Correcting Bottom-Hole Temperatures in the Denver Basin: Colorado and Nebraska

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Keywords

Geothermal, bottom-hole temperatures, bottom-hole temperature corrections, Denver Basin, Colorado, Nebraska, BHT, Harrison, Kehle, Förster

ABSTRACT

We have examined the problem of bottom-hole temperatures (BHTs) in the Colorado and Nebraska portions of the Denver Basin with the use of three existing correction schemes; the Förster Correction, the Harrison Correction, and the Kehle Correction. We integrated the results of these three equations with the results of equilibrium temperatures to quantify which existing correction works best with Denver Basin stratigraphy. Of the three existing corrections, we determined that the Förster Correction has the least amount of area between curves for the integration, thus it is the best correction. Since we had the equilibrium data, we created a tailored correction scheme for the Denver Basin: Temperature Correction Factor (Tcf) = 0.0124x + 7.8825.

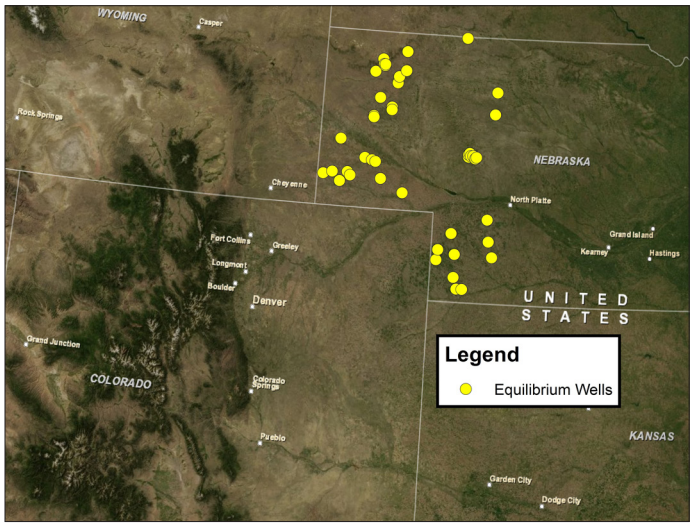

Figure 1. Locations of wells logged at equilibrium.

Introduction

The Denver Basin (Figure 2) is an asymmetric syncline with an axis that trends north-south, parallel to the Rocky Mountains, and has a surface area of approximately 155,000 km2 (Curtis, 1988; Martin, 1965). The western flanks of the basin dip downward to the east to a maximum depth of about 4,000 m and grade into a westward-dipping surface that continues into Nebraska and Kansas. A north-south-trending transect along the eastern edge of the Front Range reveals a similar asymmetrical geometry with respect to the basin's east-west asymmetry. The point of maximum depth, centered beneath El Paso county (Irwin, 1976), is much closer to the basin's southern boundary in central Colorado than to its terminus in southeastern Wyoming.

The Wet Mountain range near Pueblo, which is the brink of the southernmost extent of the Denver Basin, trends west/northwest and is characterized by a zone of westward-dipping reverse faults of varying angles (Curtis, 1988). A series of diverse fold and fault geometries (some exposed, some buried by Tertiary sediments) follow along the western border of the basin (Figure 3); including the entirety of the Front Range from the Wet Mountains in the

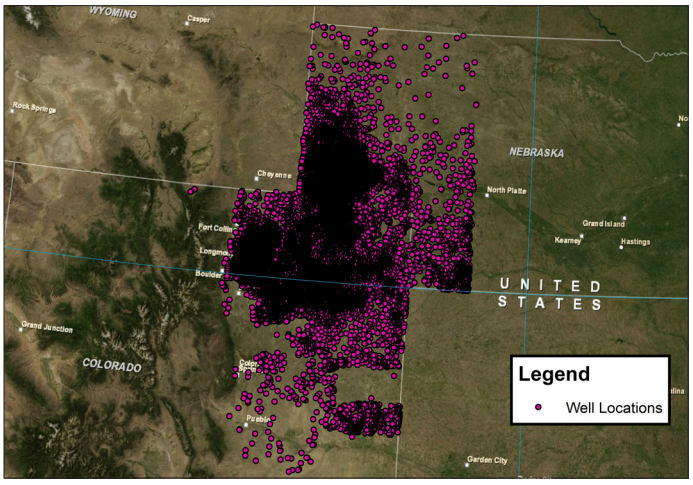

Figure 2. Spatial extent of the Denver Basin BHT data.

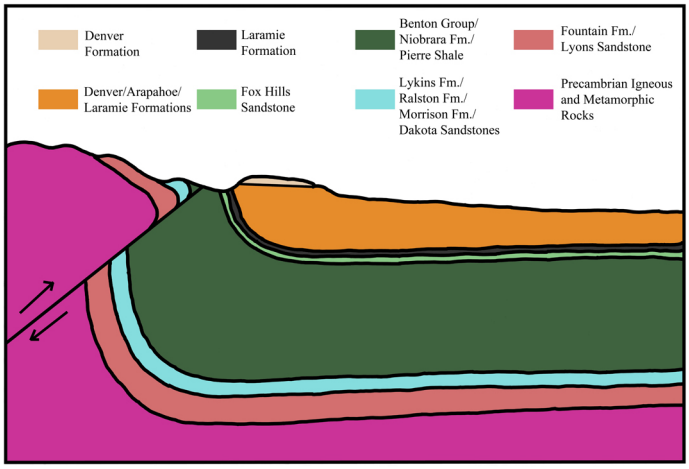

Figure 3. Cross sectional view of the Denver Basin (Modified from Noe et al, 1999).

south to the Laramie Range of southeastern Wyoming. The most prominent bounding features from the northwestern to northern edges of the basin are the Hartville and Black Hills Uplift features, both of which expose Late Archean and Early Proterozoic granites and metamorphic rocks (Sims et al., 1997). The northeastern, eastern and southeastern flanks of the Denver Basin are embodied by a semi-continuous, curvilinear series of structural arches. In Nebraska, the Chadron and Cambridge structural arches trend northeast-southwest and north-south, respectively, and constitute an Oachita-induced upwelling of Precambrian and early Paleozoic rocks (Curtis, 1988; Carlson, 1993; Martin, 1965; Reed, 1958). The north-northeasterly-trending Las Animas arch is structurally similar to the Chadron and Cambridge Arches, and trends from the Wet Mountains in Colorado, cutting through the northwestern corner of Kansas, and merging with the southern portion of the Cambridge Arch (Merewether, 1987).

The sedimentary stratigraphic record (Figure 4) of the Denver Basin begins with the Upper Cambrian (Reagan Sandstone and equivalent Sawatch Sandstone) sandstones at the base. Upper Cambrian sandstones are thin and discontinuously present, existing primarily in the northernmost portion of the basin, in outcrops in the southern Front Range, and in much of the central and western subsurface (Curtis, 1988). The Reagan Sandstone is present in Nebraska, and thins westward (Condra and Reed, 1959).

The limestones and dolomites of the lower Ordovician Arbuckle Group (equivalent Manitou Limestone) thin westward and northward from considerable thicknesses in eastern Colorado and western Nebraska portions of the basin, and appear to be present in the deepest part of the basin's trough (Irwin, 1976), although they are absent from the hinge of the Cambridge Arch (Condra and Reed, 1959).

Silurian rocks appear to be absent from the entire basin according to Curtis (1988), and from the Nebraska portion specifically according to Carlson (1993) and Condra and Reed (1959). Martin (1965) asserts that Early, Middle, and Late Silurian fossiliferous limestones are present at two localities in the Front Range on the Colorado-Wyoming border.

The Devonian system is unrepresented in the Denver Basin (Condra and Reed, 1959); however, the deposition of the limestone units of the Guernsey Formation began during the late Devonian and continued through the middle Mississippian. According to Curtis (1988), the Guernsey Formation is present in the northern extremity of the basin. Mississippian limestone units of variable thickness are observed to be present throughout the central part of the basin (almost exclusively in Colorado), and although they are often assumed to be part of the Madison Limestone, their equivalence to the formally-accepted Madison Limestone type-lithology has not been verified (Curtis, 1988). Other Mississippian units, including the Williams Canyon, Gilmore City and St. Genevieve Limestones, the Harrison Shale, and Warsaw Formation carbonates and mudstones are present in the southeastern Denver Basin along the Las Animas Arch (Kirkham and Ladwig, 1979; Merewether, 1987).

The Pennsylvanian and Permian systems have a complex lithology, and constitute a significant portion of the stratigraphic section throughout the entire basin. The Pennsylvanian system is characterized by the Fountain Formation, which extends throughout the central and southern Denver Basin and includes an array of reddish-brown arkosic conglomerates, yellow-gray arkosic sandstones, and light green and reddish-brown shales (Kirkham and Ladwig, 1979). These lithologies dominate the western

Eon	Era	Period	Epoch	Formation		Rock Type	Thickness (m)
Phanerozoic	Cenozoic	Paleogene	Paleocene	Green Mountain Conglomerate		Conglomerate, Sandstone, Shale	198
	Mesozoic	Cretaceous	Upper	Denver Formation		Claystone, Siltstone, Sandstone, and Conglomerate	290
				Araphahoe Formation		Claystone, Siltstone, Sandstone, and Conglomerate	121
				Laramie Formation		Siltstone, Claystone, and Sandstone	168
				Fox Hills Sandstone		Shale and Sandstone	55
				Pierre Shale		Shale, some Sandstone beds	1890
				Niobrara Formation	Smoky Hill Shale	Shale and Limestone	43
					Fort Hayes Limestone	Limestone	43
				Carlisle Shale		Claystone, Siltstone, Calcarenite and Hard Limestone Beds	162
				Greenhorn Limestone			
				Graneros Shale			
			Lower	Dakota Group	South Platte Formation	Sandstone and Shale	91
					Lytle Formation	Sandstone and Conglomerate	
		Jurassic	Upper	Morrison Formation		Siltstone and Claystone	91
				Ralston Creek Formation		Sandstone and Siltstone	27
		Triassic	?	Lykins Formation		Shale, Limestone, and Siltstone	137
	Paleozoic	Permian		Lyons Formation		Sanstone and Conglomerate	58
		Carbon.	Penn.	Fountain Formation		Sandstone and Conglomerate	502
Precambrian				Precambrian		Igneous and Metamorphic Rocks	

Figure 4. Stratigraphic column of the Denver Basin for the Colorado Piedmont (Modified from Abbot and Noe, 2002).

region of the basin's Pennsylvanian system and grade eastward into fine clastics and carbonates (Curtis, 1988). The Permian system is also well represented (in part by the Lyons sandstone), and consists primarily of red shales and sandstones, gypsum, salt deposits, and limestones. Pennsylvanian and Permian sections generally thicken toward the west and south, and reach a maximum combined thickness of more than 1,300 m in the southern part of the basin trough (Curtis, 1988; Irwin, 1976).

Triassic rocks are virtually non-existent in the Nebraska portion of the Denver Basin, but are present in the northwestern part of the basin, thickening into Wyoming and pinching out toward the east and south. These lithologies are mostly Chugwater and Lykins red sandstones and siltstones (Curtis, 1988; Irwin, 1976).

The Jurassic system is represented throughout the entire basin, particularly by the interbedded mudstones, limestones, sandstones, and conglomerates of the upper Jurassic Morrison Formation (Kirkham and Ladwig, 1979). Evaporites and limy siltstones and shales of the middle Jurassic Sundance, Ralston Creek, and Entrada formations underlie the Morrison and unconformably overlie Triassic and Permian units in various localities (Curtis, 1988).

Cretaceous units of the Denver Basin are historically important petroleum-source and reservoir rocks. The "D" and "J" sandstones of the Dakota Group, which consists of Cretaceous conglomeratic sandstones and gray shales (Kirkham and Ladwig, 1979), are particularly noteworthy petroleum-production units. Along with the Dakota Group, the dark shales, calcareous shales, and limestones of the overlying Graneros, Greenhorn, Carlile, and Niobrara formations extend throughout the basin. The Pierre Shale, composed of gray silty and sandy shales and interbedded sandstones, also exists throughout the basin, and is the thickest stratigraphic unit of the Denver Basin with a thickness of 900 m (3,000 ft) in western Nebraska (Condra and Reed, 1959) and 2,500 m (8,000 ft) in the central part of the basin (Curtis, 1988; Irwin, 1976). Overlying Fox Hills silty sandstones contain iron-rich concretions and thin coal beds (Kirkham and Ladwig, 1979). The Lance Formation, (equivalent Laramie) consists of coal-bearing siltstones and sandstones and caps the Denver Basin's Mesozoic stratigraphic system beneath an unconformity with overlying Tertiary sediments (Raynolds, 2002).

Tertiary rocks in the Denver basin are tectonically unperturbed, and are perhaps the most diverse of any single geologic period for the basin. They include Paleocene arkosic sandstones and conglomerates, Oligocene fluvial siltstone and sandstone of the White River Group and Wall Mountain tuffstone, and conglomerates, gravels and sands of the overlying Miocene Arikaree and Ogallala Formations. Quaternary cover throughout the basin is characterized by fluvial, alluvial, and eolian sands, silts, and loess (Burchett, 1969; Condra and Reed, 1959; Curtis, 1988; Kirkham and Ladwig, 1979).

Existing Bottom-hole Temperature Correction Schemes

The Harrison, Kehle, and Förster equations were created with a specific region or dataset in mind. This makes the application of these corrections to other basins inappropriate since all basins have different lithologies and thermal histories (Crowell and Gosnold, 2011). The Harrison Correction, created by Harrison (1983) and subsequently re-defined by Blackwell and Richards (2004), was determined using equilibrium and disequilibrium data from the Anadarko and Arkoma basins in Oklahoma. The practice was appropriate since the lithologies of both basins are very similar. The Harrison Correction equation (Figure 5), as defined by the Southern Methodist University Geothermal Laboratory (Blackwell and Richards, 2004; Blackwell et al., 2010), is:

$$Tcf\ (°C) = -16.512 + 0.0183\ x - 0.00000234\ x^2$$

where x is depth in meters.

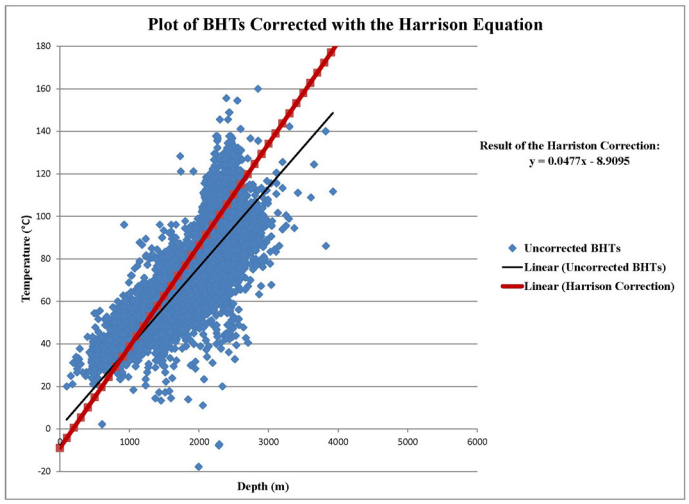

Figure 5. Plot of uncorrected bottom-hole temperatures with the equation from Harrison-corrected data.

The Kehle Correction (Figure 6) was created for the AAPG dataset (Kehle et al., 1970) to examine the process by which unreliable bottom-hole temperatures from oil and gas well header logs could be corrected. Several methods for correcting temperatures were analyzed and Gregory et al. (1980) defined the Kehle correction equation without a time variable as:

$$Tcf\ (°F) = -8.819 \times 10^{-12}\ x^3 - 2.143 \times 10^{-8}\ x^2 + 4.375 \times 10^{-3}\ x - 1.018$$

where x is depth in feet.

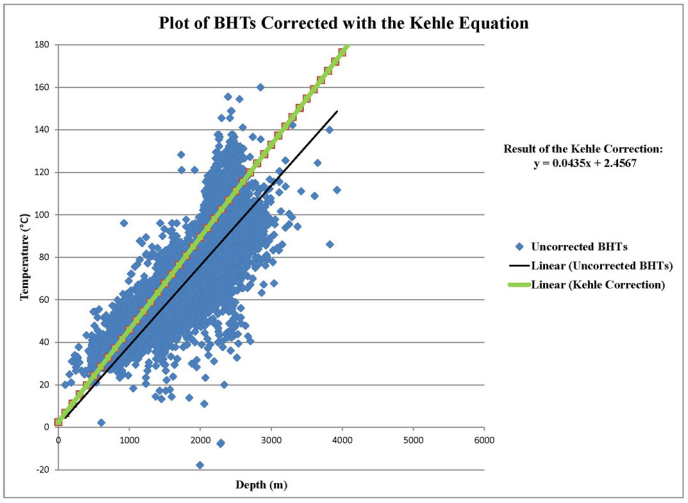

Figure 6. Plot of uncorrected bottom-hole temperatures with the equation from Kehle-corrected data.

The Förster correction (Figure 7) was created by analyzing bottom-hole temperature data in southeastern Kansas for the same reason: unreliable BHT records due to mud circulation (Förster and Merriam, 1995). Two versions of the Förster correction exist: the original Förster correction equation (Förster and Merriam, 1995), which is

$$Tcf\ (°C) = 0.012x - 3.68$$

where x is depth in meters.

and the equation that was modified by the SMU Geothermal Laboratory (Richards 2012, personal communication):

$$Tcf\ (°C) = 0.017x - 6.58$$

where x is depth in meters.

For the purpose of uniformity, we used the equation obtained from the SMU Geothermal Laboratory.

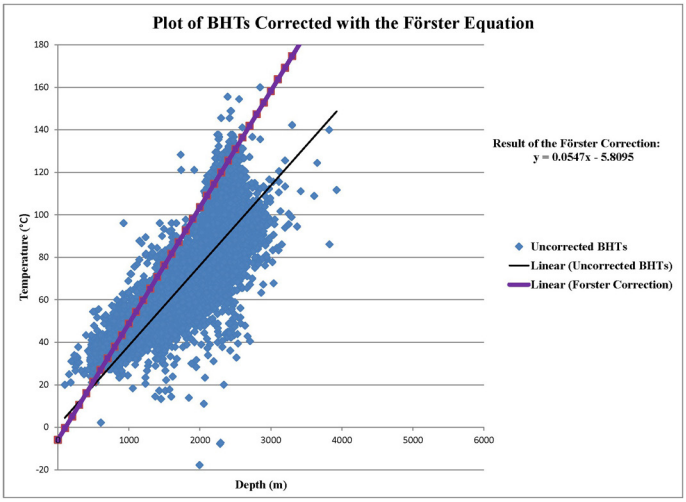

Figure 7. Plot of uncorrected bottom-hole temperatures with the equation from Förster-corrected data.

Methods

Bottom-hole temperature data was obtained from the Nebraska Oil and Gas Commission and Dr. Paul Morgan of the Colorado Geological Survey. Equilibrium well data (Figure 1) was obtained from Dr. Will Gosnold at the University of North Dakota. The equilibrium dataset was entered into an Excel spreadsheet, plotted, and fitted with a linear best fit line. The equation recorded from this best fit line is referred to as the "equilibrium equation" (Figure 8).

The uncorrected bottom-hole temperatures were then corrected using the existing correction methods (Harrison, Kehle, and Förster), resulting in the creation of three new datasets. These three new datasets were then plotted in an Excel spreadsheet and fitted with a linear best fit trendline. The equations of the trendlines were recorded and integrated with the equilibrium equation (Figure 8) to obtain the area between the curves. The area between curves is interpreted to be a method by which to quantify the most accurate correction method (Figure 9). In our case, the integration yielding the smallest area between the curves is quantifiably the best of the existing corrections, the unit of which is a degree meter as defined by Crowell and Gosnold (2011).

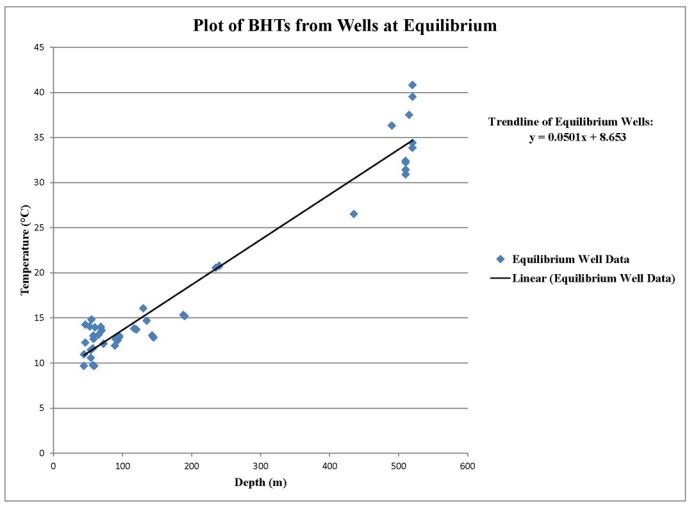

Figure 8. Plot of BHTs from wells at equilibrium.

The results of the integrations are as follows: the Kehle correction integration yielded 188,467 degree meters, the Harrison correction integration yielded 117,812.5 degree meters, and the Förster correction had the lowest area of the existing equations, with 30,657.92 degree meters.

We then determined that we had enough data to attempt a correction scheme based on the equilibrium data equation and the equation obtained from the plot of the uncorrected temperatures. The uncorrected equation was subtracted from the equilibrium equation, giving us a new correction scheme:

$$Tcf\ (°C) = 0.0124x + 7.8825$$

where x is depth in meters.

It should be noted that this correction equation is only appropriate for the Denver Basin, and possibly other basins with similar stratigraphy.

The bottom-hole data was then corrected using the new equilibrium correction scheme and plotted (Figure 10). The plot of the corrected data gives a best fit trendline that is the same as the original equilibrium equation. Figure 11 shows the corrected

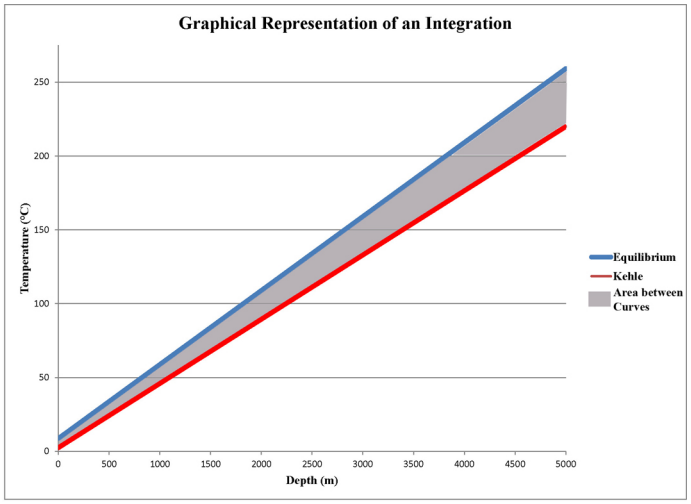

Figure 9. Graphical representation of an integration.

trendlines for the datasets, including how the best fit trendline of the equilibrium-corrected data superimposes on the best fit trendline for the equilibrium in situ data (the dashed orange line and thick blue line, respectively).

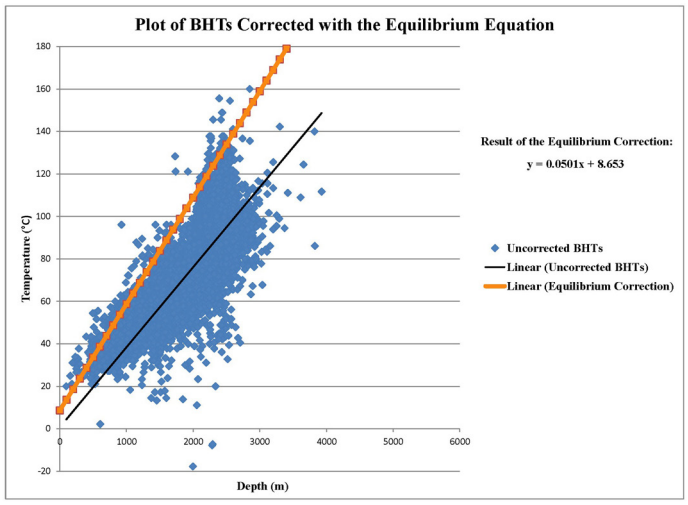

Figure10. Plot of uncorrected bottom-hole temperatures with the equation from equilibrium-corrected data.

Conclusion

Bottom-hole temperature data are unreliable, but it remains the most abundant and readily available source for subsurface temperature information. Utilizing this method in the Denver Basin, we have determined that the Förster correction (Tcf (°C) = 0.017x - 6.58) is the most accurate of the existing corrections that do not require time of mud circulation data. We have also provided a tailored correction for the Denver Basin based on equilibrium data (Tcf (°C) = 0.0124x + 7.8825). It is important to remember that the corrected data are closer to in situ equilibrium values, but does not guarantee a correction to equilibrium in situ values.

Until now, the selection of an appropriate bottom-hole temperature correction scheme has been difficult, with few parameters to quantify level of confidence in the correction. Integrating the best fit trendline of corrected bottom-hole temperatures with the best fit trendline of equilibrium data is a method to quantifiably determine the appropriate correction. Equilibrium data can also be used to create a tailored correction scheme. When equilibrium data are not available, it is possible that in-situ temperature information may be obtained by analyzing stratigraphic and thermal conductivity data (Gosnold et al., 2012).

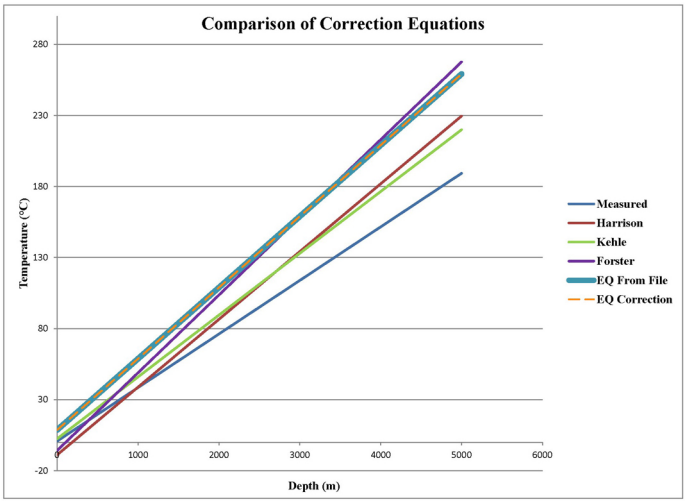

Figure 11. Comparison of correction equations.

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