OPEN-FILE REPORT 02-15

Evaluation of Bottom-hole Temperatures in the Denver and San Juan Basins of Colorado

by

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FOREWORD

The purpose of Colorado Geological Survey Open File Report 02-15 is to create a bottom-hole temperature (BHT) database and analyze the data for reliability and geologic trends. The Denver and San Juan Basins were chosen for the study. The database contains 10,072 BHTs from the Denver Basin and 836 BHTs from the San Juan Basin. The bottom-hole temperatures were entered into a Colorado Oil and Gas Conservation Commission database, graphed in Excel™ and mapped in Petra™ and ArcView™. The objective of this publication is to provide a bottom-hole temperature database and analysis to resource developers and interested citizens.

Funding for this project came from the Colorado Department of Natural Resources Severance Tax Operational Fund. Severance taxes are derived from the production of gas, oil, coal, and minerals.

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INTRODUCTION

The maximum recorded temperature or bottom-hole temperature (BHT) has been an important piece of data to drillers for managing the wellbore, to geologists for prospecting, and to reservoir analysts for calculating reserves. Much has been written about the many factors that influence the BHT such as well depth, circulation rates and duration, hole radius, specific heat capacity of the formation rock, density of the formation rock, thermal conductivity, and surface temperature. Edwardson, and others (1962) and Middleton (1982) describe complex methods of using BHTs to calculate true formation temperatures. Fertl and Wichmann (1977) and Fertl (1978, 1985) describe simpler methods of estimating formation temperatures. A great deal has been published about using BHTs for calculation purposes, but little has been published about the use of raw BHT data on its own because of the questionable reliability of the data due to many of the influences mentioned above.

The purpose of this study is not to determine true formation temperature. Instead, three other purposes are addressed in this report:

1. To create a bottom-hole temperature database
2. To look at the reliability of the raw BHT data and what factors not mentioned above might influence the temperatures
3. To determine what geologic trends, if any, can be mapped using bottom-hole temperatures.

DATA ACQUISITION

The Denver and San Juan Basins of Colorado were chosen for the study (Figure 1). Bottom-hole temperatures from the main producing formations in each basin were used as the focus of the study. The well database from the Colorado Oil and Gas Conservation Commission (COGCC) was downloaded from the Internet and loaded into an Excel™ spreadsheet. In the Denver Basin, well log headers from microfilm were used to obtain maximum temperatures and hours-since-circulation data (Appendix A). In order to be consistent, all maximum temperatures recorded or BHTs were recorded from induction logs since they were the logs most widely available throughout the basin. In the more densely drilled areas, up to 3 BHTs per section were recorded. Driller's total depth, ground elevation, and reference elevations from the log headers were corrected or added to the COGCC database. Spot checks were made in the database for location and formation at total depth. Next, the elevations of the bottom of the hole were calculated. BHTs were "normalized" by calculating temperatures using a temperature gradient of 1.7°F/100' and adjusting all to an elevation of –4000' (or 4000' below sea level).

The San Juan Basin BHT database was provided by Dick Baughman, geologist with the Southern Ute Indian Tribe (SUIT). Some Dakota Formation temperatures were added to the database. Contour maps of the BHTs were made using Petra™ and ArcView™. Graphs were made in Excel™.

DENVER BASIN ANALYSIS

The Denver Basin is an asymmetric foreland basin with a gently dipping flank to the east and a steeply dipping flank to the west. It covers much of the northeastern part of Colorado. The shape of the basin is reflected in Hemborg's 1996 Basement Structure Map of Colorado (Figure 2). Wells used in this part of the study are located in all or parts of Logan, Weld, Morgan, Washington, Adams, Arapahoe, Elbert, Boulder, and Larimer Counties. A total of 10,072 BHTs were recorded; 7,305 were from the Dakota J Sandstone. The remaining BHTs came mainly from the Sussex, Dakota D, Benton, Skull Creek, and Codell sands, and Precambrian formations (Figure 3).

The first step in analyzing the data in the Denver Basin was to record and plot temperatures from the Dakota J Sandstone in Townships 2N, 49W-70W. This was done to see if the data were reliable enough to reflect the basin's structural configuration with the deepest part in the west, rising to shallow depths in the east. The temperature trends were plotted and compared to the basement structure map. Figure 4 shows a greater scatter of the hotter BHTs in the western part of the basin and less scatter of the cooler BHTs in the eastern portion of the basin. The BHTs were then normalized by adjusting the temperatures to an elevation of –4000′ using an overall gradient of 1.7°F/100′, but are plotted at original elevations so the data do not plot along a single line at –4000′ (Figure 5). The normalization of BHTs flattens the data somewhat, but the large scatter of temperatures in the western part of the basin and the "bend" in a zone around Ranges 55W-60W indicate that there is more than one temperature gradient within the basin.

Next, BHTs were recorded and analyzed throughout the Denver Basin. In spot-checking the formations at total depth on the log with formations at total depth on the COGCC database, there were some inconsistencies in recording the Dakota Formation D and J sands. A plot of elevation-versus-maximum temperature of the two sands showed no significant difference in trends (Figure 6), so the data were grouped together and henceforth will be referred to as the "Dakota Formation".

Figure 7 is a plot of bottom-hole temperatures of all Dakota Formation wells showing elevation-versus- maximum temperature. The plots are oriented to reflect the temperature increasing as it would when drilling, top to bottom, and the elevations of the basin shallowing from left or right or west to east. There is a great deal of scatter in the data in the western part of the basin, but a tightening of the data to the east. Considering all that has been said and written about the unreliability of BHT temperatures, the data are amazingly well behaved. Of course, the degree of reliability depends on for what purpose the data are being used. The normalized BHTs were plotted to determine if the data might tighten when all depths were the same (Figure 8). As with the graphs of the Township 2N data, the normalized temperatures were plotted using original elevations. Data in the western part of the basin remained scattered, but the central and eastern data tightened somewhat. The same bend in the trend as seen in the Township 2N data (Figure 5) is seen in the all wells data indicating a change in the temperature gradient in the eastern part of the basin. The next step was to try to determine what geologic factors might cause the scattering of the data in the western part of the basin.

Two contour maps were made using Petra ™ and ArcView ™. The first was a contour map using the raw BHTs with the Dakota Formation at TD (Figure 9). Contours from Hemborg's (1996) basement structure map overlay the BHT contours. A strong hot trend runs through the center of the Wattenberg field and continues, less strongly in a northeasterly direction, seen by the warmer contour colors. There is also a general increase in temperatures along the Front Range. The hot trend cuts across Hemborg's basement contours, indicating that the trend is not related to the overall structural trend of the basement. There were not enough basement penetrations for Hemborg to map details of the basement. The second map made was from the normalized BHT contours with the same basement structure overlay (Figure 10). Although the hot trend was still present in the normalized BHT map, it was not as obvious, probably because the normalizing introduces as many errors as it corrects for depth. Next, the raw BHT contour map was overlain by the Muddy (J) Sandstone structure contour map from Hemborg (1993) (Figure 11). Looking at the overall color bands, rather than the individual contours, the BHT contours generally follow the trend of the Muddy contours in the eastern and central parts of the Basin. The hot trend in the Wattenberg Field has the same trend as the main faults mapped in the western part of the basin. Finally, the BHT contour map was overlain by Weimer's (1996) wrench faults that are a northeast extension of the Colorado Mineral Belt (Figure 12). The BHT hot trend in the Wattenberg Field is bound by two of the wrench faults; both have the same northeasterly trend. These faults are thought by some to have only vertical movement characteristic of normal faults. Other geologists, however, believe that movement along the faults has both a vertical and horizontal component, typical of wrench faults. Regardless of the actual displacement, the faults appear to be deep-seated enough to provide a conduit for heat into the Denver Basin. The BHT hot trend is also coincidental with an area having an increase in the temperature gradient described by Myer and McGee (1985) and overpressuring described by Hemborg (1993).

One of the factors influencing BHT is the amount of time between when mud circulation ceases and when logging begins and the bottom-hole temperature is recorded, or "hours since circulation". Trend lines were plotted on a BHT graph of wells with Dakota Formation at total depth (Figure 13). The wells were divided by hours since circulation: 1-3 hours, 3-5 hours, and greater than 5 hours. In the deepest part of the basin, the trend lines are separated by about 30°F from the least amount of time to the greatest amount of time, with the greatest amount of time being the hottest. However, in the shallower part of the basin, time becomes less of an influence and the trend lines cross. Edwardson, and others (1962) found differences in dynamics between temperatures in deeper holes and shallower holes. The trends found in the Denver Basin seem to support that finding. The hot trend in the western part of the Basin also influences the trend lines.

Several less-obvious influences on BHTs were plotted. A comparison of temperatures and completion dates was made. Figure 14 shows an increase in bottom-hole temperatures starting in about 1970. A plot of elevation-versus-completion date correlates that increase in maximum temperature with an increase in drilling depth (Figure 15). Another comparison of BHTs of oil wells-versus-gas wells was made. When development oil wells were plotted with development gas wells, the gas trend line was about 10°F hotter than the oil-trend line throughout the basin (Figure 16). However, when the Wattenberg wells in the hot area were removed from the plot, the separation of trend lines did not hold up (Figure 17).

Since surface temperature is one of the factors used in calculating true formation temperatures, BHTs were plotted by month of completion (Figure 18). No significant trend was noted. Finally, BHTs were plotted by operator (Figure 19) to see if trends might give some indication of logging practices that might affect the recorded BHTs. The wells plotted were limited to Wattenberg wells to limit some of the geological variability. Only five operators with the greatest number of wells used in the database were plotted. HS Resources' wells tend to be hotter than other operators, but those high BHTs were generally located in the BHT hot zone.

SAN JUAN BASIN ANALYSIS

The San Juan Basin is located in southwestern Colorado, in parts of La Plata and Archuleta Counties (Figure 20). The northern part of the basin was presumably uplifted with the formation of the Silverton Caldera located north of the map area. The Dulce-Archuleta Dikes are located in the southeastern part of the basin in New Mexico.

The database used in this part of the study was from Dick Baughman's (SUIT) 608 BHTs from the Fruitland Formation and Pictured Cliffs Sandstone, with an additional 228 BHTs from the Dakota Formation and one from the Pre-Cambrian (Figure 21). These temperatures were not normalized as in the Denver Basin because the data appeared to be most useful in its raw form.

First, the Picture Cliffs Sandstone and Fruitland Formation BHTs were plotted as maximum temperature-versus-elevation (Figure 22). The data are scattered and did not exhibit a tight trend. To see if the BHTs increased with depth, the data were plotted as driller's total depth -versus-maximum temperature (Figure 23). Again, the data show scatter, but it is clear that temperatures did generally increase with depth. Next, the Dakota Formation wells were plotted with the Fruitland Formation and Pictured Cliffs Sandstone data (Figure 24). The Dakota Formation BHTs were scattered, also, exhibiting similar characteristics of the scatter found in the Wattenberg area of the Denver Basin.

A contour map of the Fruitland Formation and Pictured Cliffs Sandstone BHTs (Figure 25) shows somewhat of a "hot" trend cutting through the Basin from southeast to northwest. The trend parallels the Point Lookout Formation and Fruitland Formation coalbed methane producing fairways as well as a "hingeline" assumed to be a margin between Precambrian blocks (Baughman, 2001, personal communication). The Dakota Formation BHTs were plotted and overlain on the Fruitland Formation and Pictured Cliffs Sandstone contour map (Figure 26). Because of the uneven distribution and few data points, the Dakota Formation wells were not contoured, but wells with temperatures less than 230°F were plotted in black and wells with temperatures greater than 230°F were plotted in red. The Dakota Formation "hot" wells generally follow the trend of the Fruitland Formation and Pictured Cliffs Sandstone hot trend. The coincidence of the two "hot" trends leads credence to the deeper structure influencing the temperatures.

The San Juan Basin BHTs were plotted with the Denver Basin BHTs for general comparison purposes. Although the San Juan Basin temperatures were more scattered, they did follow the general trend of the Denver Basin temperatures (Figure 27). The San Juan Basin BHTs never tightened as in the Denver Basin probably because the data are all located in and around the hot trend, whereas the Denver Basin data extends east, away from the influence of the deep structures. One San Juan Basin Precambrian BHT was plotted with 14 Denver Basin Precambrian or Granite BHTs. Driller's total depth was used rather than elevation because of the elevation differences between the two basins (Figure 28).

CONCLUSIONS

Each wellbore is subject to many influences that affect the BHT measurement recorded on the log, including drilling and circulation times, formation temperatures, and tool and operator error. These influences all work together to alter the measured BHT from the actual formation temperature. But, since most of the wells in an area are drilled under similar conditions, the BHTs will be influenced similarly, and thus will still reflect relative differences in temperature. Whereas the single BHT may not be a widely useful number, the greater number of BHTs may average out the influences and errors and give us useable temperatures.

Both the Denver Basin and the San Juan Basin bottom-hole temperatures exhibit trends or zones of higher temperatures. The Denver Basin hot trend appears better developed than the hot trend in the San Juan Basin. That may be due, in part, to the greater number and distribution of data in the Denver Basin. The relationship between the hot trend with well-documented deep structures in the Denver Basin and the hot trend with less-well document structures in the San Juan Basin show that BHTs are reliable enough to be used for something in addition to estimating formation temperatures and calculating reserves.

A summary of the conclusions of bottom-hole temperatures from the Denver Basin and the San Juan Basin are as follows:

1. Bottom-hole temperatures reflect deep-seated "hot trends" in the Denver and San Juan Basins.
2. Normalizing bottom-hole temperatures introduces errors and is not as useful as actual bottom-hole temperatures.
3. Bottom-hole temperatures increase as the "hours since circulation" increase.
4. The increase in Denver Basin BHTs over time correlates with the increase in drilling depths.
5. There is no apparent difference in bottom-hole temperatures between oil wells and gas wells.
6. The surface temperature, when plotted by month, has little apparent affect on the bottom-hole temperature.

7. Operator drilling practices do not appear to affect the bottom-hole temperature.
8. Deep-seated "hot trends" and the depth of the well appear to have the greatest effects on bottom-hole temperatures.

ACKNOWLEDGEMENTS

I wish to thank a number of people who helped make this study possible: to Joe Poole, of Schlumberger, for his discussions of the aspects of measuring bottom-hole temperature; to Jim Cappa, Cheryl Brchan, Nicole Koenig, and Jason Wilson, of the Colorado Geological Survey, for their technical guidance and assistance; and to Dick Baughman, of SUIT, for contributing his San Juan Basin BHT database. Finally, I give my sincere appreciation to Laura Wray whose help and encouragement throughout the study was invaluable.

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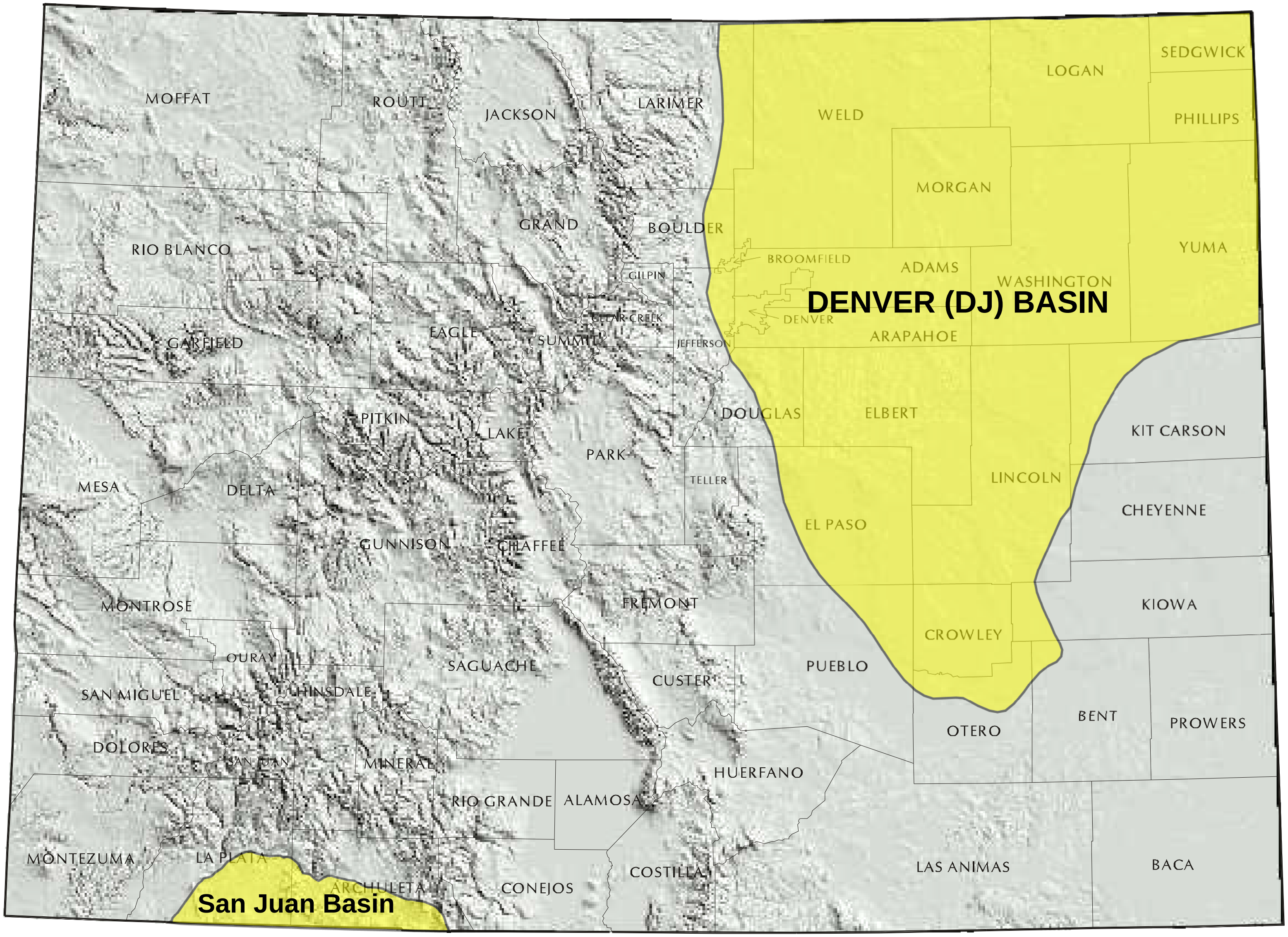

Figure 1. Colorado index map showing location of Denver (DJ) and San Juan Basins.

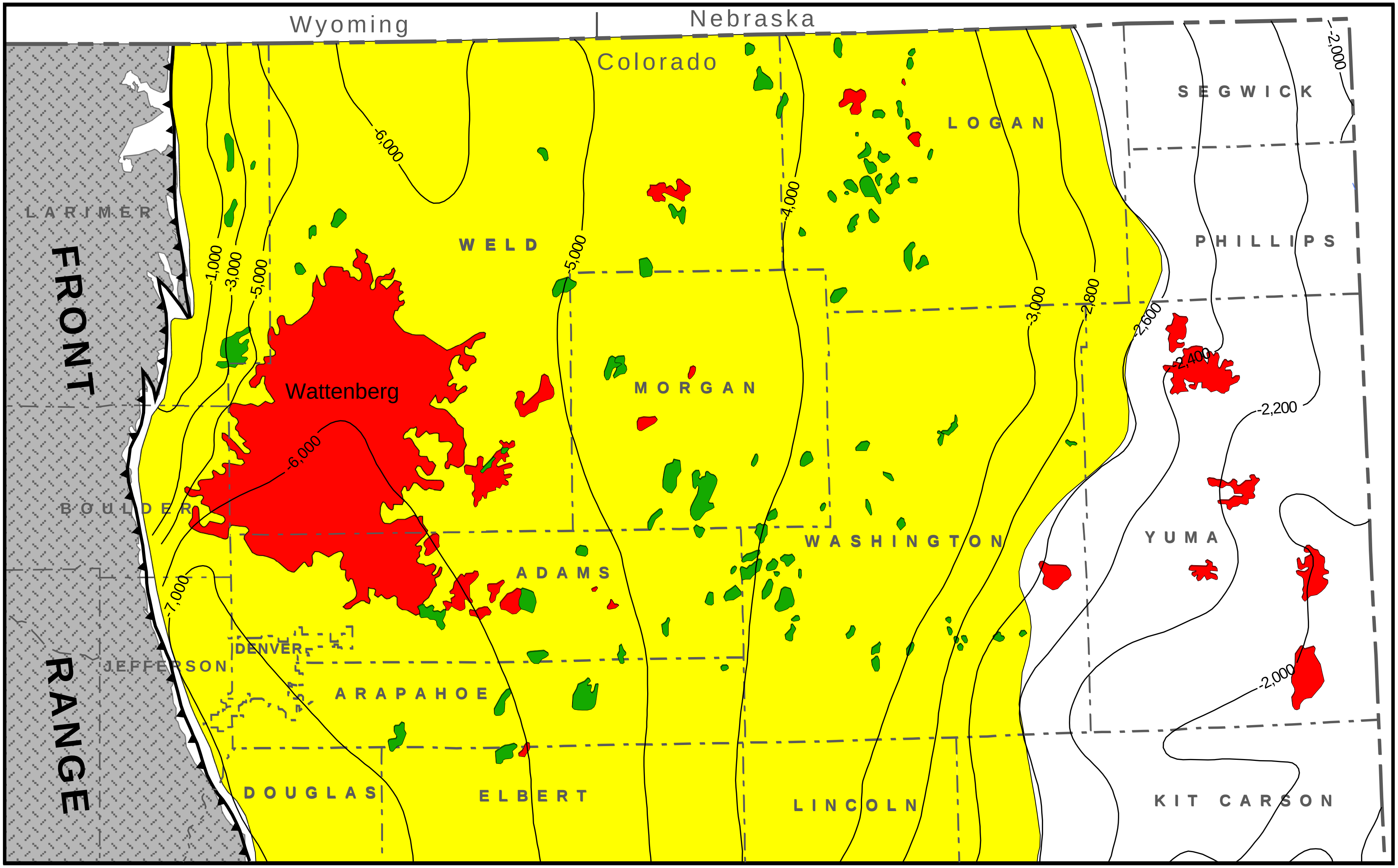

Figure 2. Denver Basin, showing the major oil and gas fields and basement structure contours. After Hemborg, 1996. Structure contours in feet above and below sea level. Oil fields are colored green. Gas fields are colored red.

STRATIGRAPHIC SECTION OF THE DENVER BASIN

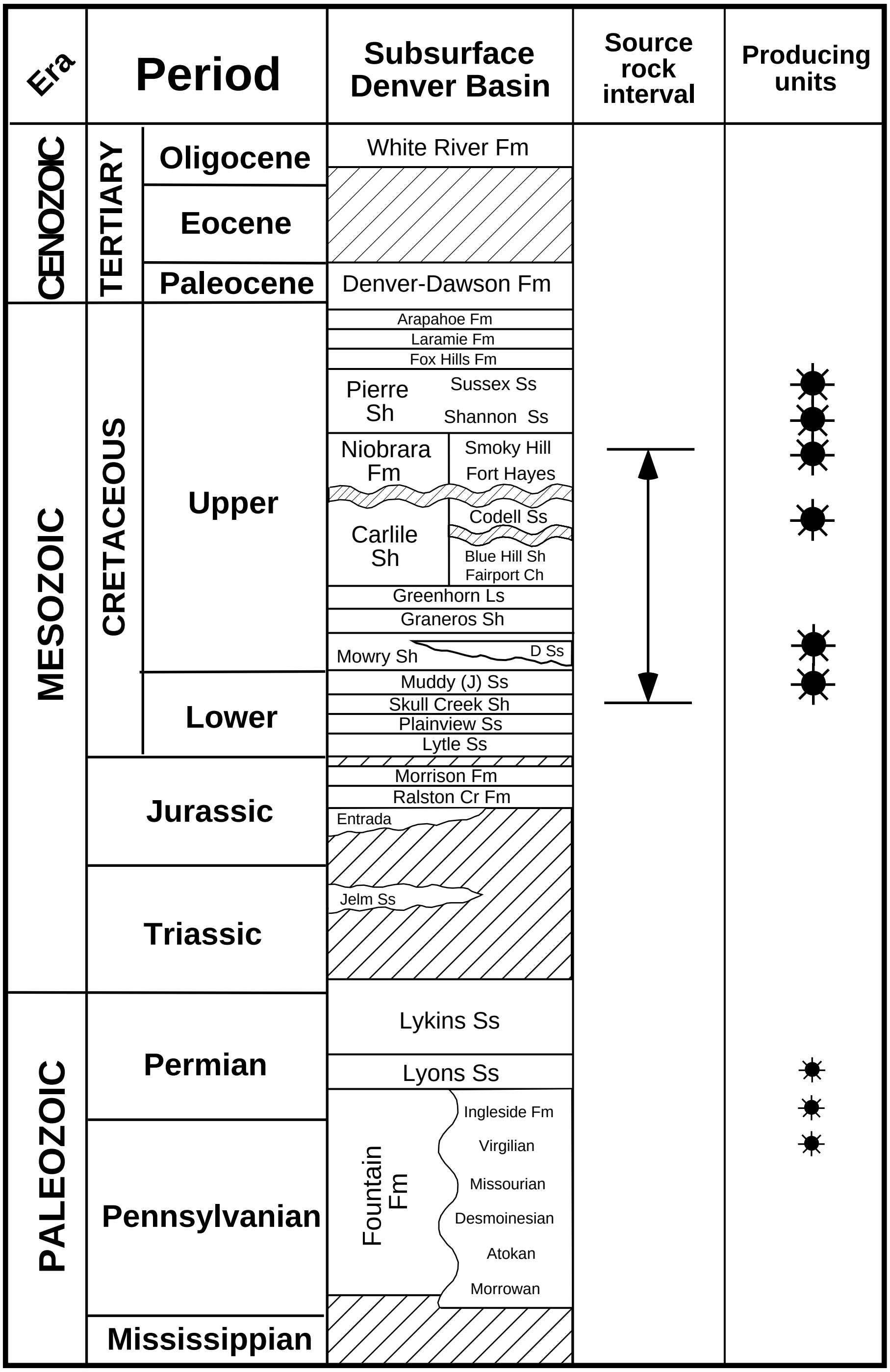

Figure 3. Stratigraphic section of the Denver Basin (from Atlas of Major Rocky Mountain Gas Reservoirs, 1993).

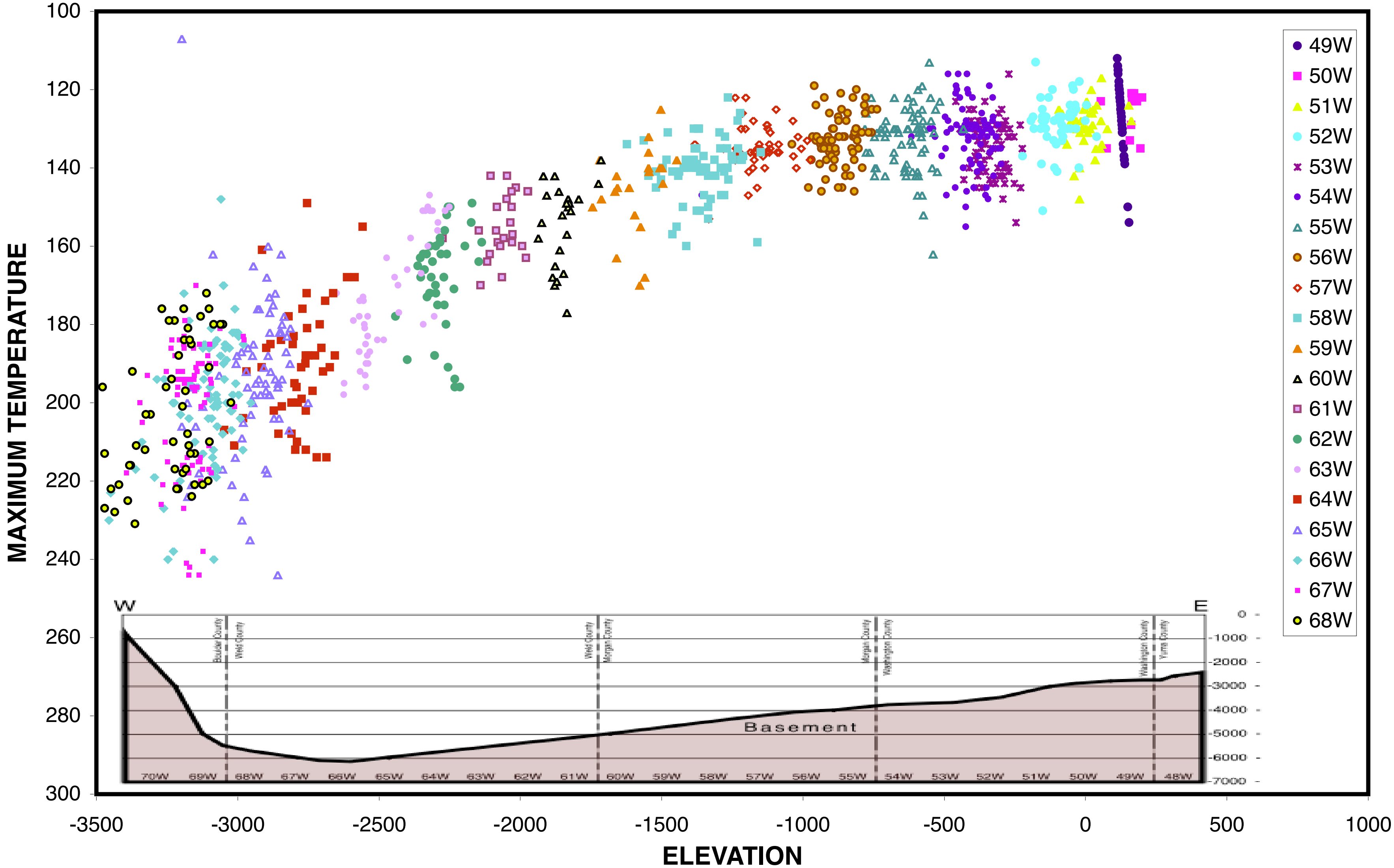

Figure 4: Plot of maximum temperature-versus-elevation, Dakota Formation at total depth compared with the basement profile of the Denver Basin. Township 2N, Ranges 49W-70W

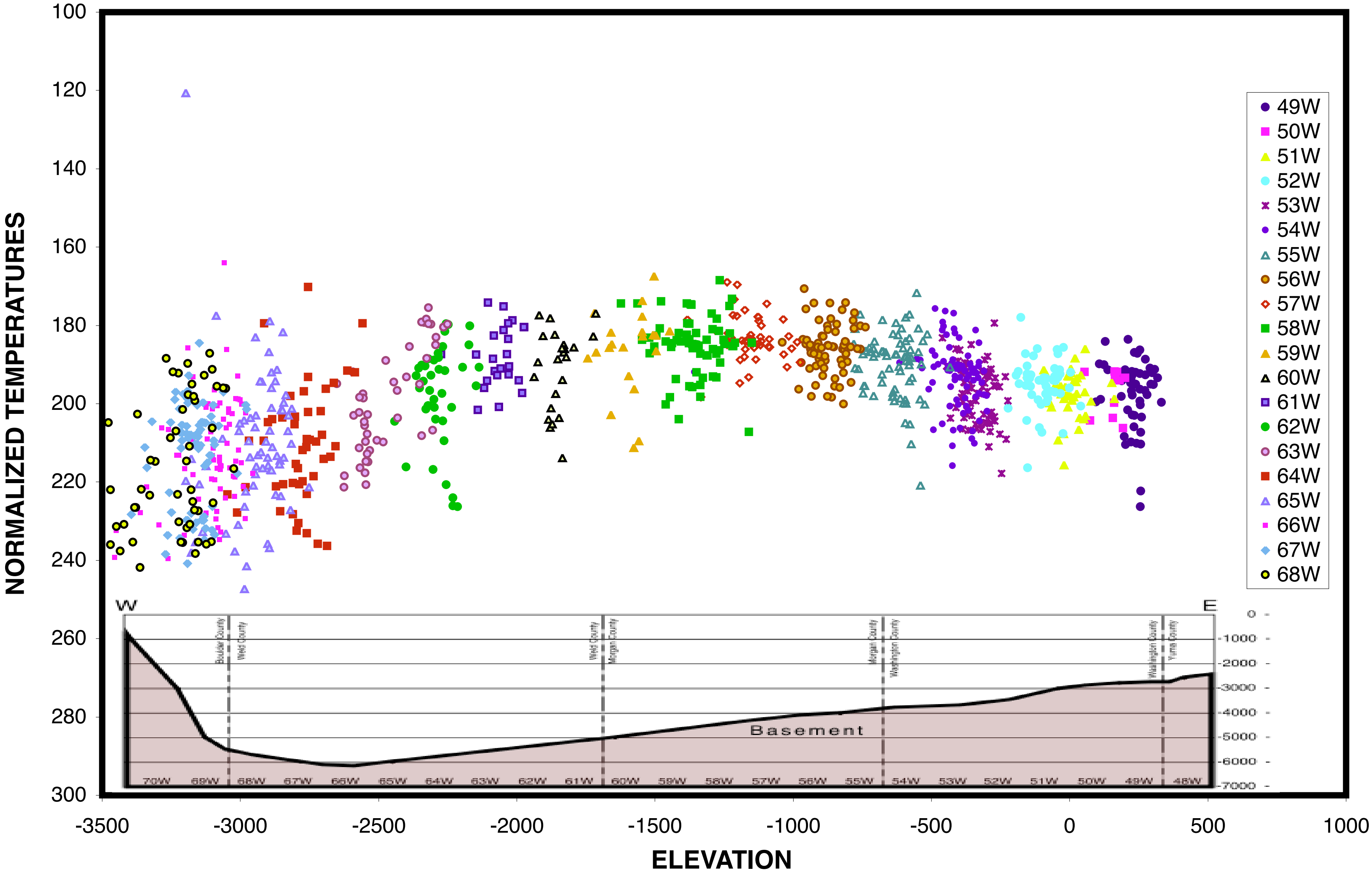

Figure 5: Plot of normalized temperatures-versus-elevation, Dakota Formation at total depth, compared with the basement profile of the Denver Basin. Township 2N, Ranges 49W-70W

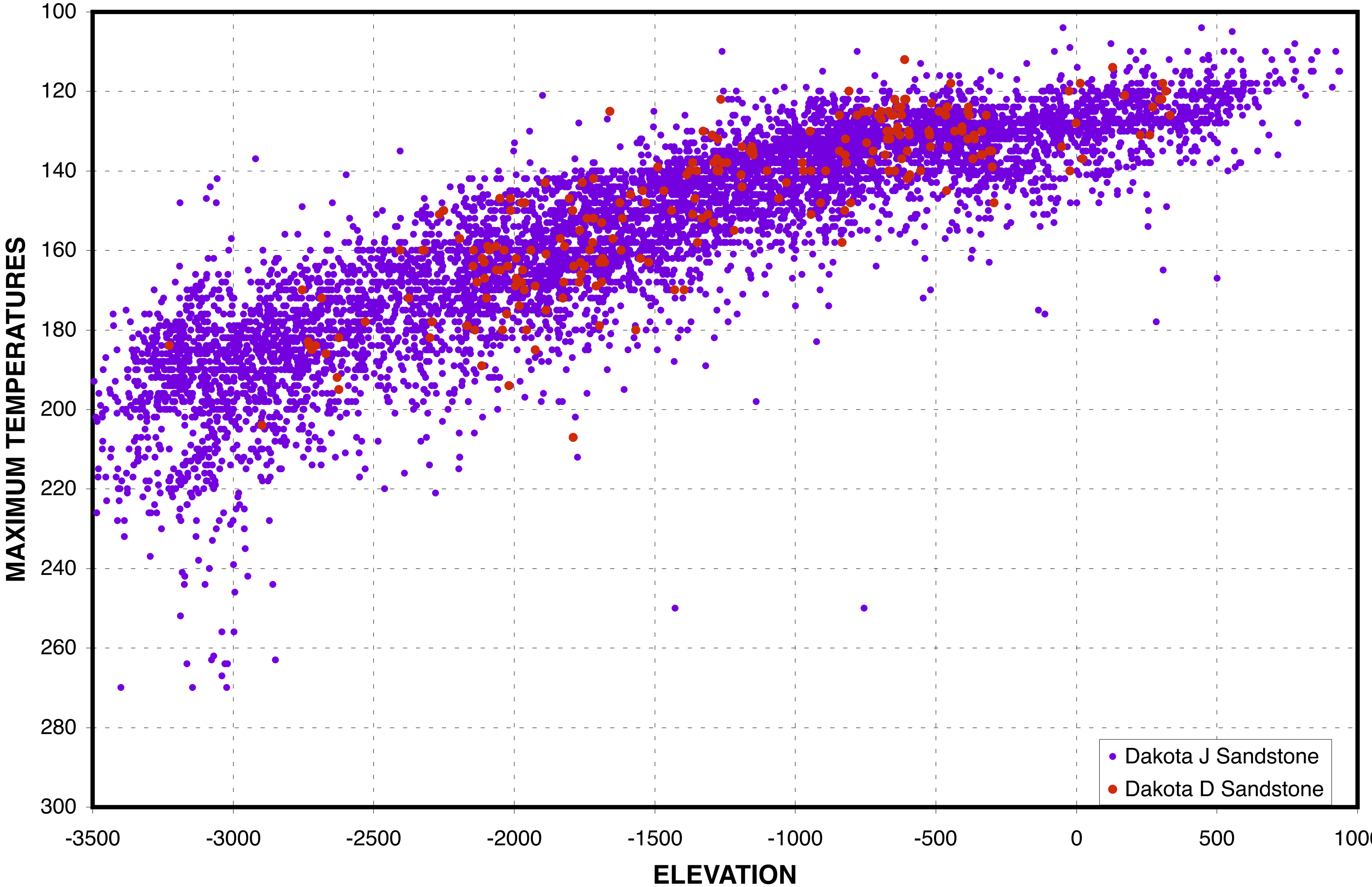

Figure 6: Plot of maximum temperatures-versus-elevation, Dakota J sands compared with the Dakota D sands.

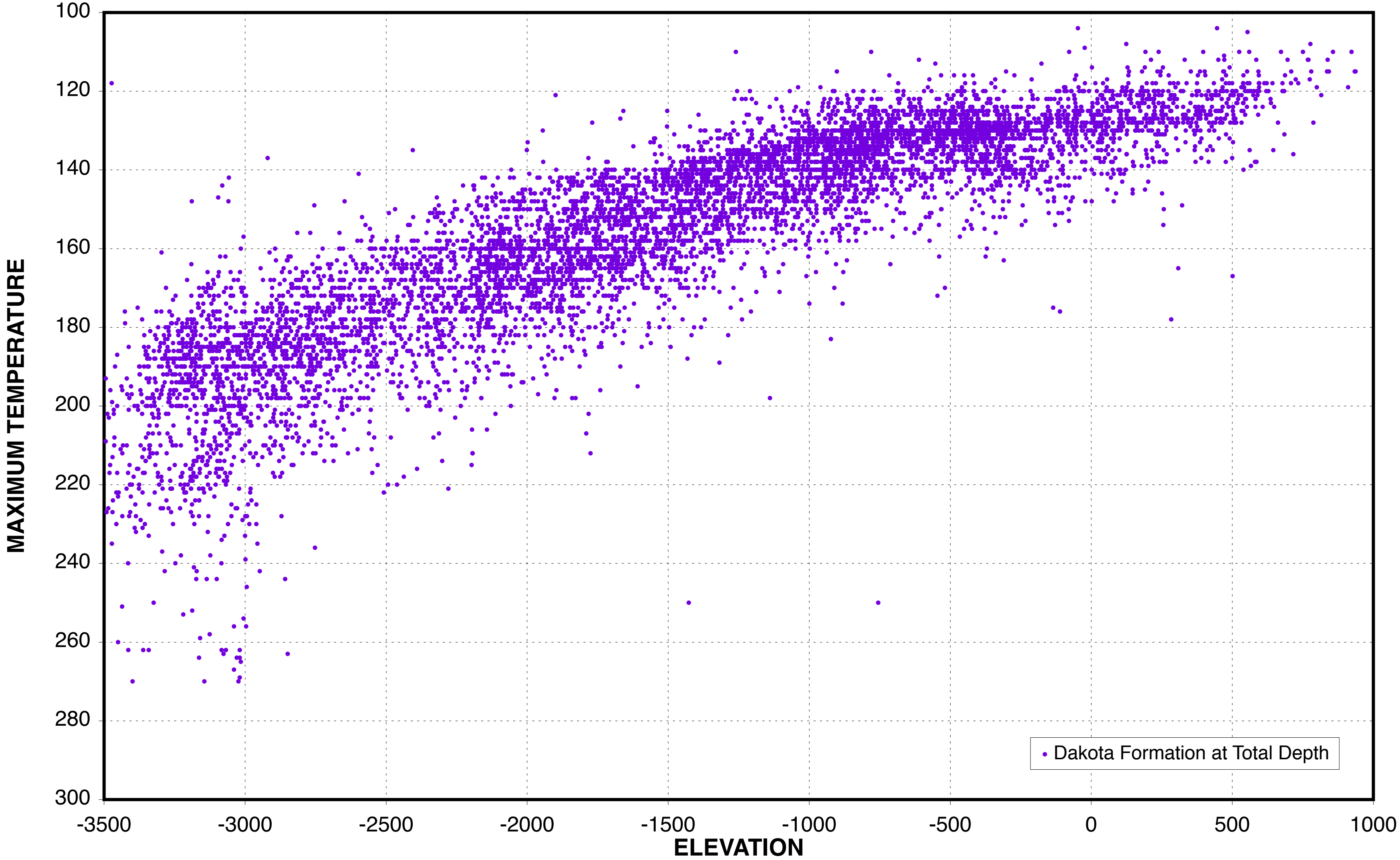

Figure 7: Plot of elevation-versus maximum temperature, Dakota Formation at total depth.

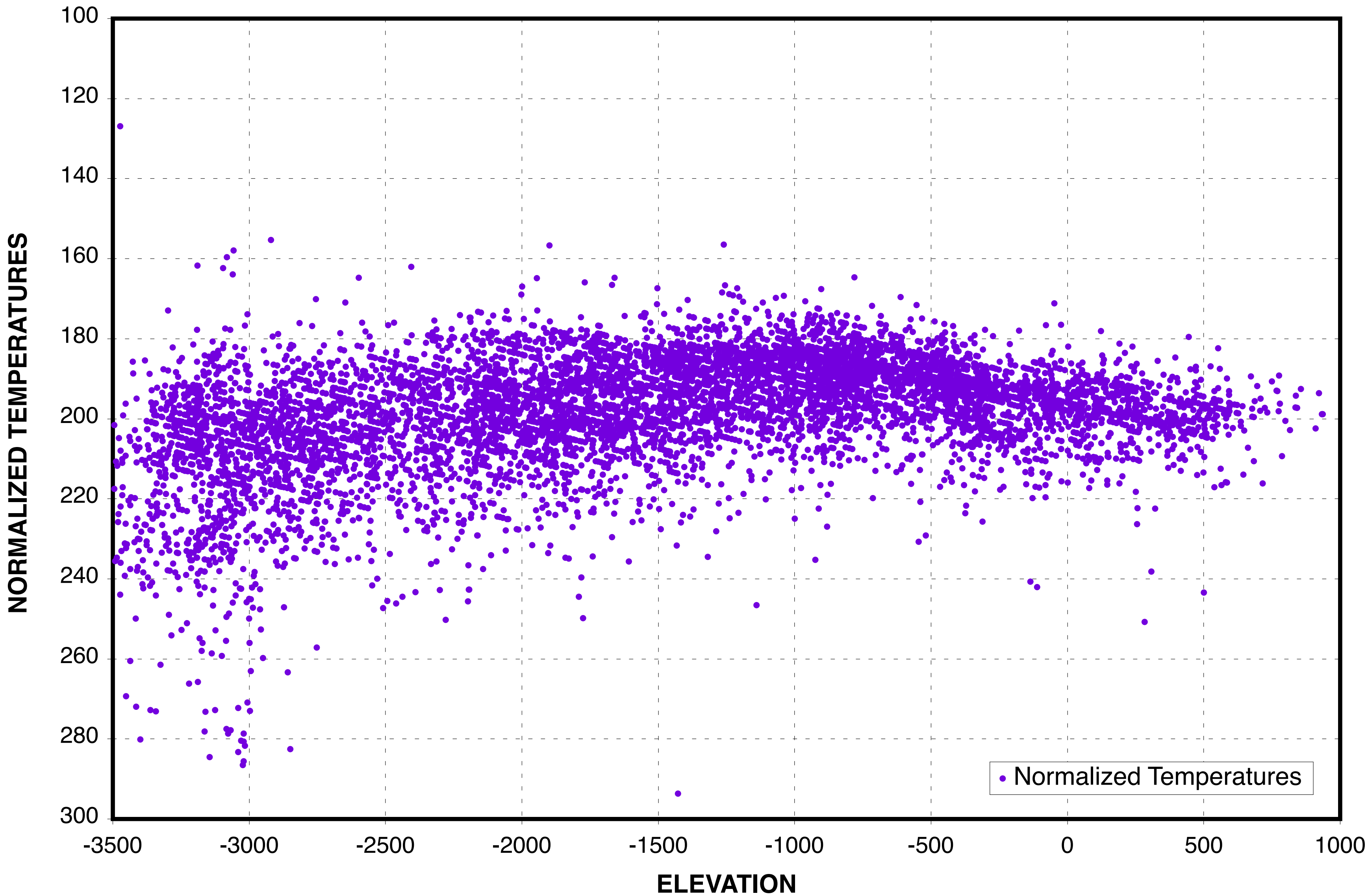

Figure 8. Plot of elevation-versus-normalized temperature, Dakota Formation at total depth.

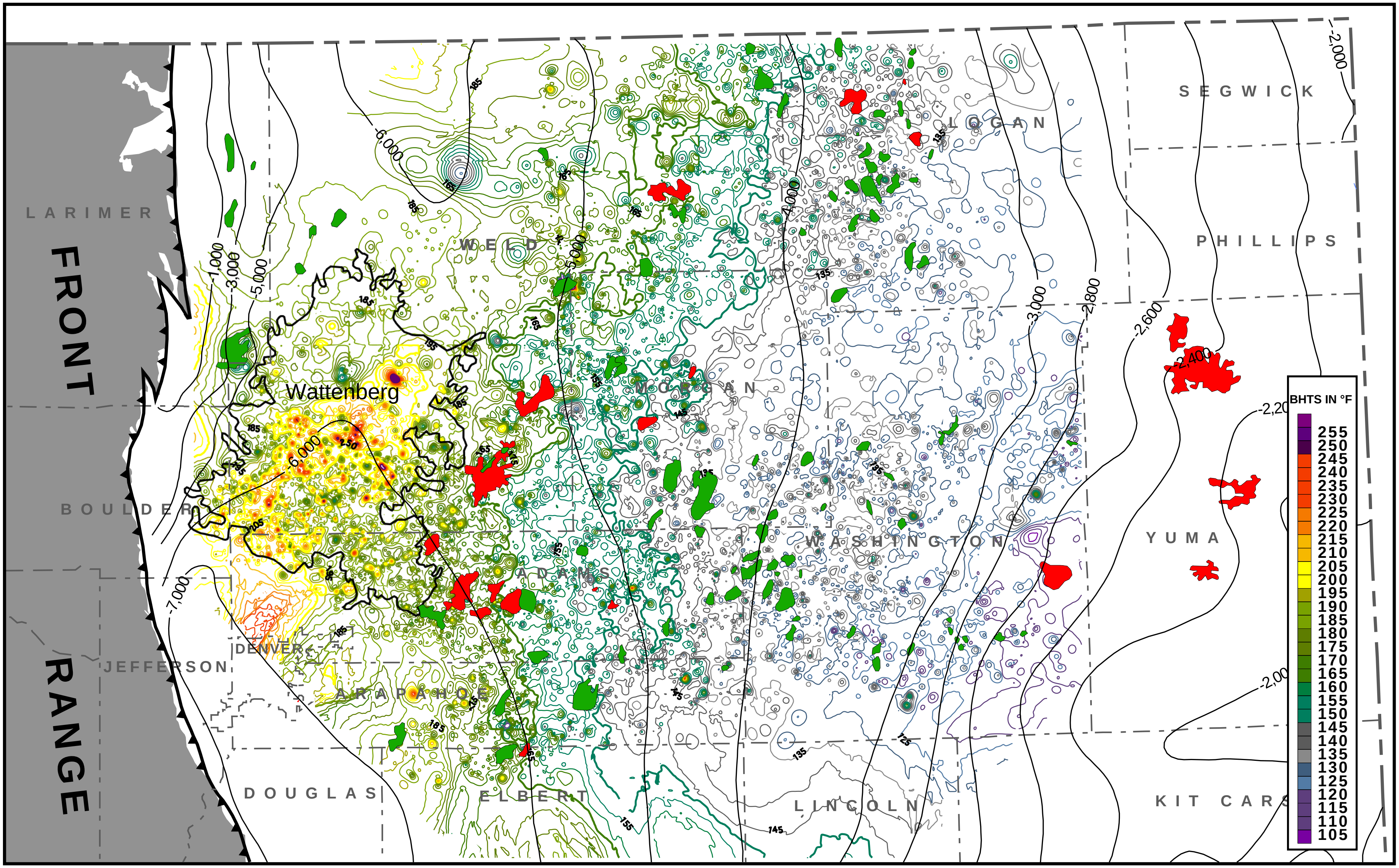

Figure 9. Contour map of BHTs of the Denver Basin wells, Dakota Formation at TD, overlain by basement structure contours. After Hemborg, 1996. Structure contours in feet above and below sea level. Oil fields are colored green. Gas fields are colored red.

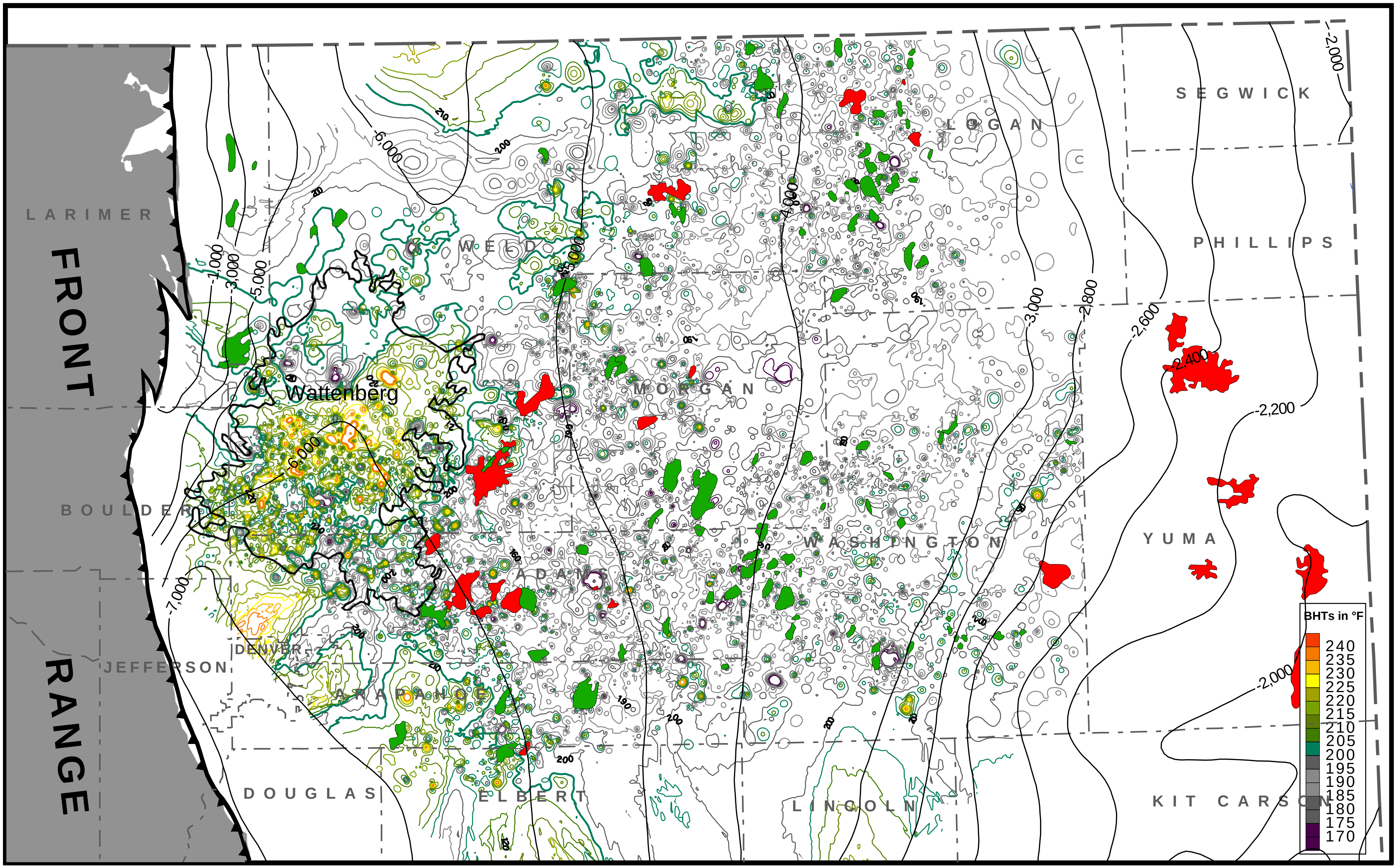

Figure 10. Contour map of normalized bottom hole temperature contours overlain by basement contours. After Hemborg, 1996. Structure contours in feet above and below sea level. Oil fields are colored green. Gas fields are colored red.

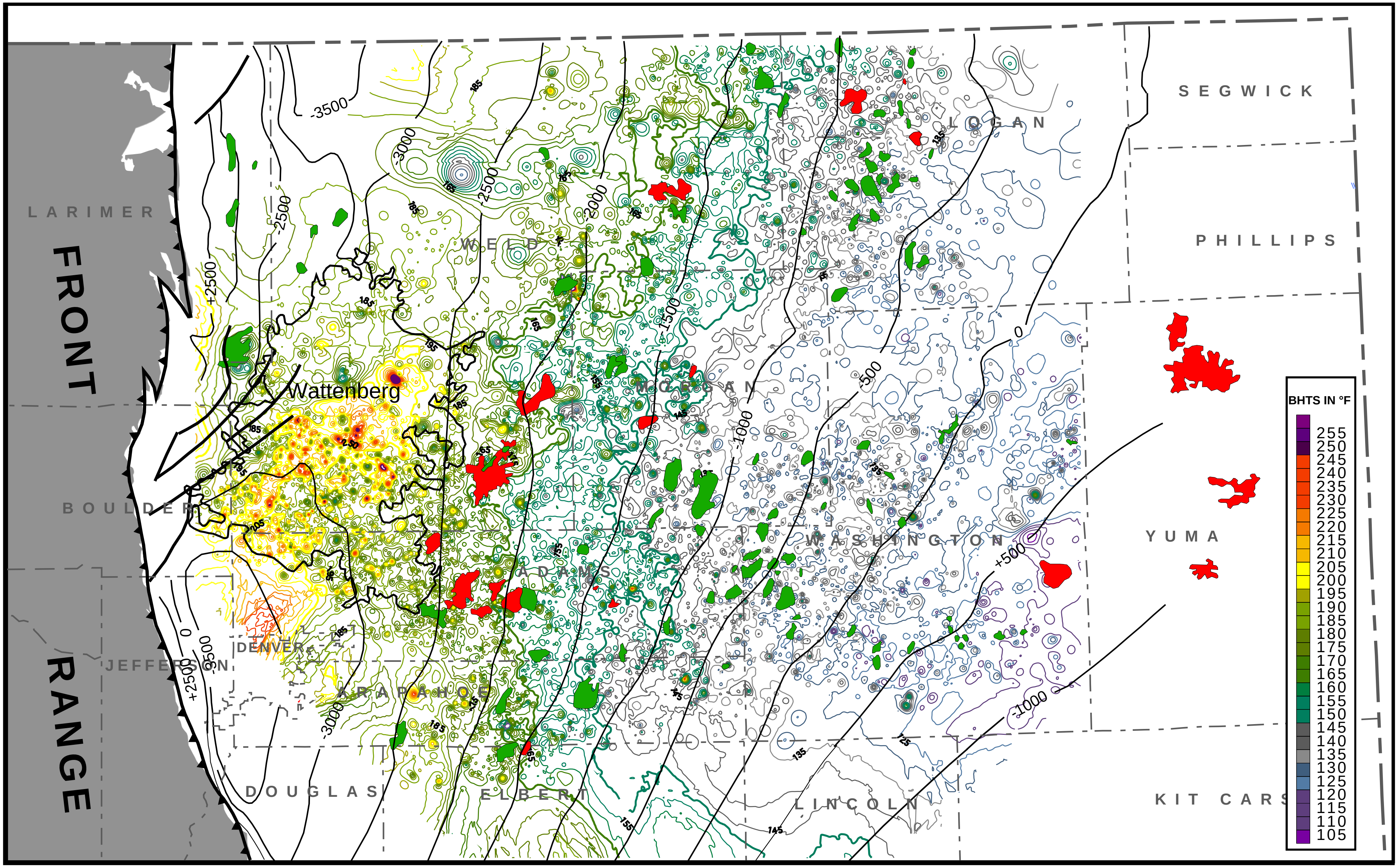

FIGURE 11. Contour map of BHTs of the Denver Basin wells, Dakota Formation at TD, overlain by Muddy (J) Sandstone structures. After Hemborg, 1993. Structure contours in feet above and below sea level. Oil fields are colored green. Gas fields are colored red.

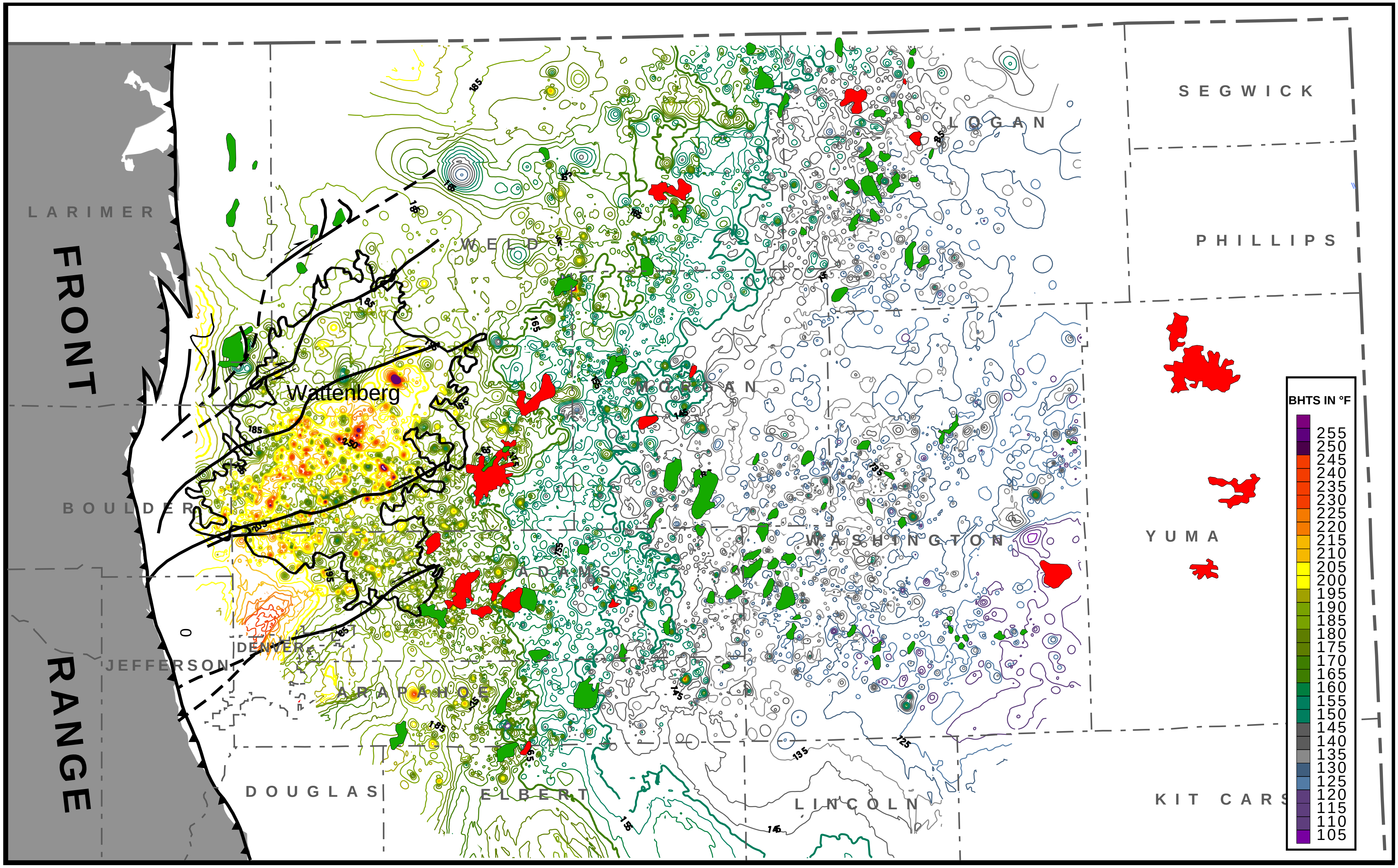

FIGURE 12. Contour map of BHTs of the Denver Basin wells, Dakota Formation at TD, overlain by wrench faults. After Weimer, 1996. Oil fields are colored green. Gas fields are colored red.

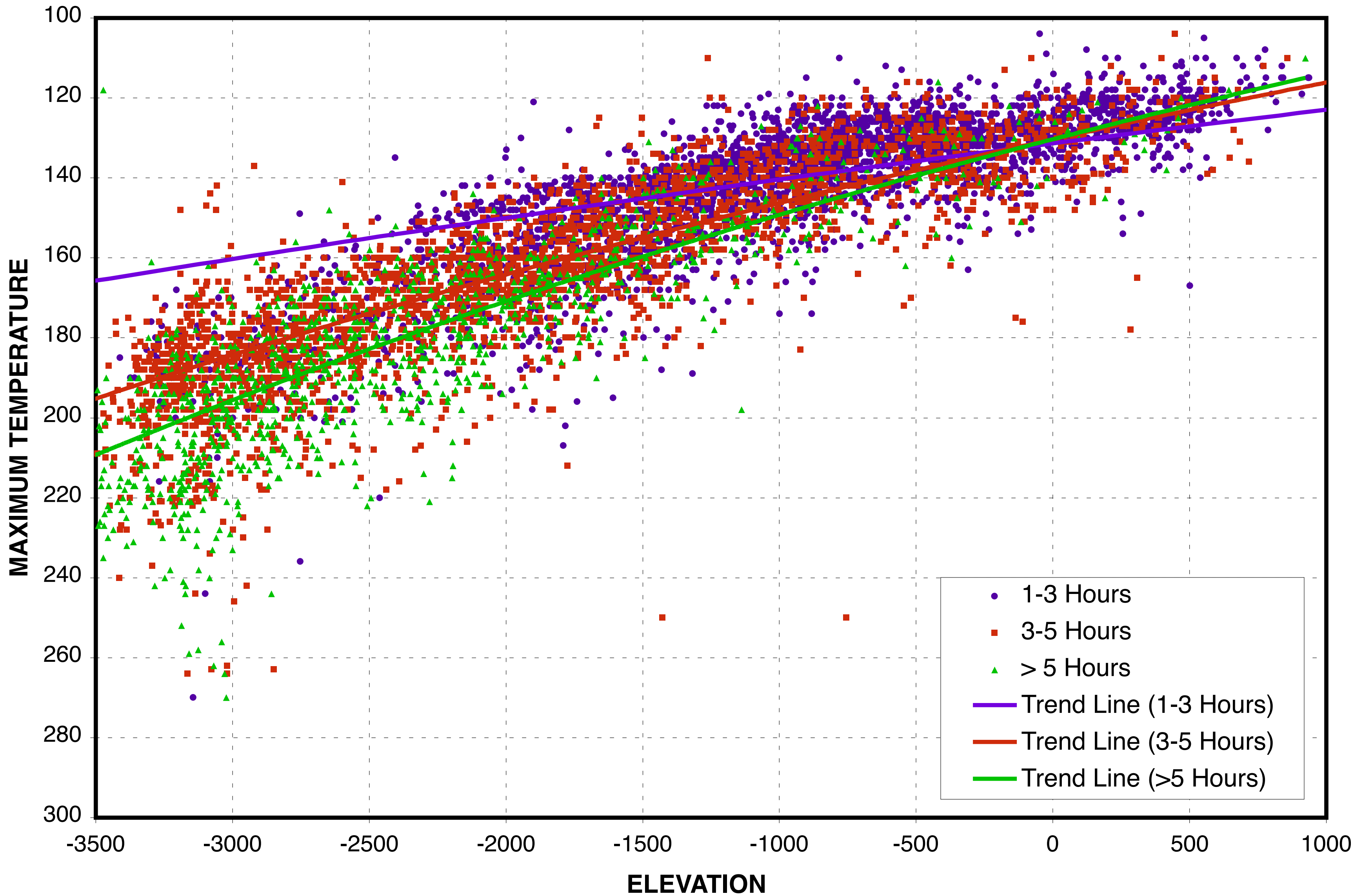

Figure 13. Plot of elevation-versus-maximum temperature, Dakota Formation at total depth, hours since circulation.

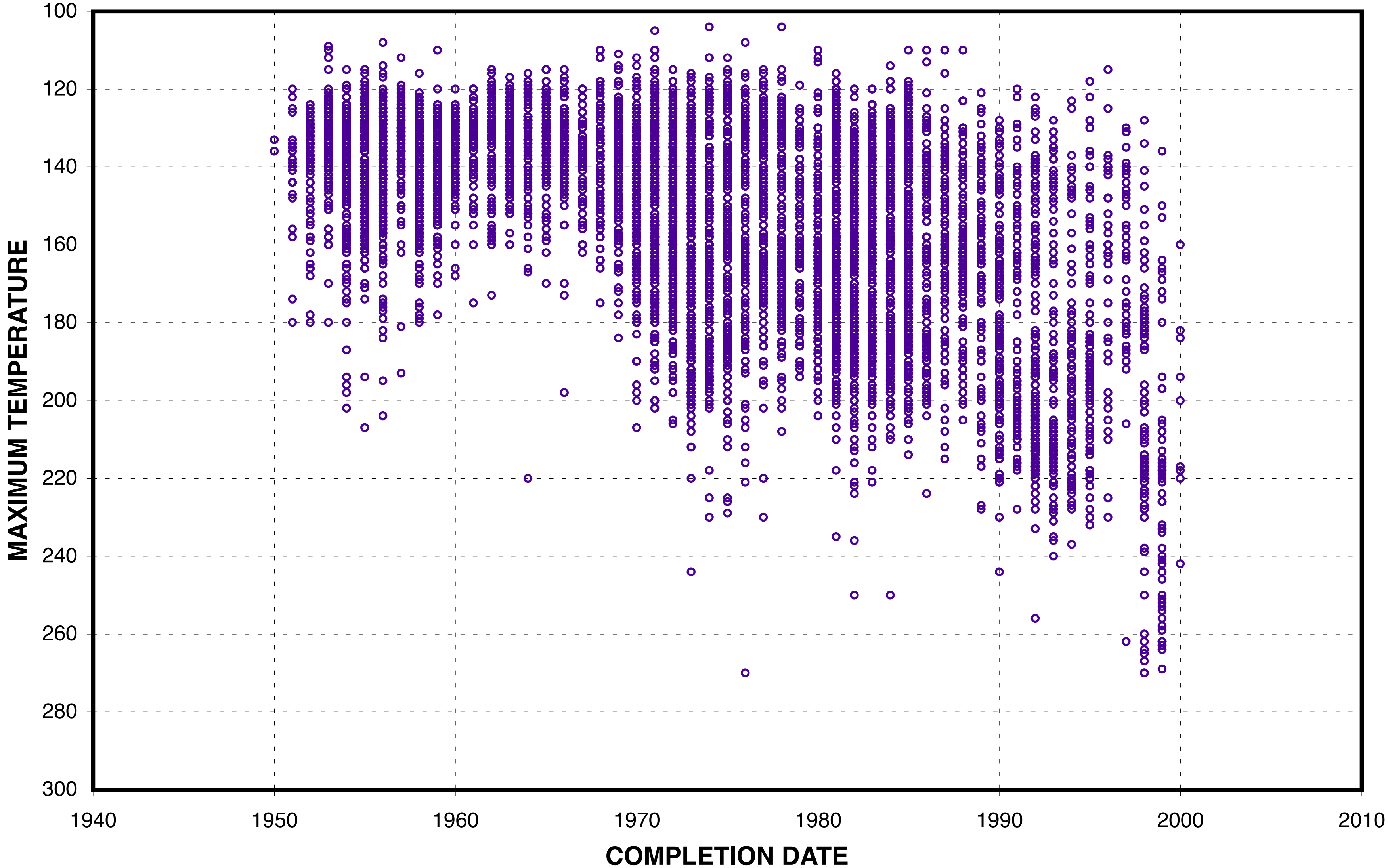

Figure 14. Completion date-versus-maximum temperature, Dakota Formation at total depth.

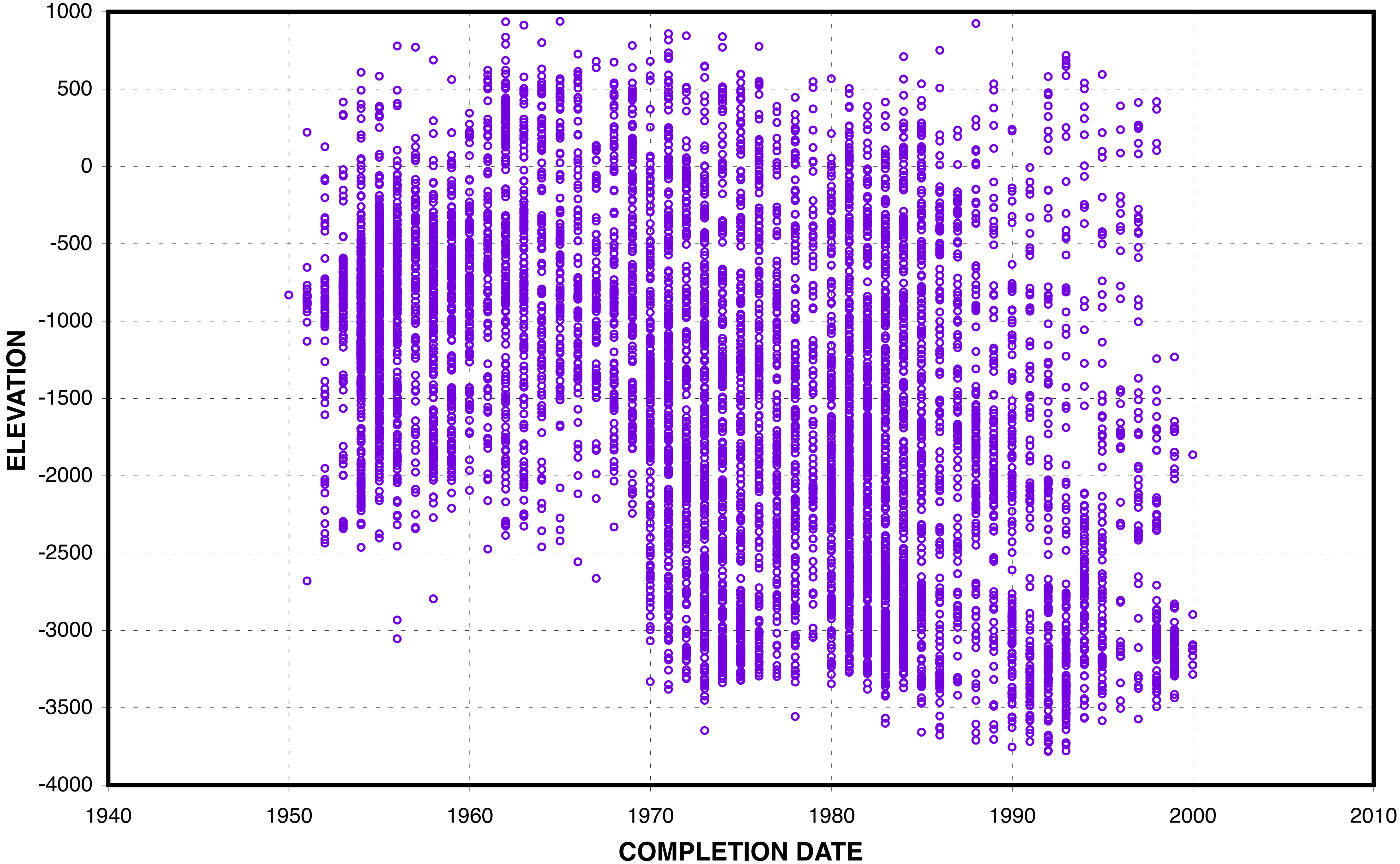

Figure 15. Plot of completion date-versus-maximum temperature, Dakota Formation at total depth.

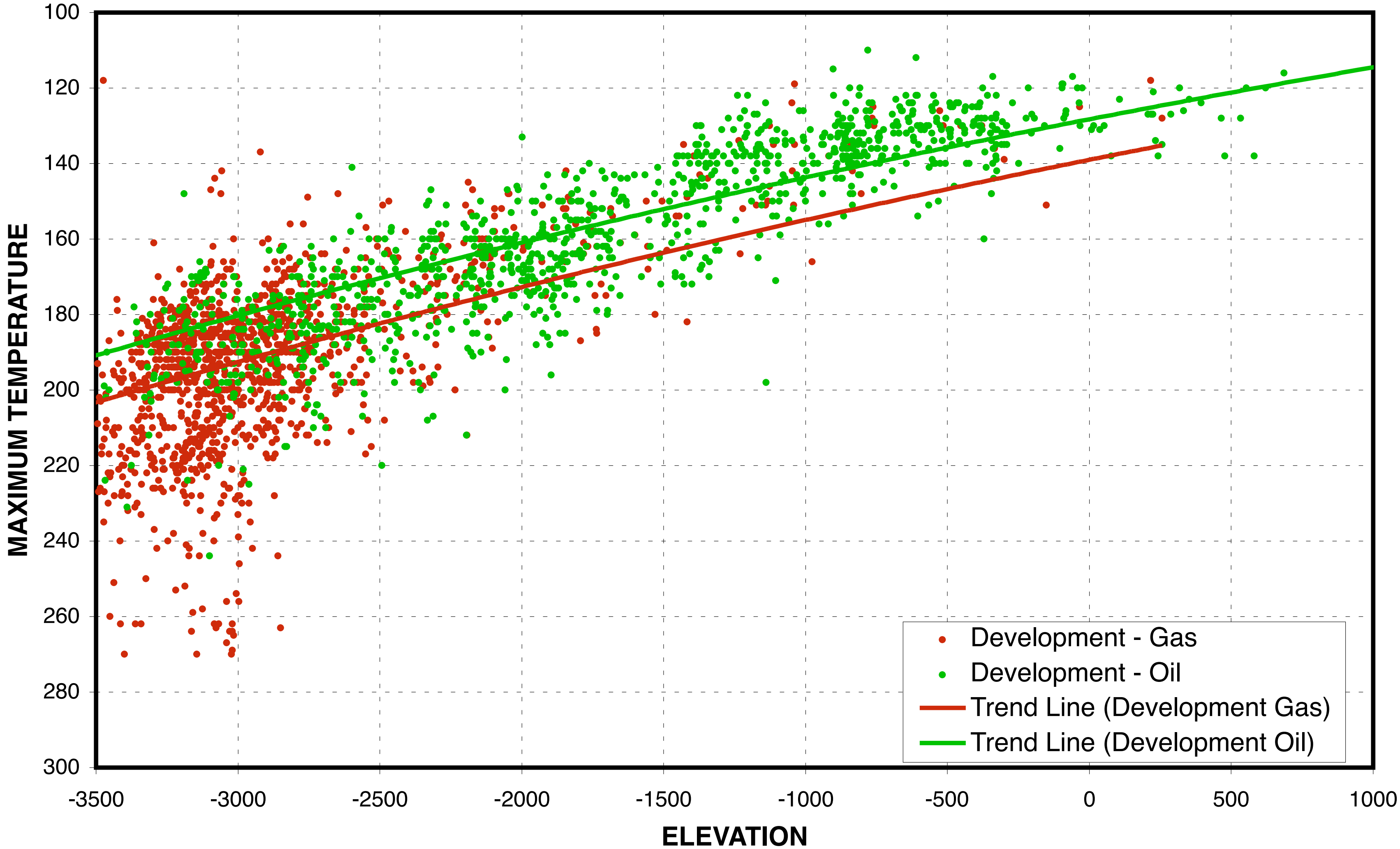

Figure 16. Plot of elevation-versus-maximum temperature, comparing temperatures of development gas wells with development oil wells.

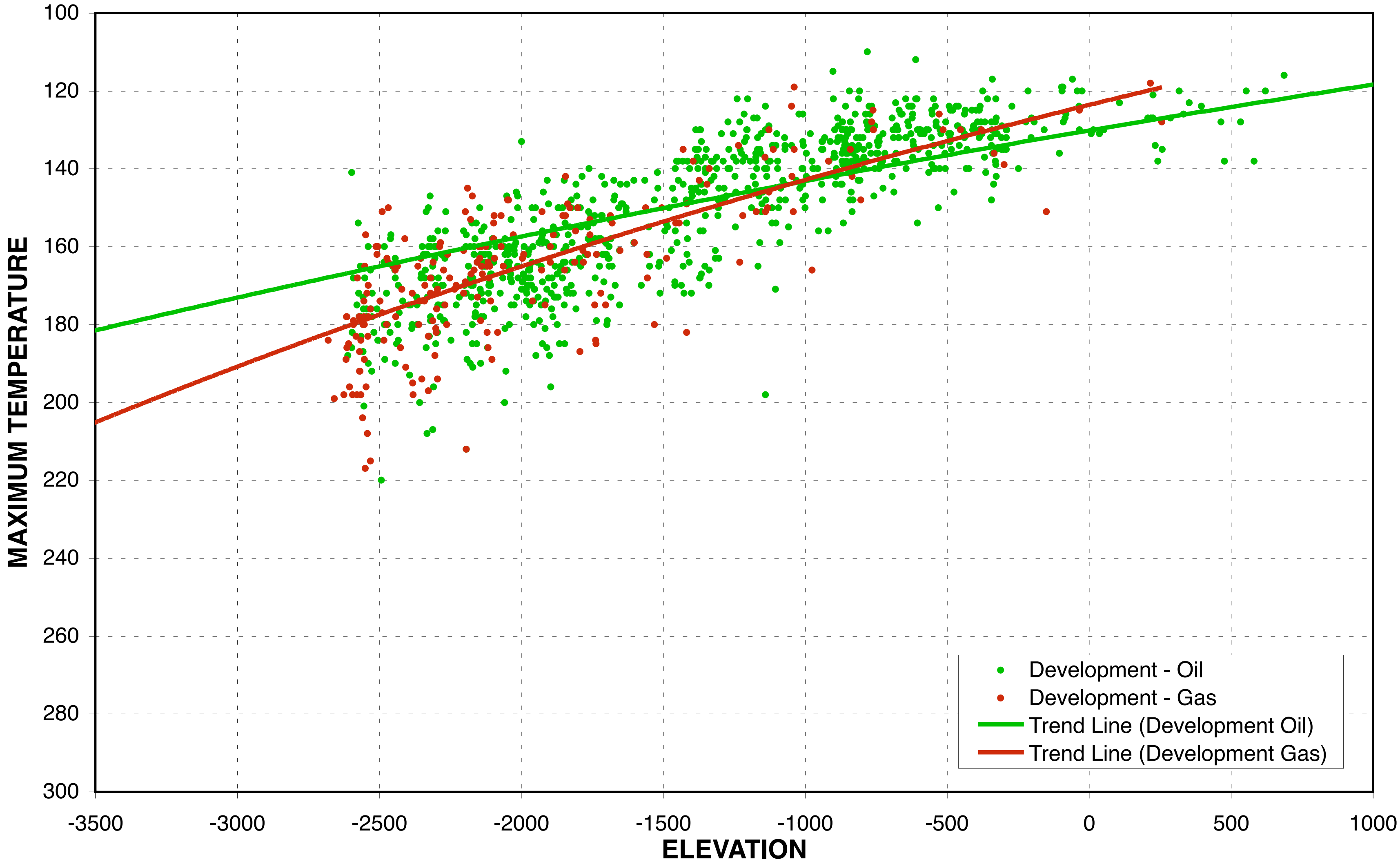

Figure 17. Plot of elevation-versus-maximum temperature, comparing temperatures of development gas wells with development oil wells, excluding Wattenburg "hot trend" wells.

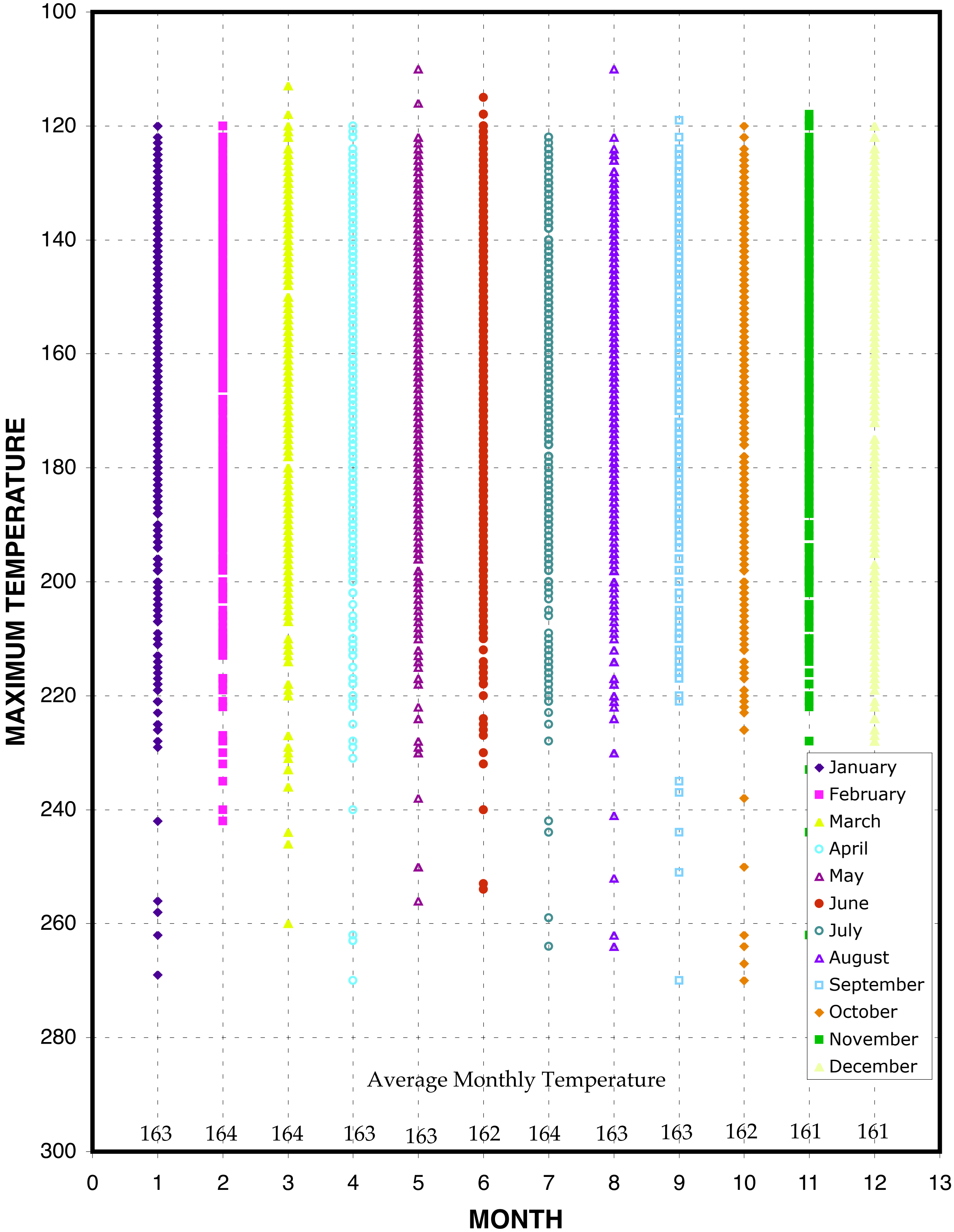

Figure 18. Plot of month-versus-maximum temperature, Dakota Formation to total depth.

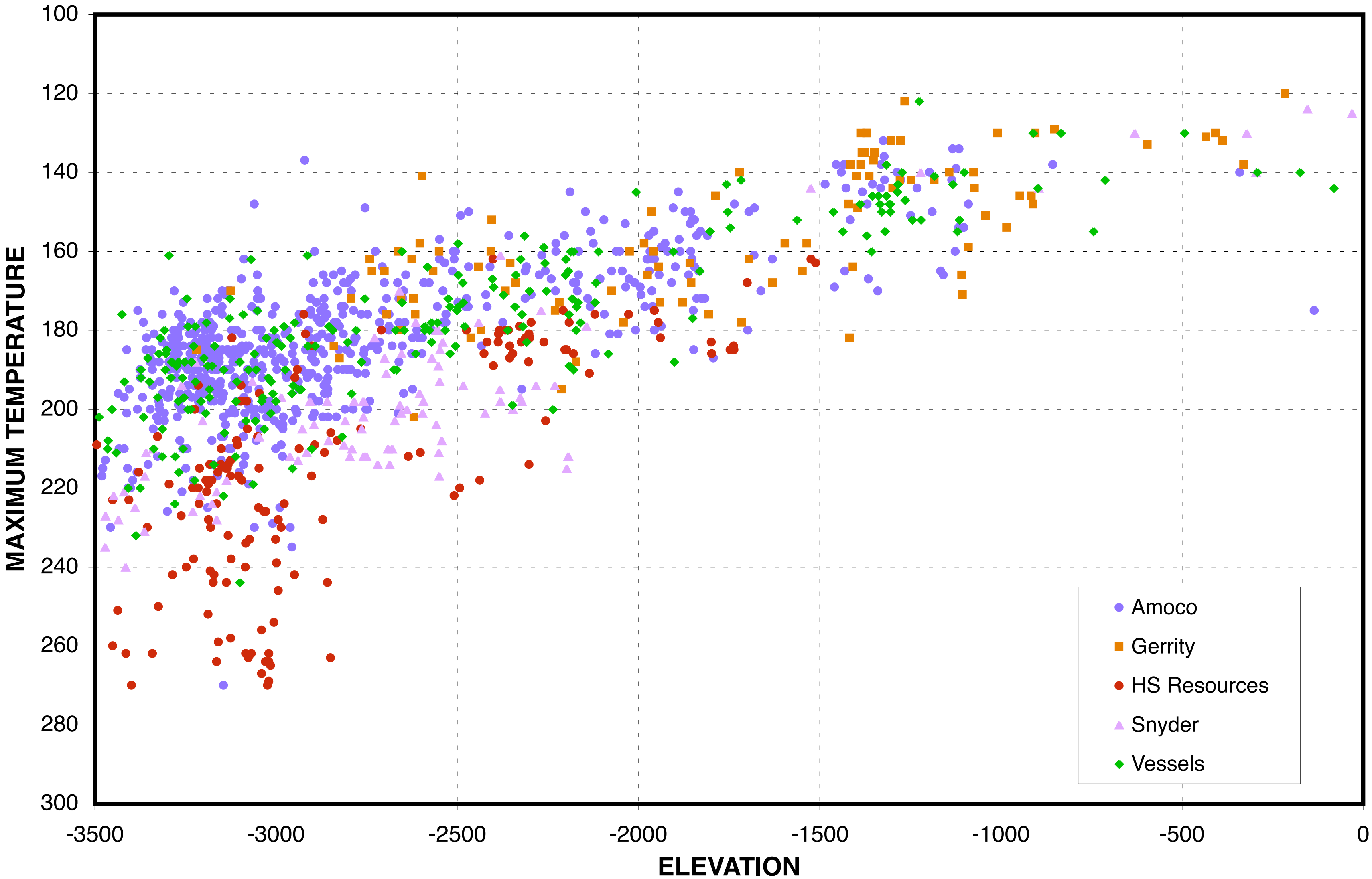

Figure 19. Plot of elevation-versus-maximum temperature, comparing BHTs of five operators in the Wattenburg Field.

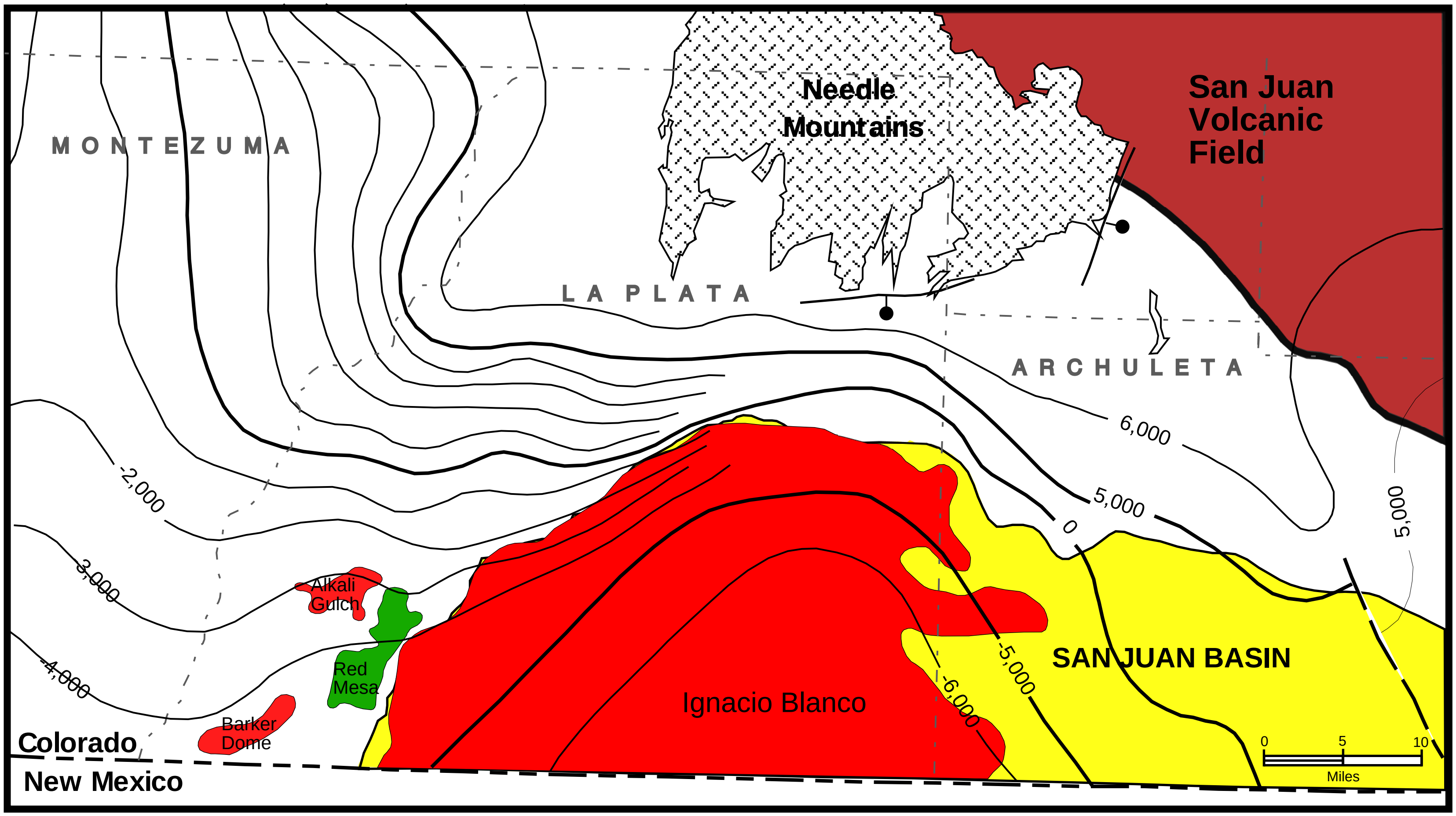

Figure 20. San Juan Basin map showing basement structure contours and major oil and gas fields. After Hemborg, 1996. Structure contours in feet above and below sea level. Oil fields are colored green. Gas fields are colored red.

NORTHERN SAN JUAN BASIN
GEOLOGIC COLUMN

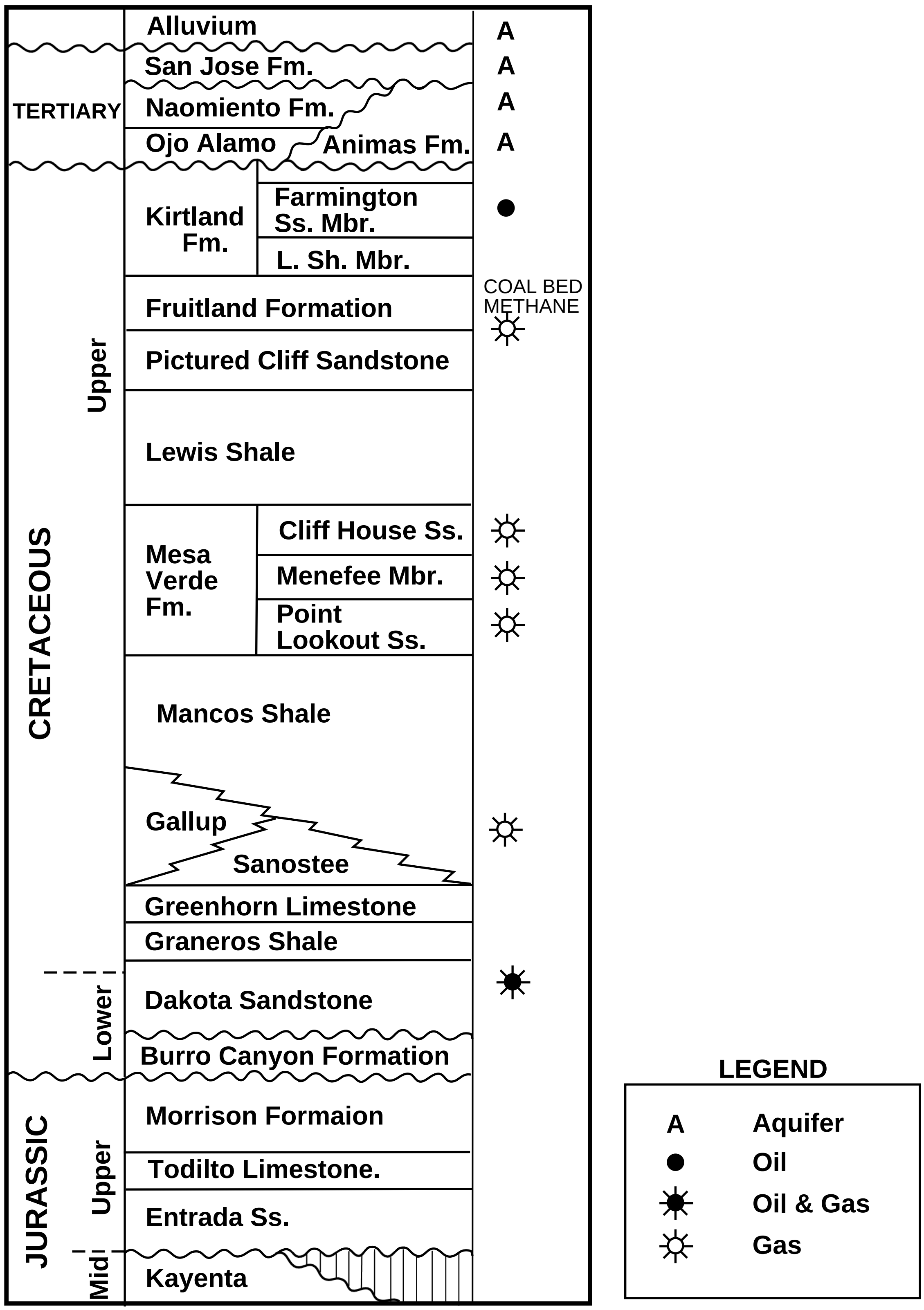

Figure 21. Stratigraphic section of the San Juan Basin, modified from Amoco, 1994.

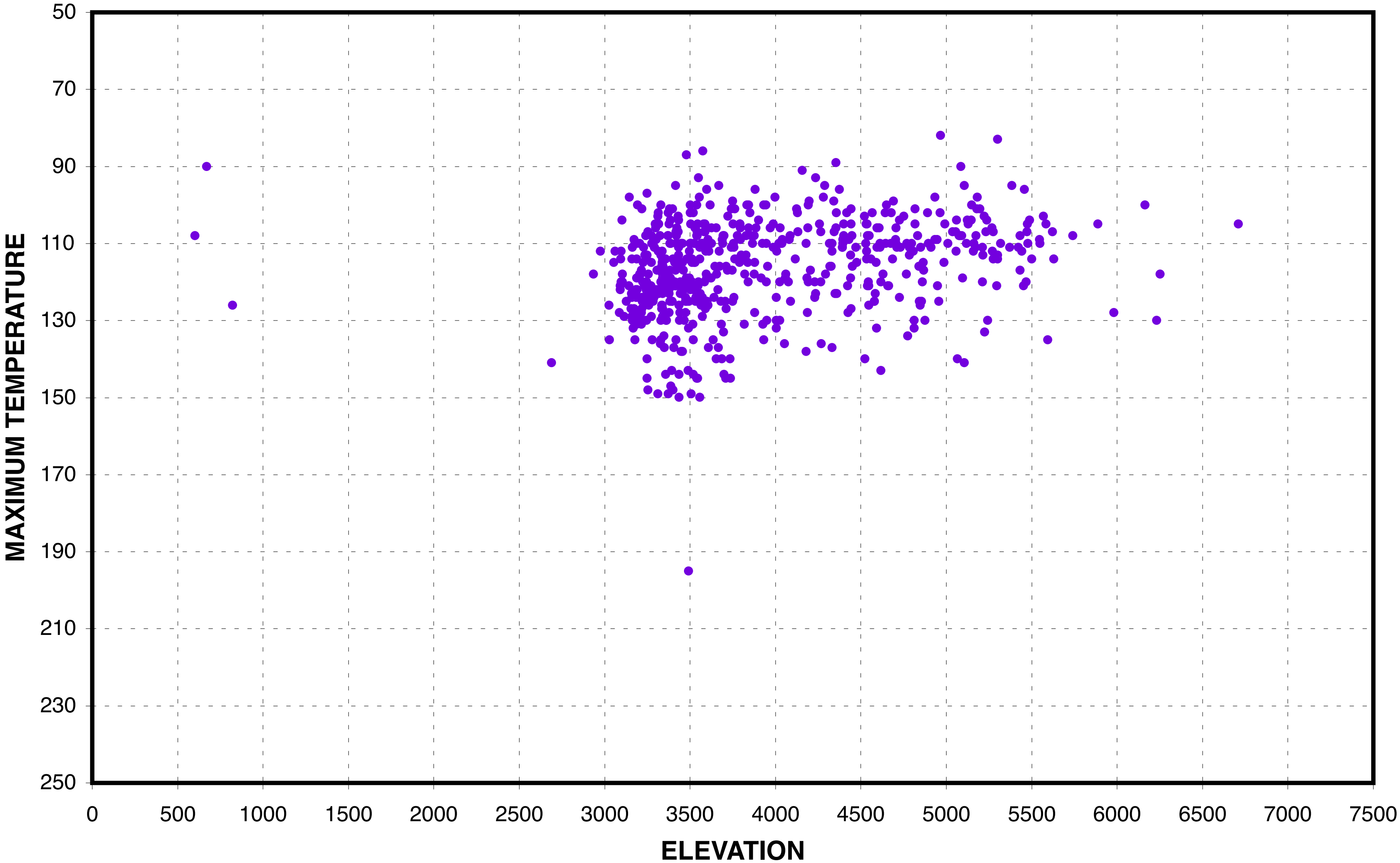

Figure 22. Plot of elevation-versus-maximum temperature, Fruitland Formation and Pictured Cliffs Sandstone at total depth.

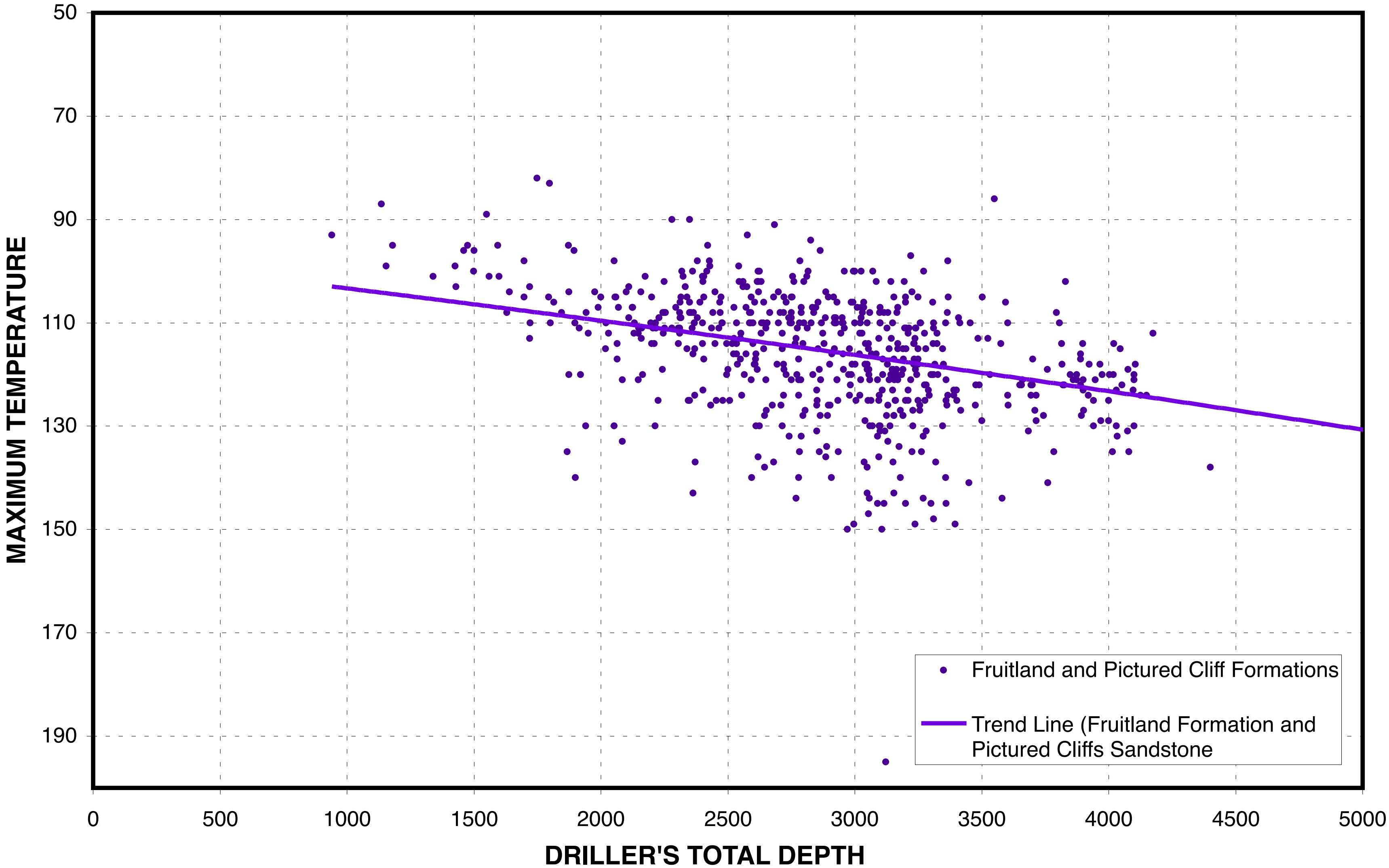

Figure 23. Plot of driller's total depth-versus-maximum temperature, Fruitland Formation and Pictured Cliffs Sandstone at total depth.

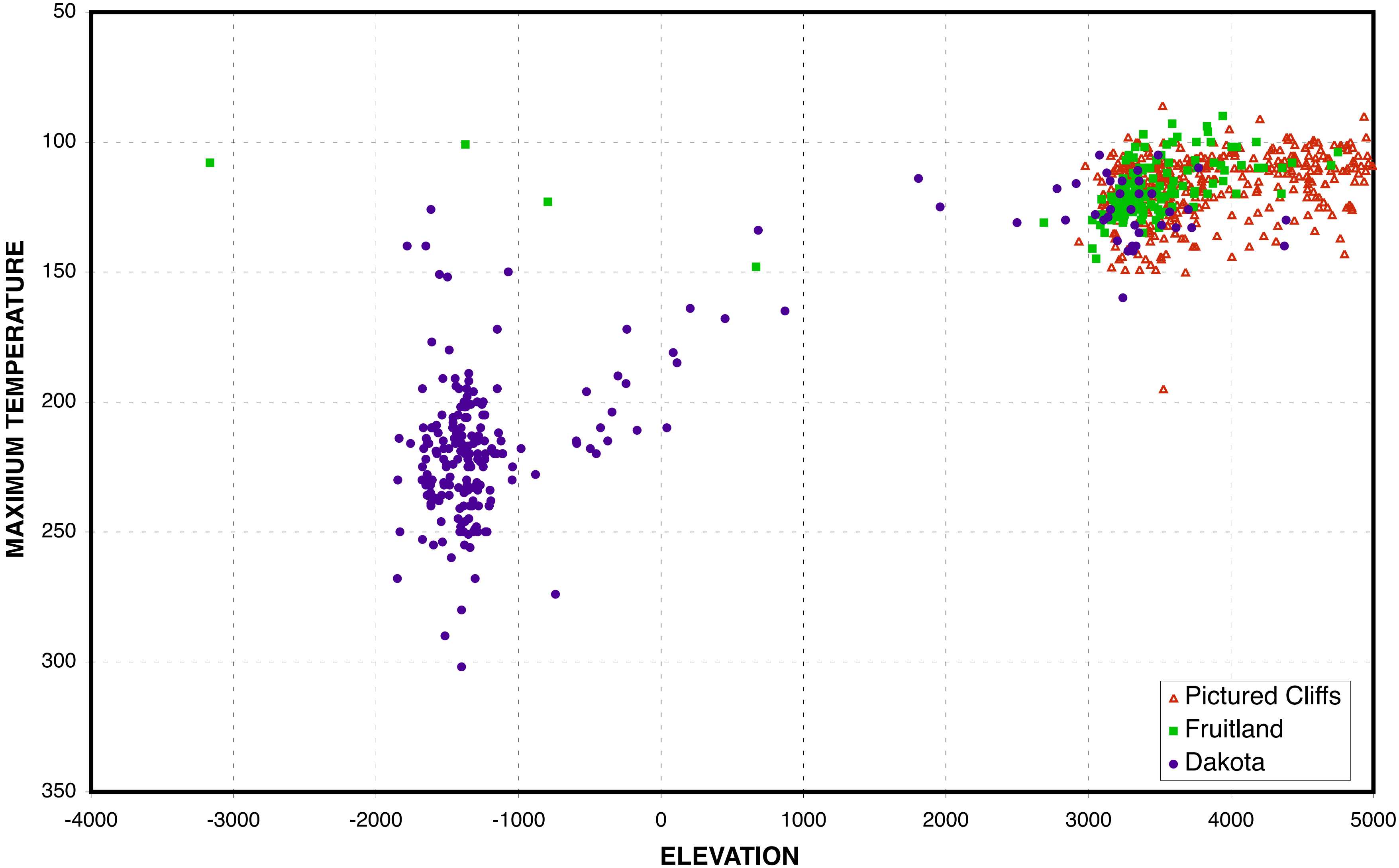

Figure 24. Plot of elevation-versus-maximum temperature, comparing Fruitland Formation, Pictured Cliffs Sandstone, and Dakota Formation at total depth.

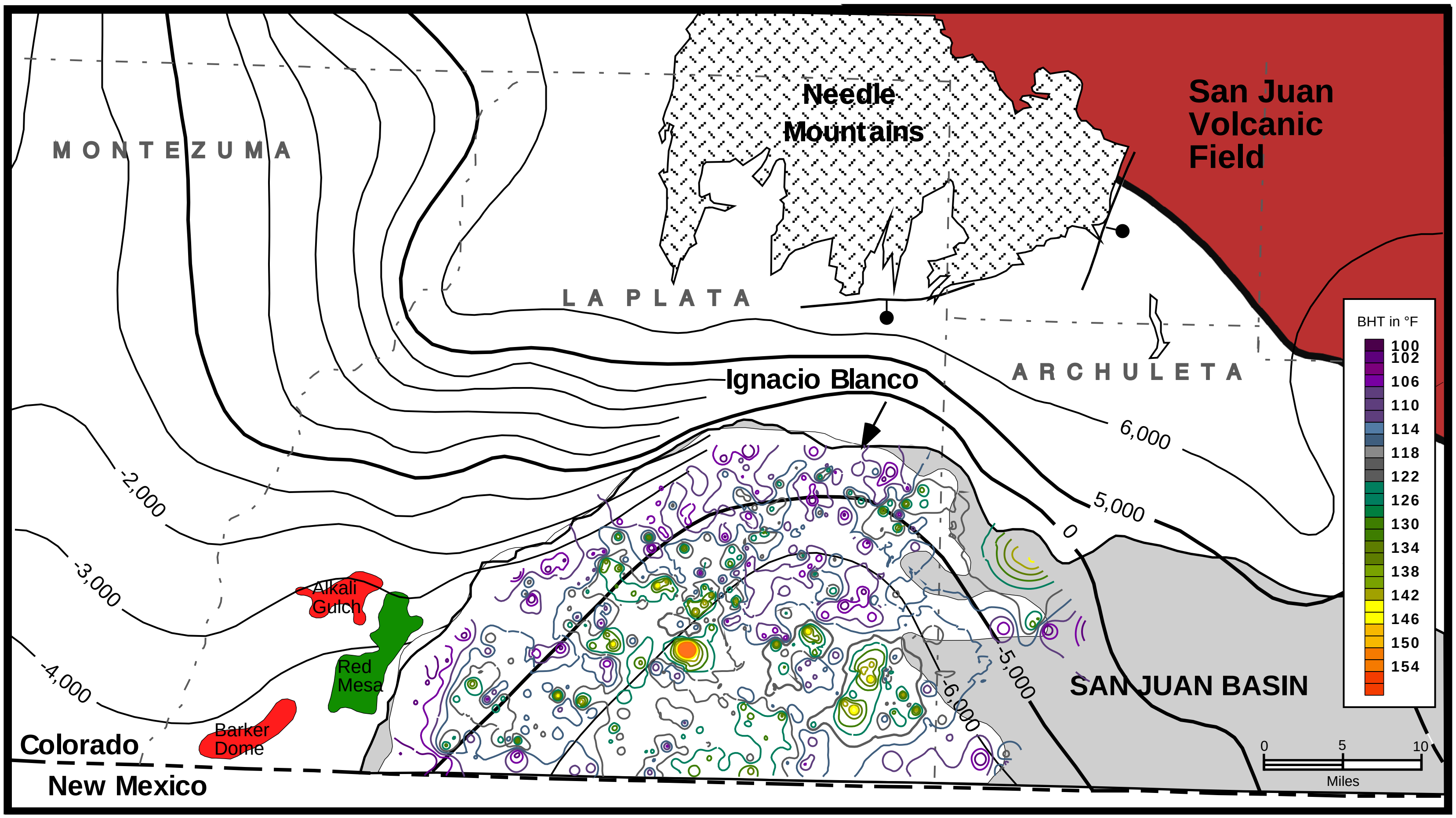

Figure 25. Contour map of Fruitland Formation and Pictured Cliffs Sandstone BHTs overlain by basement structure contours. After Hemborg, 1996. Structure contours are in feet above and below sea level. Oil fields are colored green. Gas fields are colored red.

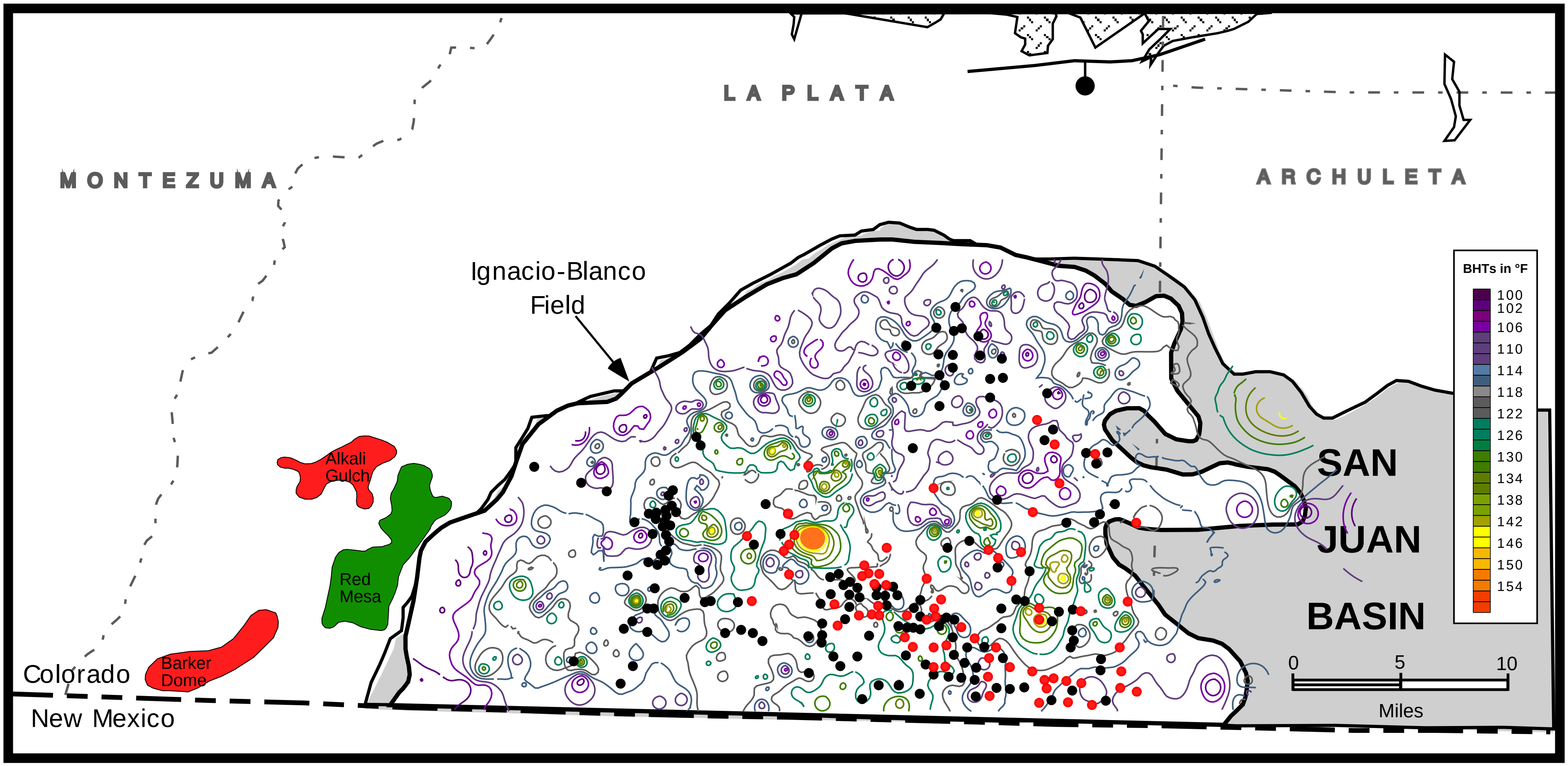

Figure 26. Map showing the BHT contours of the Fruitland and Pictured Cliff Formations overlain by the BHTs of the Dakota sands. Dakota Formation wells with temperatures less than 230°F are shown in black. Wells with temperatures greater than 230°F are shown in red.

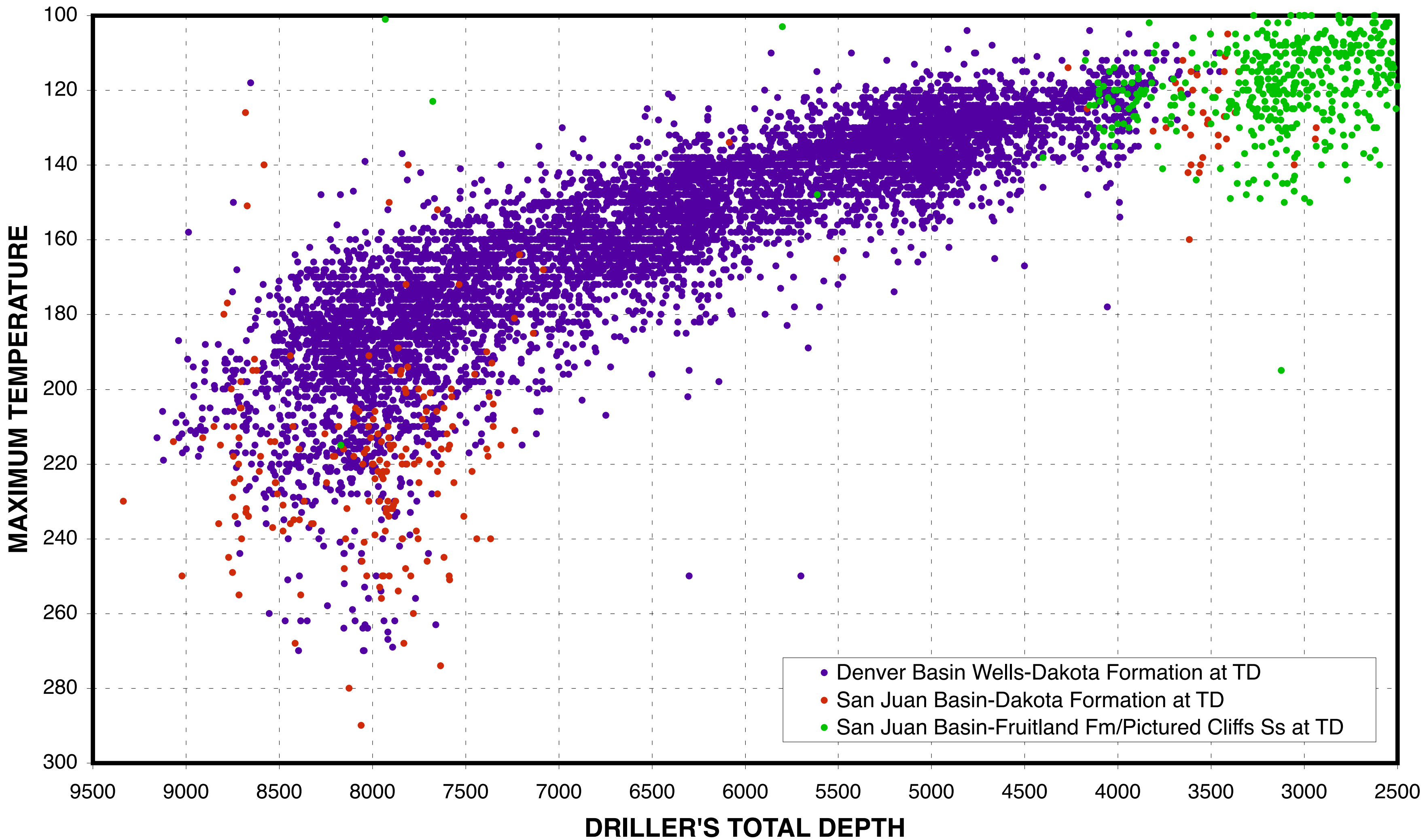

Figure 27. Plot of driller's total depth-versus-maximum temperature comparing Denver Basin wells with Dakota Formation at TD, and San Juan Basin wells with Dakota Formation, Fruitland Formation, and Pictured Cliffs Sandstone at TD.

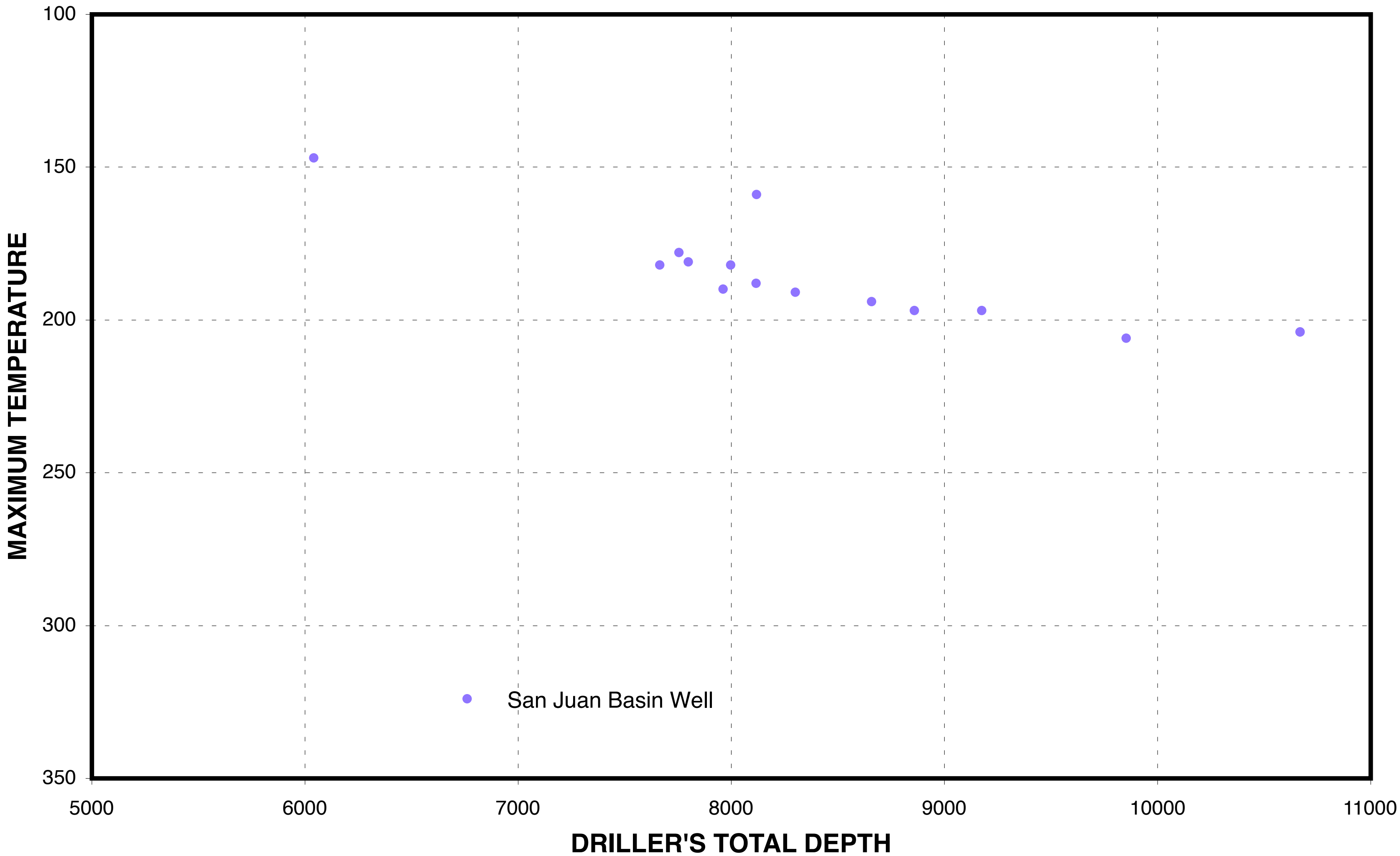

Figure 28. Plot of maximum temperature versus driller's total depth. Wells are drilled to the Precambrian in the Denver and San Juan Basins.