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Temperature-depth plots for selected petroleum exploration wells, Canadian Arctic Islands

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Summary

Temperature data collected from 164 petroleum exploration wells and shallow temperature surveys, as well as other temperature indicators in the Canadian High Arctic Archipelago are analyzed. Eighty-six wells with multi-point data measurements are selected to represent the present day temperature – depth (T-D) relationship. This report presents the preliminary results of data analyses and the T-D relationships from these selected wells.

Introduction

Thermal histories and present day temperature of sedimentary basins are important for petroleum system analysis as well as studies of gas hydrate stability conditions and geothermal energy potential. Formation temperatures measured during drill stem test (DST) and bottom hole temperature (BHT) data are publically available from well history reports of the 164 petroleum wells drilled in last century in the Canadian High Arctic. Temperature survey data collected from shallow depth intervals are available from the Canadian geothermal data compilation project (Judge et al., 1981) and provide an important addition to this study. Other indirect indications of surface and subsurface temperature, such as the base of permafrost, historical surface air temperature observations, and temperatures at the sea floor are also important constraints. A combination of all these types of temperature data provides a better picture of the temperature-depth relations for this region with increased reliability.

This report presents the preliminary results of data analyses and the T-D relationships from eighty six selected wells to reveal the characteristics of the present-day temperature field across the Canadian Arctic Archipelago (Figure 1). The raw data will be released in a separate GSC open file and will not be discussed here in this report.

Data Sources

The temperature data have been compiled as a part of the ESS GEM Energy program. The temperature data compiled in this report include BHTs and measured temperatures from DSTs in well history reports of 192 petroleum exploration wells drilled in 1969-1986. Among the 192 wells, 164 wells have at least one measured temperature data point. Part of the BHT readings accompanied by well logging survey has gone through equilibrium corrections using the “Horner” plot (Dowdle and Cobb, 1975). The remaining BHTs are not corrected due to lack of information. The DST temperatures are taken as they are, no particular correction is applied. Hu et al. (2010) provides a general overview on the possible environmental impacts of the bottom hole temperature measurements as well as available techniques for the corrections.

About 30 wells have shallow temperature data from multi-year (repeated) surveys in the uppermost intervals of the wells. The shallow temperature measurements were obtained from the Canadian Geothermal Data Collection project conducted from 1955 to 1980 (Judge et al., 1981). The temperatures at shallow depth appear to have approached equilibrium after years of thermal

equilibration following the completion of drilling; thus the most recent temperature readings likely represent approximately the actual formation temperatures. Otherwise, the temperature readings have to be corrected for thermal equilibrium. For specific details of the data collection and corrections, readers are referred to Judge et al., (1981).

Efforts were made to constrain the temperature measurements using available geological and geophysical data. Additional temperature constraints include observed/inferred base of permafrost, noted by the drillers in well history reports or indicated by geophysical evidence, such as well logs and seismic check-shot or crystal cable velocities. The base of permafrost is a well-defined boundary on geophysical logs because an ice-saturated porous medium has a much higher acoustic travel velocity and formation resistivity than a water-saturated porous interval. The base of the ice-bearing permafrost zone is assumed to be -1 °C based on analogy with the Mallik 5L-38 gas hydrate research well in the Beaufort-Mackenzie Basin (Henninges *et al.*, 2005). The climate records from the last 30 years at the Resolute Bay station (from Environment Canada) show an annual mean temperature of –17 °C, suggesting that the temperature within the interval stretching from the inferred base of permafrost to ground surface should not be greater than -1 °C. Another constraint for the surface temperature is the temperature at the sea floor, an approximation of -3 °C is set for all water depths in this report because no such data are available to this study.

Data analysis and preliminary results

A preliminary analysis of the data indicates that the quality of DST temperature and BHTs is poor in general. This is because of the complexity of geological and environmental settings of the region and also due to the nature of the drilling technology used when the data were acquired between 1969 and 1986.

Among the various data types, the repeated shallow temperature surveys provides the most reliable temperature data after environmental corrections, and the uncorrected BHTs are the worst. A combined use of DST temperatures, BHTs and corrected shallow survey temperatures, constrained by indirect temperature indicator from the inferred base of permafrost zone, appears to be useful for constructing a generalized regional temperature profile and providing a better representation of present day geothermal structure in this region.

Figure 2 is a cross plot of the raw temperature values from BHTs and DST temperature measurements collected from the 164 petroleum wells versus depth. A wide range of variations in temperature values at the same depth is obvious, suggesting variable data qualities and a variable geothermal condition across the region.

To eliminate the impact of poor data quality on the observed temperature variation, data from wells containing at lest 5 temperature data points (including the observed/inferred base of permafrost) and which show a consistent T-D relationship are selected. As a results, data from eighty six wells are plotted in Figure 3, with additional temperature data points from the Canadian geothermal compilation dataset. A linear model fit to the temperature–depth relationship gives an average temperature gradient of 23 °C/km with a correlation coefficient of 0.92. This suggests that the overall geothermal gradient is low in the region.

A few remarkable features are observed from this plot (Figure 3). First, although the scatter of the temperature data points at the same depth becomes much smaller than those from all wells on Figure 2, the data points still show a wide range of temperature variation. The difference in temperature at the same depth could be up to about 40°C at 2000m and downwards. Second, temperature readings from the shallow temperature survey forms an envelope defining the upper and lower boundaries approximately for the range of temperature variation, which is consistent with the range of variation from the BHTs and DST temperatures. Third, as the temperature data from repeated shallow temperature surveys are a more reliable data source, the similar range of temperature variation at the same depth suggests that the large variation in temperature across the basin may be true and could be a reflection of complexity of the regional geological setting. Fourth, all temperature data, except one, from the reservoirs of the existing discoveries show higher than average temperature as can be seen on Figure 3 (marked by open blue circles). These temperature data points are accompanied by the reserve estimation sheets of the PanArctic discoveries. Whether this high temperature anomaly associated with discoveries indicates an active petroleum system with recent deep fluid flux requires further investigations.

Temperature profiles

To better characterize temperature variation and the geological controls on the variation, we examine the T–D relationship at each well location and then investigate the possible cause of the variation in the present-day temperature field. All temperature data points are plotted against the depth for each of the 86 wells selected from the data analysis. The repeated shallow temperatures survey provides far

more consistent and accurate T-D relationship at shallow depth and forms a firm basis for extending the T-D relationship to deeper intervals.

Examples of T-D plots from a few specific geological settings are briefly explained. Typical vertical temperature variation in the central part of the western Sverdrup Basin is shown in an example T-D plot from the Sutherland O-23 well (Figure 4). The T-D relationship is depicted by the temperature measurements from the shallow temperature survey at shallow depth. The variation in the intermediate depth is provided by corrected BHTs and DST temperatures. There are two uncorrected BHTs in the deep part, which appears to be off the general temperature trend. Uncorrected BHTs appear to underestimate the formation temperature as indicated by the deviation from a general T-D relationship defined by other temperature data in this well. Similarly, uncorrected BHTs in the deep part of petroleum wells elsewhere in the Canadian High Arctic shows biases consistent with the observation in the Sutherland O-33 well.

A typical temperature profile at the southeast edge of the western Sverdrup Basin is shown on a T-D plot of the Bent Horn F-72A well (Figure 5). The temperature-depth relationship is depicted by the measurements from the shallow temperature survey. The inferred base of permafrost fits well with the temperature survey data. There are five measured temperature points from different sources, all which appear to underestimated the formation temperature in this well. The overall average temperature gradient is very low (<20 °C/km). This temperature profile may represent the lower end of T-D relationship in the region. This type of T-D relationship occurs along the Mesozoic basin margin and is likely associated with basin margin boundary faults.

A typical T-D relationship close to salt diapirs in the southeast part of the western Sverdrup Basin is shown in a temperature-depth plot of the Hazen F-54 well (Figure 6). The average temperature gradient reaches about 40 °C/km. Salt is a more efficient thermal conductor than clastic rocks and may elevate temperature. A similar temperature profile is seen from the Cape Norem A-80 well (Plot 3 in Appendix A) where the temperature gradient is slightly higher than 30 °C/km.

The volcanic intrusions appear to have no significant impact on the geothermal fields in this region. Figure 7 is an example of the T-D relationship at the location of Amund Central Dome H-40 well, where many intrusion intervals are observed. The overall average temperature gradient is only slightly higher than 20 °C/km, below the regional average temperature gradient of 23 °C/km. Other wells also

have multiple observed intrusion intervals, such as Cornwall O-30, Fosheim N-27 and Mid Fiord J-53 wells, and show similar temperature gradients.

Temperature-depth plots for the 86 selected wells are provided in Appendix A and Table 1 lists the well names and relevant information. A preliminary examination of individual plots suggests that most of the temperature profile has a convex shape, particularly in the uppermost 1500 meters, indicating an elevated temperature field, a typical feature of exhumed basins with surface forcing of cold surface condition (Allen and Allen, 2004; Chen et al., 2010). Further analyses and dedicated studies would provide a better understanding of the geological controls on the present-day temperature field and its spatial variation in the Arctic Archipelago.

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Figure Captions

Figure 1. Map of the Canadian Arctic Archipelago and the locations of petroleum exploration wells.

Figure 2. Cross-plot of the raw temperature values vs. depth from bottom hole temperature (BHT) and drill-stem test (DST) temperature measurements collected from the 164 petroleum wells. Note a large range of variation of temperature at a given depth.

Figure 3. Cross-plot of temperature versus depth from the BHT and DST data points of 86 selected wells and shallow temperature data, showing a general relationship between present day temperature – depth. The indirect temperature information, such as the base of inferred/recorded permafrost is also plotted in this figure.

Figure 4. Temperature-depth plot of the Sutherland O-23 well showing a typical temperature profile in the central part of the western Sverdrup Basin. This plot also illustrates the possible biases of uncorrected BHTs. (also Plot 35 in Appendix A)

Figure 5. Temperature-depth plot of the Bent Horn F-72A well showing a typical temperature profile associated with the Mesozoic basin margin boundary faults in the southeast. (also Plot 59 in Appendix A).

Figure 6. Temperature-depth plot of the Hazen F-54 well showing typical high temperatures associated with salt diaper in the southeast part of the western Sverdrup Basin. (Also Plot 74 in Appendix A).

Figure 7. Temperature-depth plot of the Amund Central Dome H-40 well suggesting no significant thermal effect of the volcanic intrusions on the present-day temperature relationship.

Table

Table 1. List of the 86 selected wells in Canadian Arctic Archipelago for the temperature–depth plots in Appendix A.

Plot number	Well name	UWI	Lat	Long
1	DRAKE POINT L-67	300L677630108300	76.4436	-108.9231
2	HOODOO DOME H-37	300H377810099300	78.1075	-99.7605
3	CAPE NOREM A-80	300A807730110000	77.4869	-110.4514
4	WILKINS E-60	300E607800111000	77.9886	-111.3625
5	AMUND CENTRAL DOME H-40	300H407820096000	78.3245	-96.2641
6	JAMESON BAY C-31	300C317650116300	76.67	-116.7293
7	SKYBATTLE BAY C-15	300C157720105000	77.2368	-105.0992
8	KING CHRISTIAN N-06	300N067750101000	77.765	-101.0386
9	STORKERSON BAY A-15	300A157300124300	72.9	-124.5581
10	HOTSPUR J-20	300J207610104000	76.1603	-104.0786
11	FOSHEIM N-27	300N277940084300	79.6151	-84.7219
12	KRISTOFFER BAY B-06	300B067820102300	78.2503	-102.5403
13	BROCK C-50	300C507750114000	77.8167	-114.29
14	SATELLITE F-68	300F687720116300	77.2908	-116.9194
15	DUMBBELLS E-49	300E497830100000	78.4734	-100.4034
16	DRAKE F-16	300F167630108300	76.421	-108.594
17	BROCK I-20	300I207800114300	77.9944	-114.5642
18	DOME BAY P-36	300P367830103000	78.4312	-103.2632
19	HOODOO L-41	300L417820099300	78.1769	-99.9036
20	ROMULUS C-42	300C428000084000	79.8513	-84.3783
21	DRAKE B-44	300B447630108000	76.3858	-108.2676
22	NOICE G-44	300G447830104000	78.3898	-104.3609
23	HELICOPTER J-12	300J127850100300	78.6926	-100.6136
24	DUNDAS C-80	300C807440113000	74.6506	-113.3833
25	LOUISE O-25	300O257850102300	78.7492	-102.6994
26	WALLIS K-62	300K627800102000	77.8622	-102.4212
27	GEMINI E-10	300E108000084000	79.9894	-84.0694
28	POLLUX G-60	300G607910104300	79.1565	-104.9565
29	HECLA I-69	300I697620110000	76.3102	-110.3876
30	EMERALD K-33	300K337650113300	76.7119	-113.7225
31	MOKKA A-02	300A027940087000	79.52	-87.0206
32	THOR H-28	300H287810103000	78.123	-103.1759
33	DEPOT PT. L-24	300L247930085300	79.3944	-85.7394
34	LINCKENS ISLAND P-46	300P467750097300	77.7631	-97.7574
35	SUTHERLAND O-23	300O237750102000	77.7147	-102.1442
36	ISACHSEN J-37	300J377920105000	79.2777	-105.2766
37	APOLLO C-73	300C737540111300	75.5333	-111.9828
38	MAY POINT H-02	300H027930085000	79.3566	-85.0131
39	WEATHERALL O-10	300O107550108300	75.8311	-108.5306
40	TALEMEN J-34	300J348000083300	79.8946	-83.7813
41	SIRIUS K-28	300K287920103300	79.2928	-103.7272
42	DRAKE POINT D-68	300D687630108300	76.4514	-108.9285
43	BENT HORN N-72	300N727630103300	76.3642	-103.97
44	NEIL O-15	300O158050083000	80.7458	-83.1139
45	ELVE M-40	300M407810101300	78.1664	-101.8286
46	DRAKE E-78	300E787630108000	76.4554	-108.4903

47	EGLINTON P-24	300P247600118000	75.8981	-118.1275
48	N. SABINE H-49	300H497650108300	76.8042	-108.7531
49	ROBERT HARBOUR K-07	300K077640104000	76.6089	-104.0373
50	PEDDER POINT D-49	300D497540118300	75.6358	-118.8044
51	CROCKER I-53	300I538010098300	80.0456	-98.9222
52	BLUE FIORD E-46	300E467720086000	77.2575	-86.3022
53	COLLINGWOOD K-33	300K337640108300	76.5457	-108.7243
54	PAT BAY A-72	300A727730105000	77.3504	-105.4492
55	DRAKE D-73	300D737630108000	76.3684	-108.4915
56	CHADS CREEK B-64	300B647630109300	76.3856	-109.9058
57	MOCKLIN POINT D-23	300D237830104300	78.3689	-104.7472
58	BENT HORN F-72	300F727630103300	76.3576	-103.9708
59	BENT HORN F-72A	300F727630103301	76.3576	-103.9708
60	DYER BAY L-49	300L497610121300	76.1432	-121.8102
61	SABINE BAY A-07	300A077530110000	75.435	-110.0139
62	W. HECLA P-62	300P627630110300	76.3642	-110.8764
63	W. BENT HORN E-43	300E437630104000	76.3711	-104.3124
64	KEY POINT O-51	300O517620104000	76.1818	-104.3346
65	CHARLES POINT G-07	300G077630103000	76.4408	-103.0175
66	W. BENT HORN M-12	300M127630104000	76.365	-104.1158
67	SOPHIE PT. G-19	300G197620103000	76.3065	-103.0821
68	CAPE ALLISON L-50	300L507750100000	77.8252	-100.3001
69	ROCHE PT. O-43	300J437650109300	76.7125	-109.7728
70	BEVERLEY INLET G-13	300G137510108000	75.0389	-108.0897
71	NOICE D-41	300D417830104000	78.3343	-104.4038
72	HOODOO E-05	300E057810099300	78.0713	-99.5632
73	HEARNE F-85	300F857450110300	74.7378	-110.9328
74	HAZEN F-54	300F547710110000	77.0546	-110.3539
75	CORNWALL O-30	300O307730094300	77.4964	-94.6494
76	MACLEAN I-72	300I727740103300	77.5275	-103.9397
77	CISCO B-66	300B667730106000	77.417	-106.3933
78	WHITEFISH A-26	300A267720106300	77.2526	-106.6371
79	CISCO K-58	300K587730106000	77.46	-106.3525
80	GRENADIER A-26	300A267730099300	77.4184	-99.6365
81	MARRYATT K-71	300K717630108300	76.3438	-108.9739
82	CISCO M-22	300M227730106000	77.3668	-106.1866
83	SKATE C-59	300C597750104300	77.8042	-104.8578
84	CAPE ALLISON C-47	300C477750100000	77.7681	-100.2889
85	SKYBATTLE BAY M-11	300M117720105000	77.1821	-105.1123
86	W. CORNWALL N-49	300N497730097000	77.4814	-97.2923

Appendix

Appendix A. T-D plots of 86 selected petroleum wells in the Canadian Arctic Archipelagos.