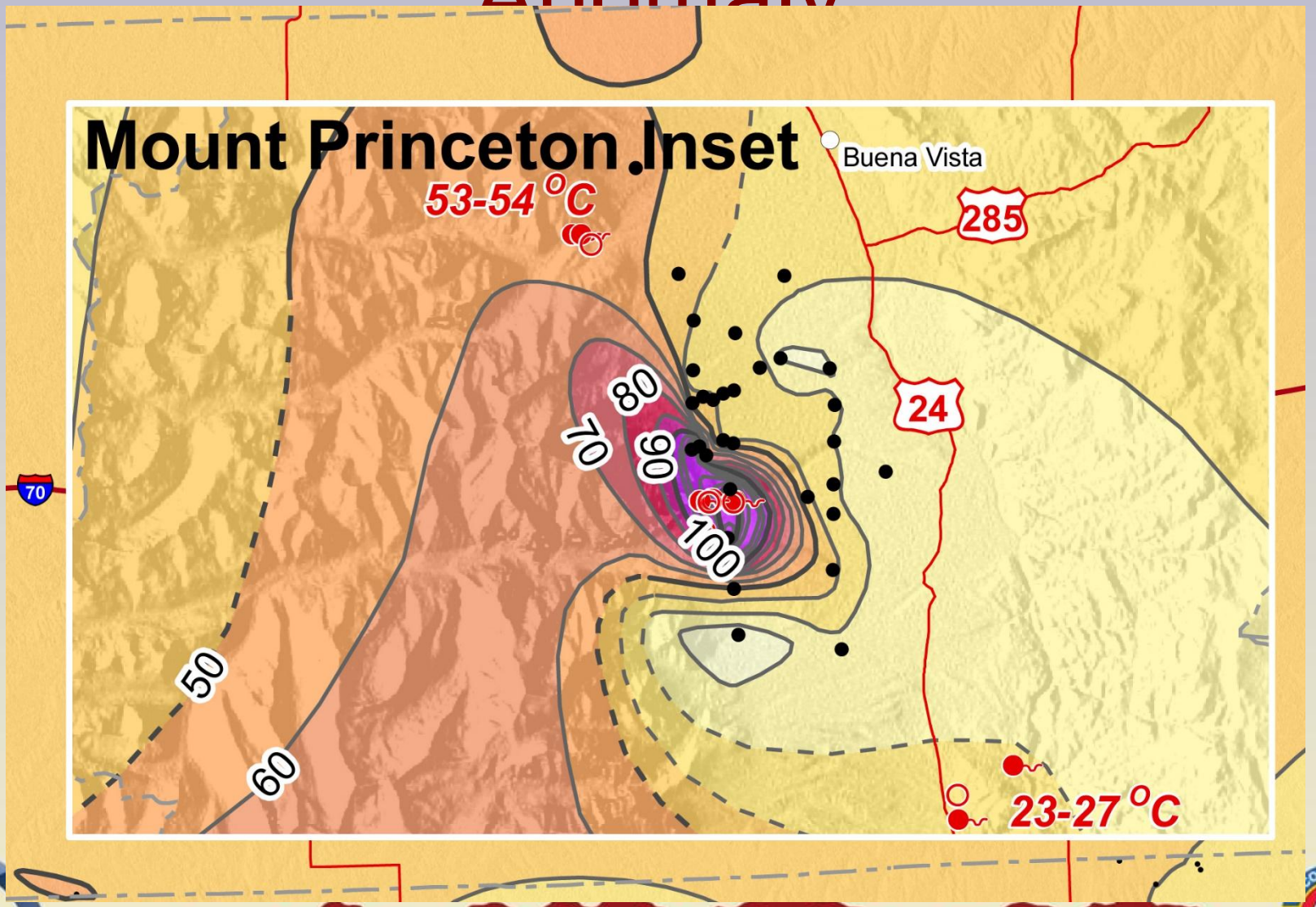
Dense Data Coverage



Sparse Data Coverage



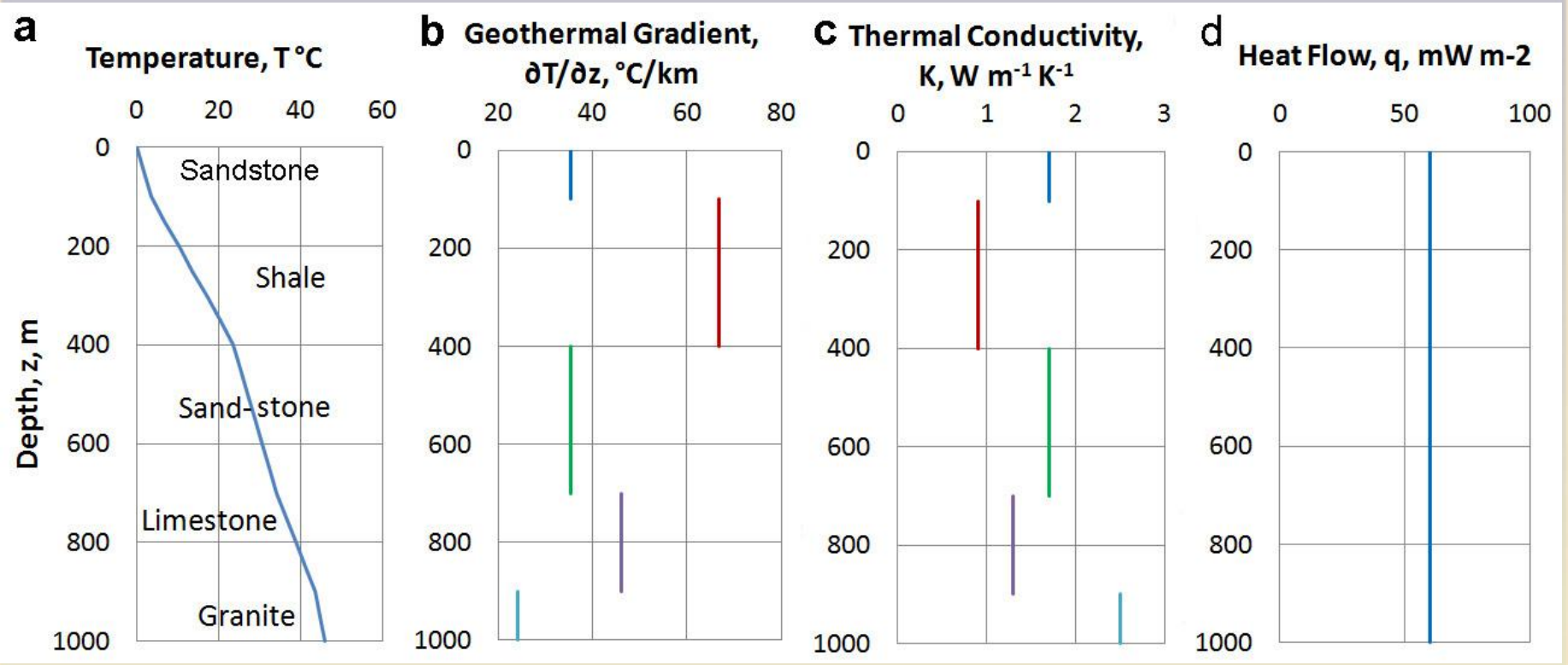
Well-Defined Geothermal Anomaly



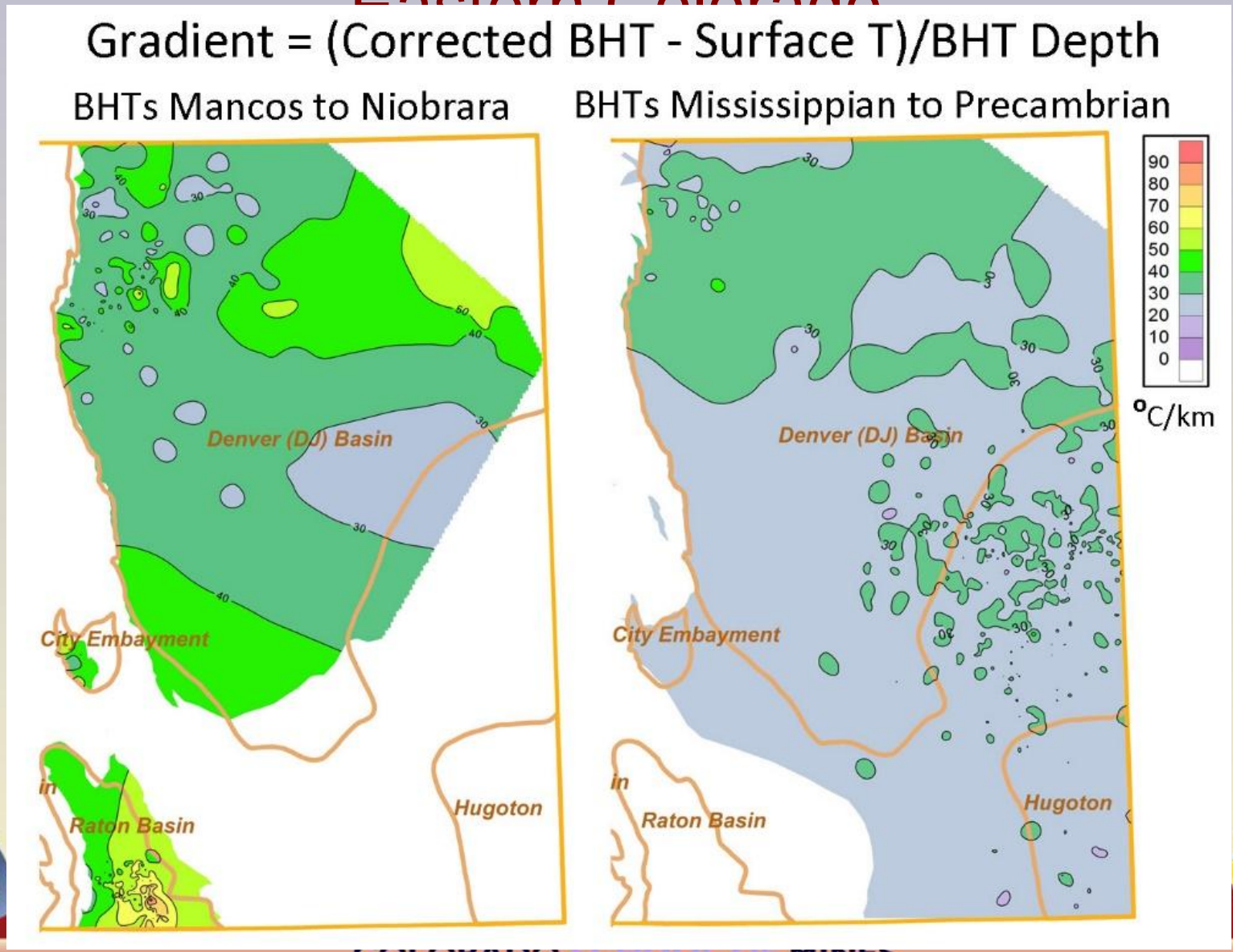
Features of Second 'Geothermal' Map

- Map generated during period of renewed Interest in renewable resources to reduce CO_2 emissions (starting in about 2000)
- Contours in °C/km covering all state at 10°C/km intervals: based on oil and gas well bottom-hole temperatures (BHTs) in sedimentary basins (coal-bed methane well BHTs in Raton and Sand Wash Basins); corrected using corrections derived from basins outside Colorado; gradients also included from geothermal measurements and heat-flow studies (very variable depth).
- A correlation among gradients and thermal spring temperatures was made – thermal spring temperatures plotted on map and used in contouring.
- No indication of depth of BHTs: how deep could gradients be extrapolated?
- Computer contoured – sparse high data points, especially thermal springs resulted, in relatively large areas contoured as having a high geothermal gradient.

Problem with Presenting Geothermal Gradients



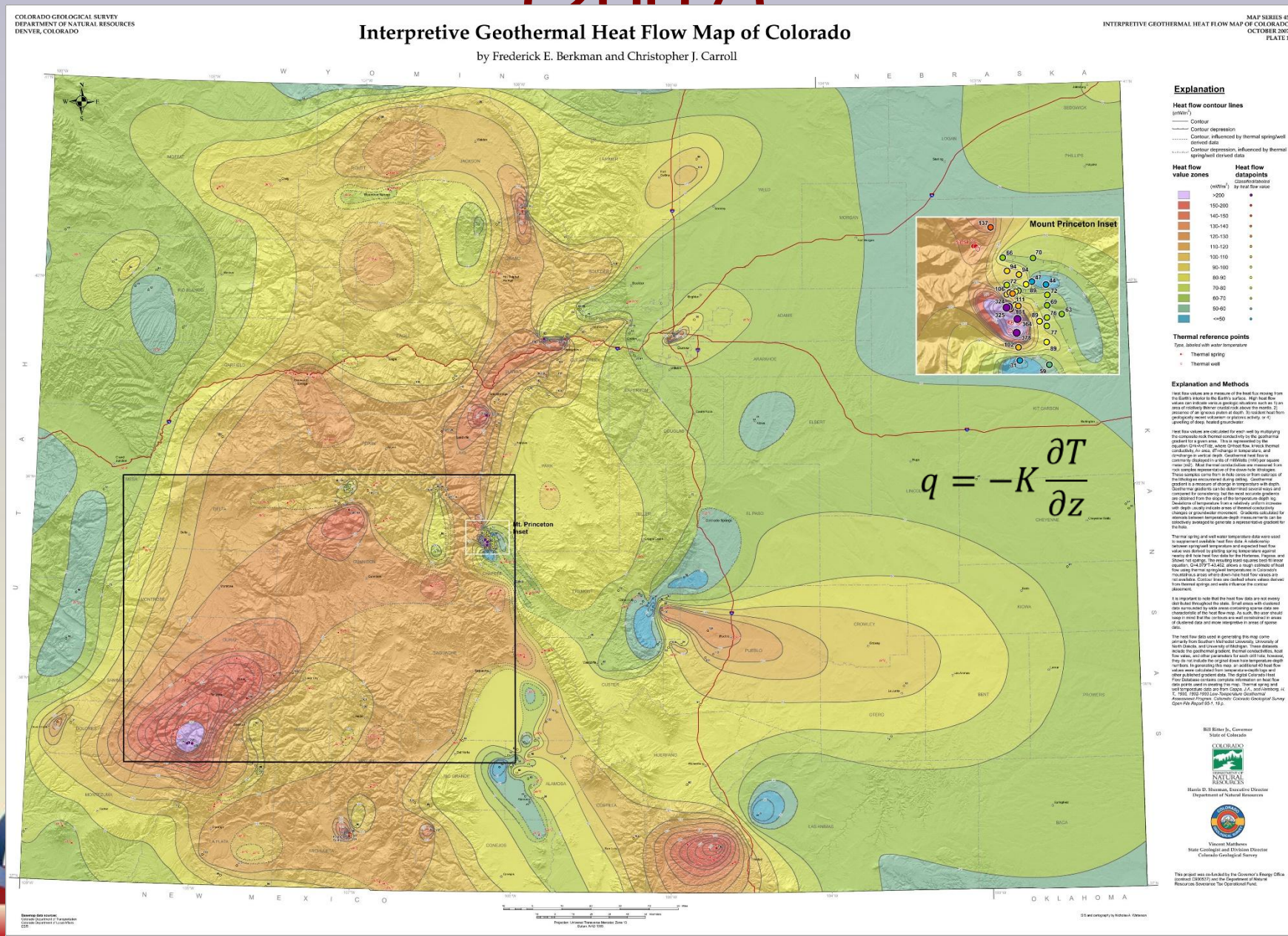
Geothermal Gradient Maps Using BHTs from Specific Stratigraphic Intervals: Example: Eastern Colorado



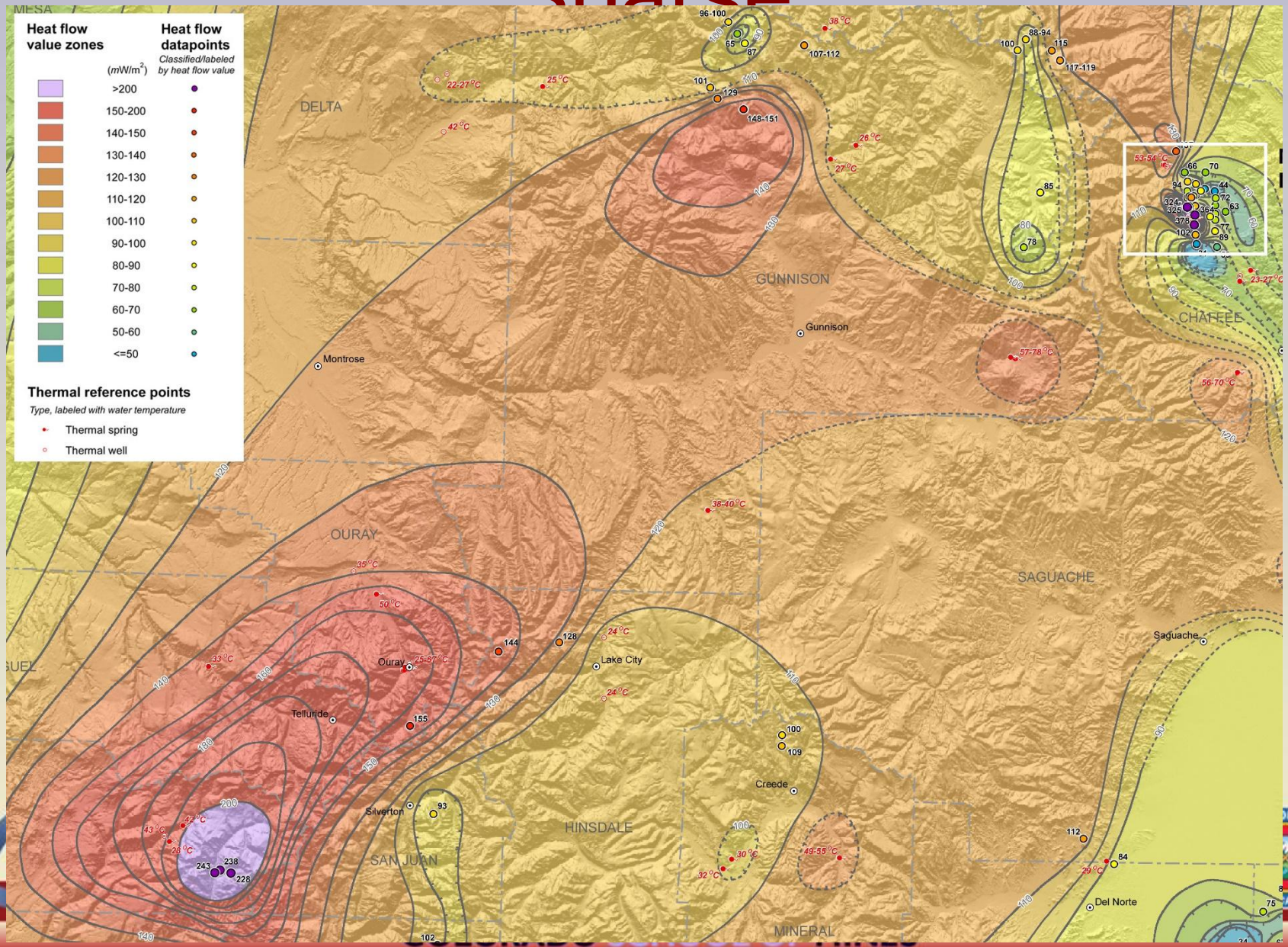
Gradients from BHTs Divided by Stratigraphy

- Statewide gradient maps made for BHTs in 8 stratigraphic intervals in °C/km and °F/100 feet, with 8 accompanying maps showing data points:
  - Maps only contoured in areas with data.
- Advantage:
  - gradient maps may be used to calculate temperatures in the specific stratigraphic interval of the BHTs used to create the map when correlated with stratigraphic information.
- Disadvantage:
  - multiple gradient maps required to cover essentially the same area

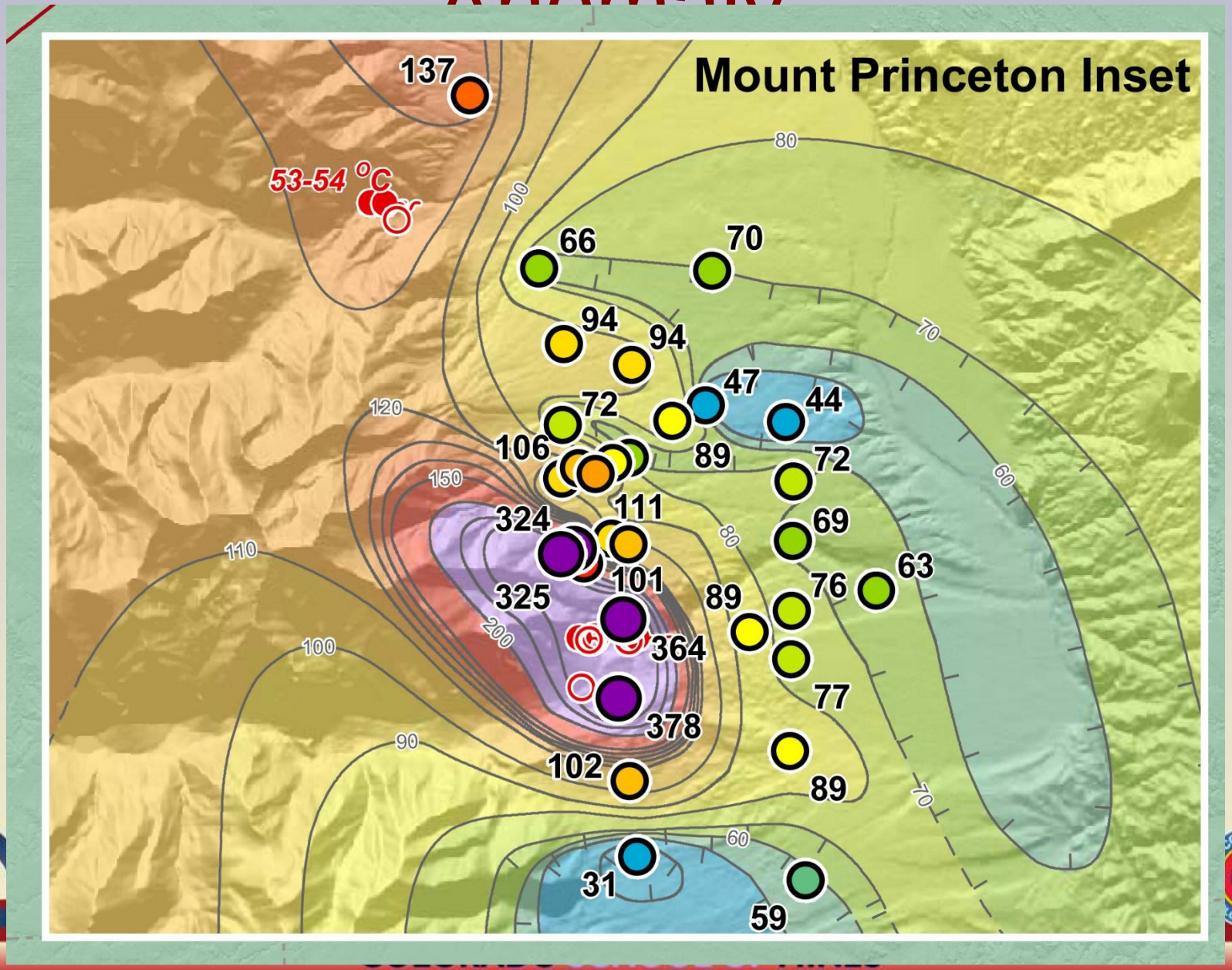
Colorado Heat-Flow Map (2007)



Heat-Flow Data Generally Sparse



Well-Defined Geothermal Anomaly



Features of Heat-Flow Map

- Map generated during period of renewed Interest in renewable resources to reduce CO_2 emissions.
- Contours in mW m^2 covering all state at 10 mW m^2 intervals based heat – flow measurements (determination of thermal gradient and thermal conductivity
- A correlation among heat flow and thermal spring temperatures was made – thermal spring temperatures plotted on map and used in contouring.
- Heat flow is independent of thermal conductivity – can be extrapolated to depth as long as thermal regime is conductive (excludes thermal springs!)
- Computer contoured – sparse high data points, especially thermal springs, resulted in relatively large areas contoured as having high heat flow.

What Guidelines Should be Used When Plotting Data on a (Geothermal) Map?

- I swear to plot the data, the whole data, and nothing but the data.
- Only plot contours in areas where there is a sufficient data density to define the contours.
- Only plot contours that have some limit or definition to their extrapolation.
- Do not commingle different types of data that have very different depth signatures, e.g. heat flow, geothermal gradients, and thermal springs.

Revised Colorado Geothermal Map

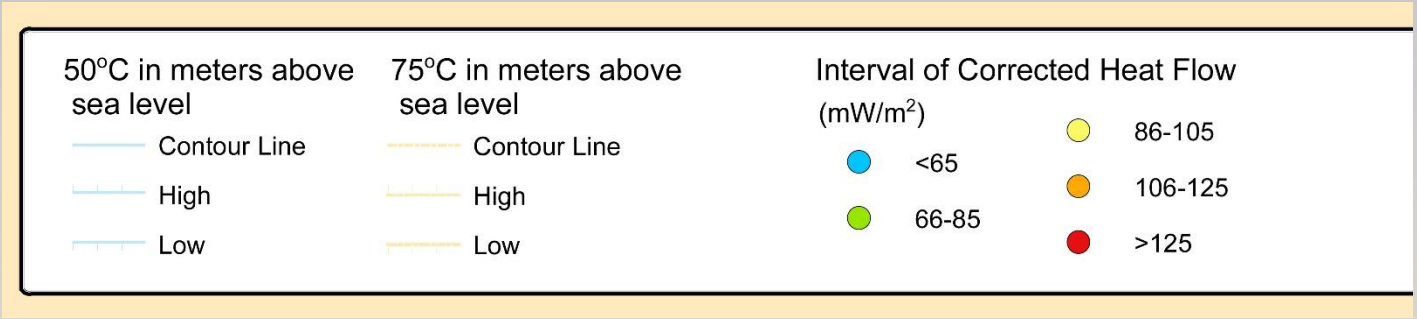
- Map not to be produced as a ‘stock’ (paper or CD) item: a ‘standard’ version with explanatory text will be available for download as a PDF file and as GIS layers or printed on demand at cost. All data used to produce map will be available for download. Map (and downloadable databases) will be revised/updated as new data become available.
- Second (preferred) option will be an online version of the map in which different data sets and base maps may be chosen. If point datasets are chosen (e.g., heat-flow, thermal springs), when the cursor is moved over these points a box will pop-up with basic information defining the data such as basic parameters and location. An option will be available for downloading a printable version of the build-it-yourself geothermal map.

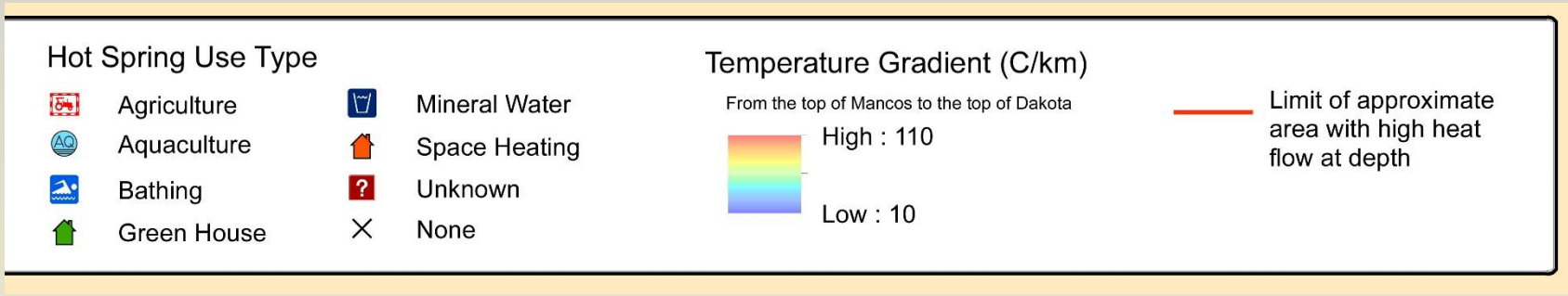
Basic Features to be Included on the 'Standard' Geothermal Map*

- Shaded topography base map.
- Geothermal gradients contoured from corrected BHTs from stratigraphic interval from Mancos to Dakota.
- Contours of depths to 50°C and 75°C isotherms based on corrected BHTs where BHTs reached these temperatures.
- Point data for heat-flow, thermal springs, and thermal-spring direct use.
- Outline of "most prospective" area for geothermal resources.

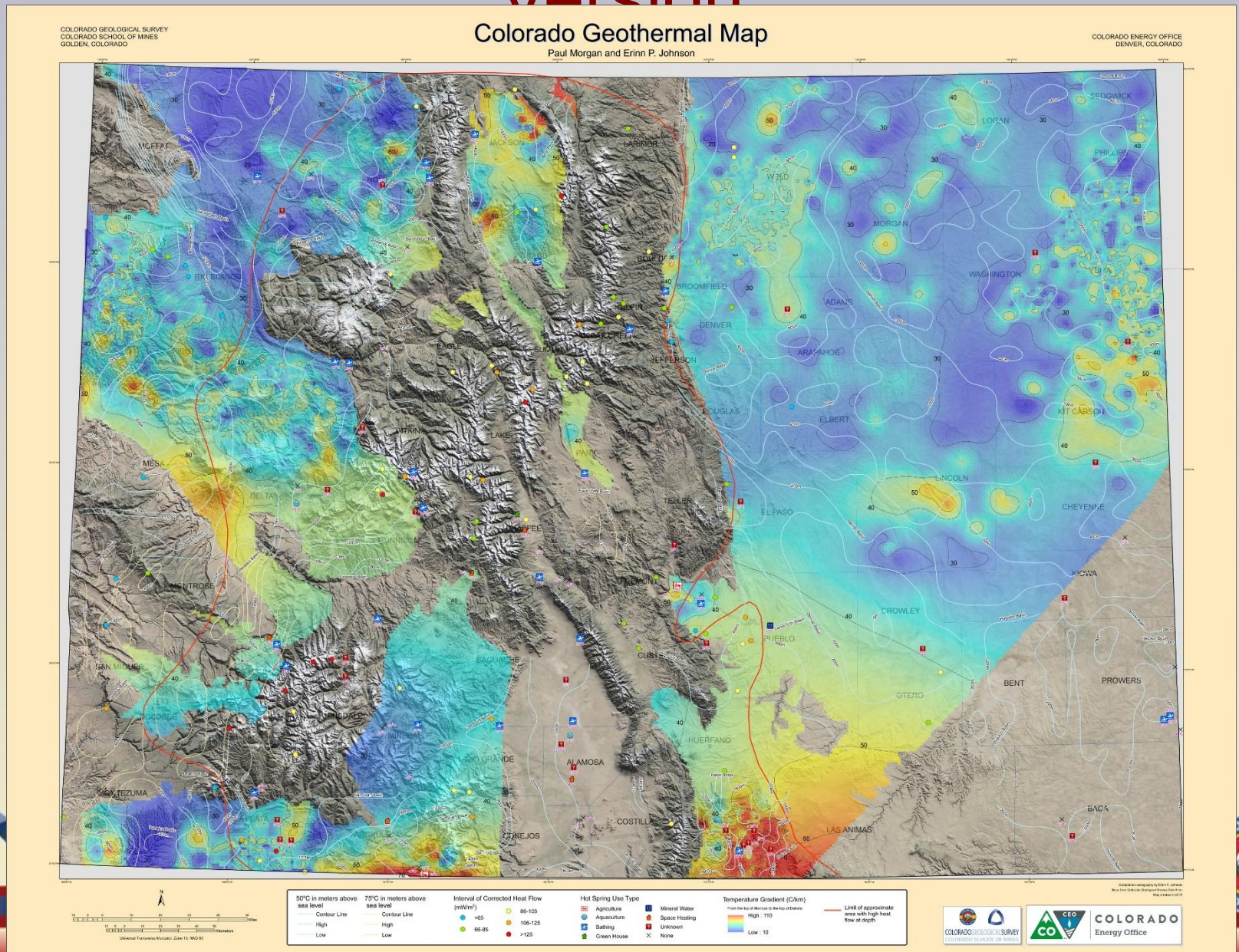
* two versions of map, one SI units and one Imperial units

Key to Basic Geothermal features on ‘Standard’ Map – Metric Version

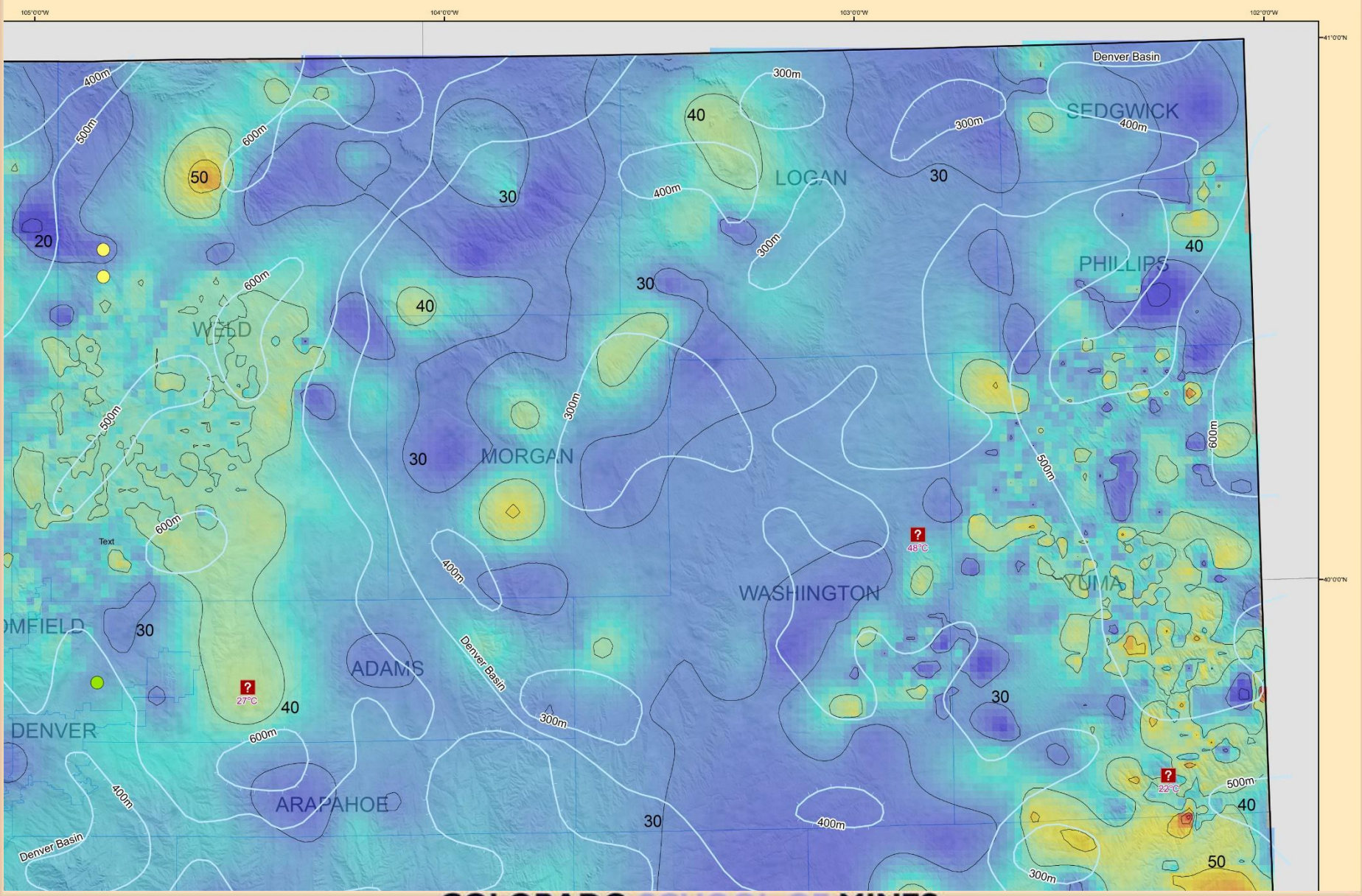




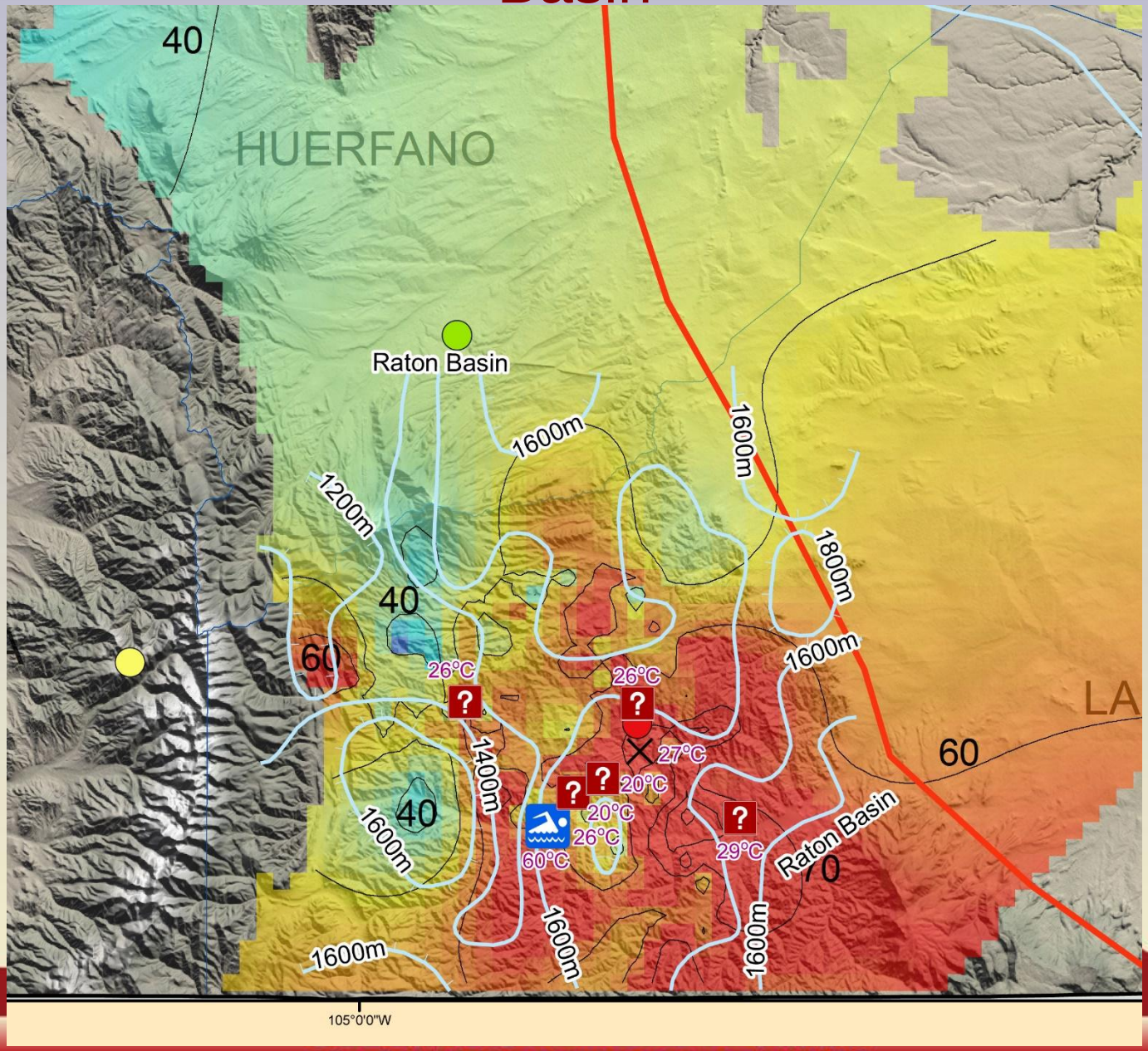
‘Standard’ Geothermal Map - Metric Version



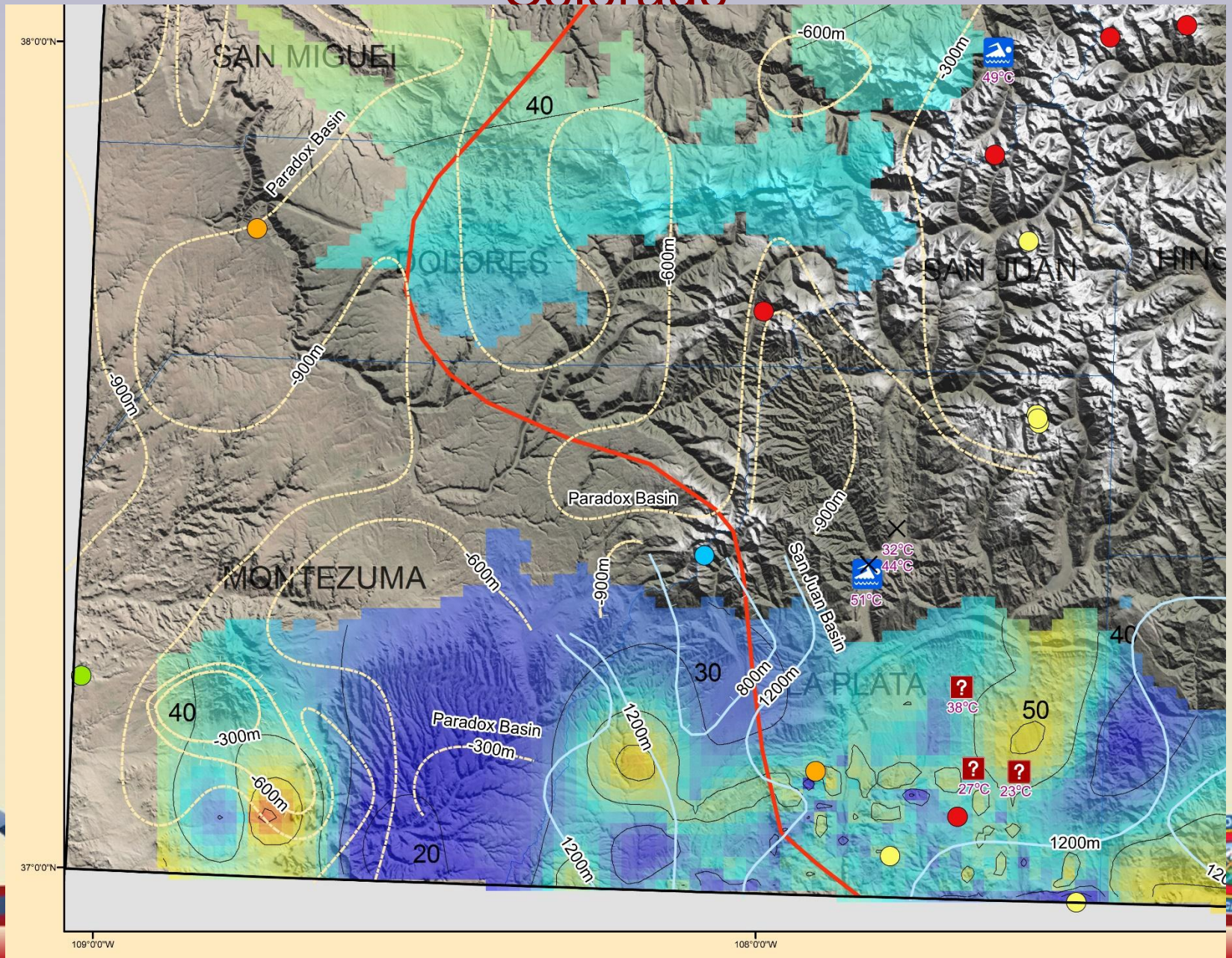
‘Standard’ Geothermal Map – Metric Version – NE Colorado



‘Standard’ Geothermal Map – Metric Version – Raton Basin



‘Standard’ Geothermal Map – Metric Version – NE Colorado



Concluding Remarks

- New map(s) and definitions of “practical” and “useful” used here have been designed based on observations of how clients have used previous versions of “geothermal” maps of Colorado – if an area is contoured as “hot”, regardless of data density, the map is generally assumed by clients to be correct.
- Clients like to extrapolate temperatures to depths far beyond their validity – useful for a map to indicate a limit to the validity to which mapped observations may be extrapolated.
- Current technology that allows the creation of custom maps on the web has made standardized paper and CD maps obsolete.
- Thank you for your attention.