# Criteria to Determine Borehole Formation Temperatures for Calibration of Basin and Petroleum System Models*

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## Abstract

Production test and drill stem test (DST) temperatures based on high flow volumes of oil or water from the producing formation are generally the most reliable temperature data for calibration of basin and petroleum system models. However, the down-hole gauge must be located within or near the formation and gas production zones should be avoided because of the Joule-Thompson effect. Long-term static tests are also generally reliable, but they are rare. Bottom-hole temperatures (BHT) from well log headers are common, but require correction because they are biased lower than true formation temperature. Care must be taken to avoid short static times, re-circulation between measurements, and spurious records of times or temperatures from logs. Criteria for reliable Horner corrected BHT data include a minimum of three logging runs that record time and temperature for each run, temperature extrapolation less than the range of temperature data, and deviations from the least squares regression line that are less than measurement uncertainty (±1-3°C or ±2-5°F).

Based on published comparisons of DST and Horner-corrected BHT data from the same depths, the standard deviation of corrected bottom-hole temperatures is about ±8°C (±14°F). Some studies show that corrected data may still be systematically biased lower than true formation temperature. For a Petromod® one-dimensional basin and petroleum system model of the upper Cook Inlet in Alaska, error of ±8°C resulted in calculated depth to top of the oil window in the Jurassic Tuxedni Group source rock of as much as 305 m

(1,001 ft) above and 6.2 my earlier or 231 m (758 ft) below and 4.5 my later than that calculated using a corrected BHT formation temperature of 92.4°C. In summary, BHT data are an important source of uncertainty that needs to be considered when calibrating basin and petroleum system models.

## Selected References


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# *Criteria to Determine Borehole Formation Temperatures for Calibration of Basin and Petroleum System Models*

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# Accurate Formation Temperatures Are Important Because Temperature Affects:

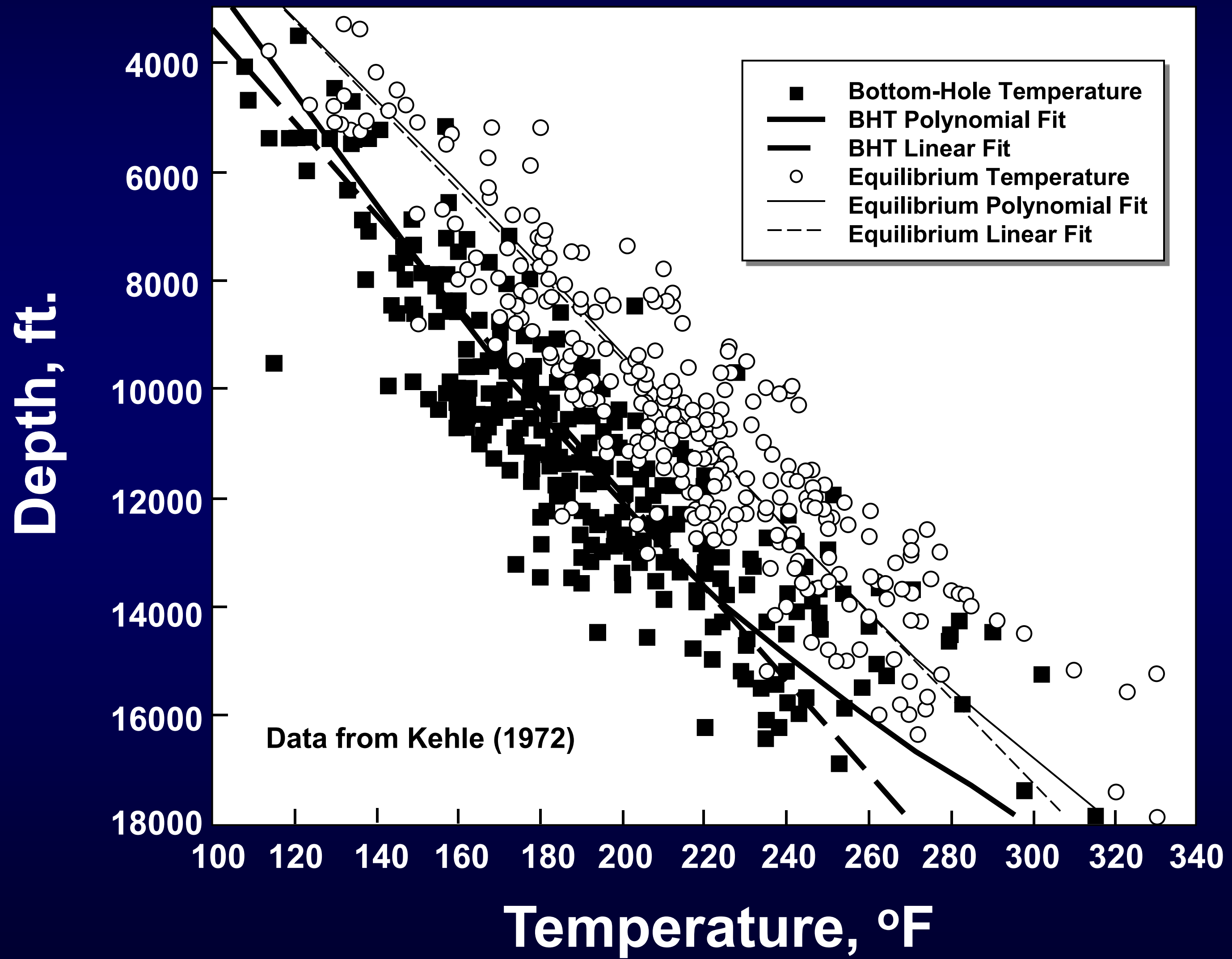
- water resistivity (needed to calculate oil saturations from resistivity logs)
- reservoir-fluid formation volume factors (needed for reserve estimates)
- geothermal gradients (needed to estimate temperatures of deep zones)
- calibration of petroleum system models (needed to calculate generation timing and yields)

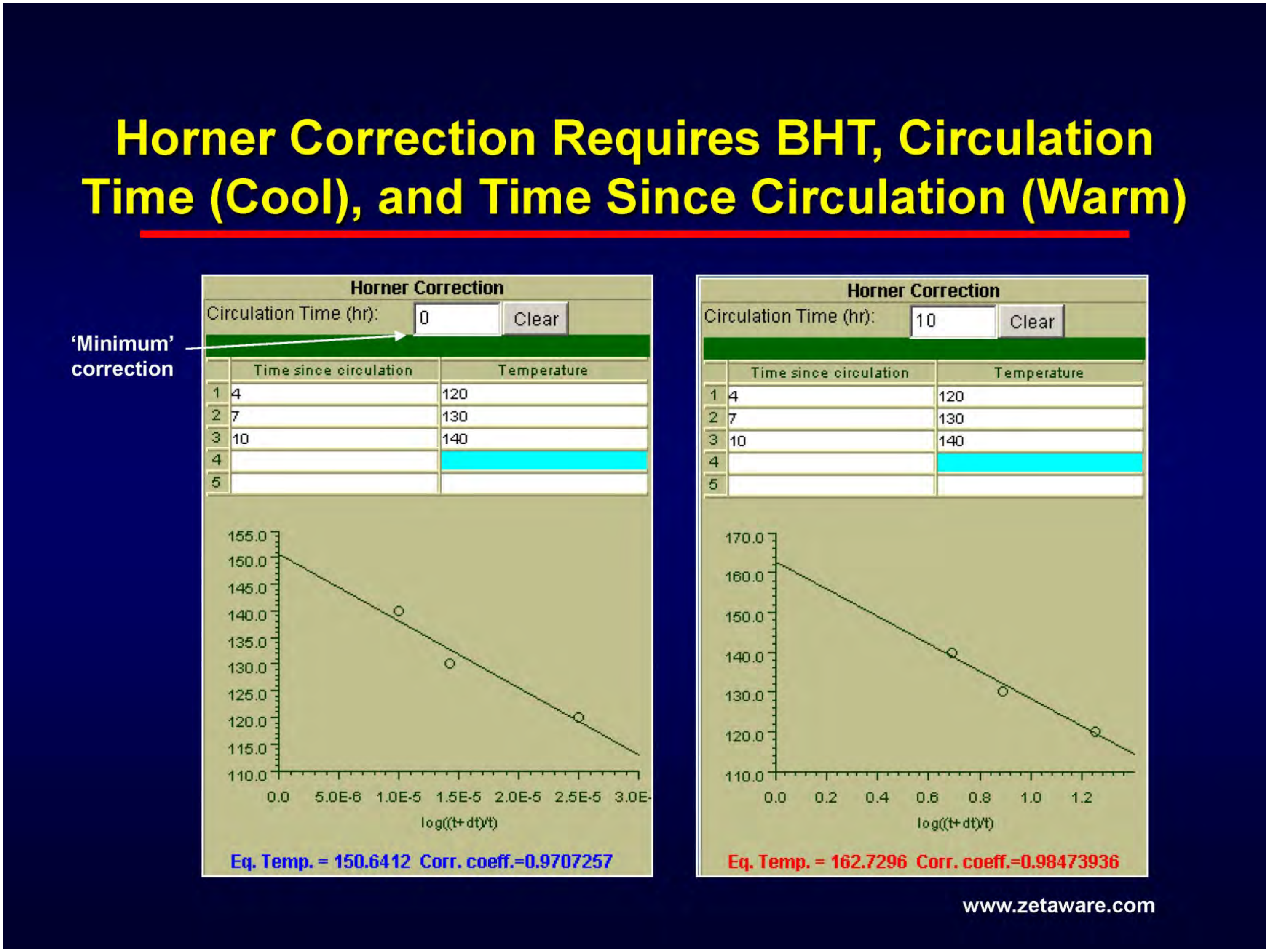
# How Do Measured Subsurface Temperatures Affect Predictions From Basin and Petroleum System Models?

## Purpose

- Identify types of temperature (T) data and their relative value for calibration
- Establish criteria to evaluate reliability of T data
- Provide guidelines for use and examples of various T corrections
- Show the sensitivity of T error in calibration of a simple 1D model from the Cook Inlet, Alaska

# Bottom-Hole Temperatures (BHT) Usually Underestimate 'True' Formation T





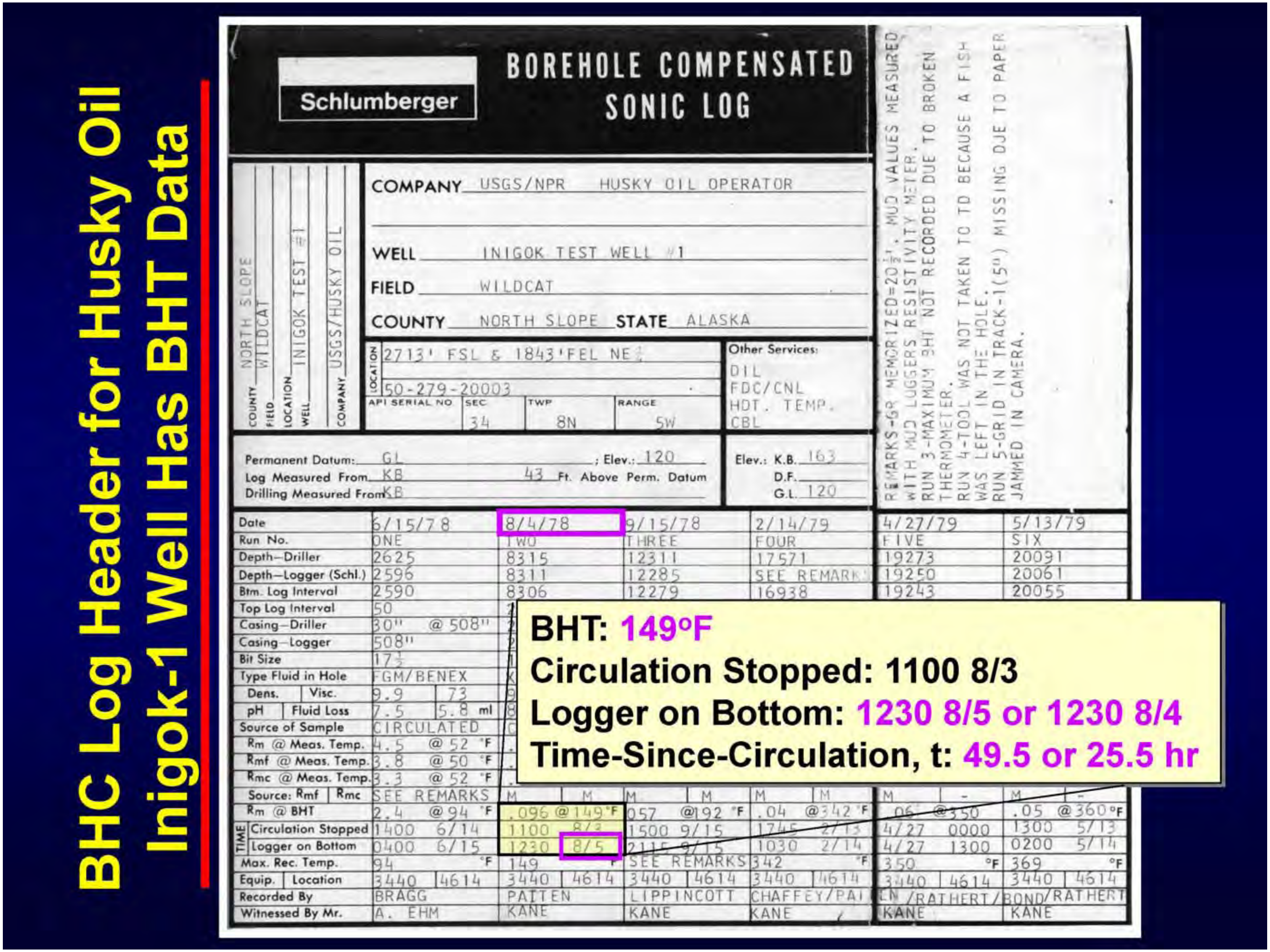

A Horner correction is recommended if three of more self-consistent BHTs from a given depth are available. Based on a study of 983 BHT and associated equilibrium temperature estimate (Teq) pairs, the Teq uncertainty (1 sigma) using the Horner correction is ±14 °F (±8 °C).
T = circulation time (cooling); dt = time since circulation stopped (warming)

The Horner suite has to record the T-history of a passively re-equilibrating, mechanically static system. For the Horner method to work, it is important that the well not be circulated during logging. Also, it must not be circulated between the several logging runs of a Horner suite.

Time since circulation = time between when circulation was shut off and the time the logging tool reached maximum depth for that run

# Criteria Can Be Used to Define the Quality of Horner Corrections

- Minimum of 3 logging runs that record time and temperature
- Temperature extrapolation less than range of temperature data
- Deviation from least squares regression less than measurement uncertainty (<5°F or 3°C)

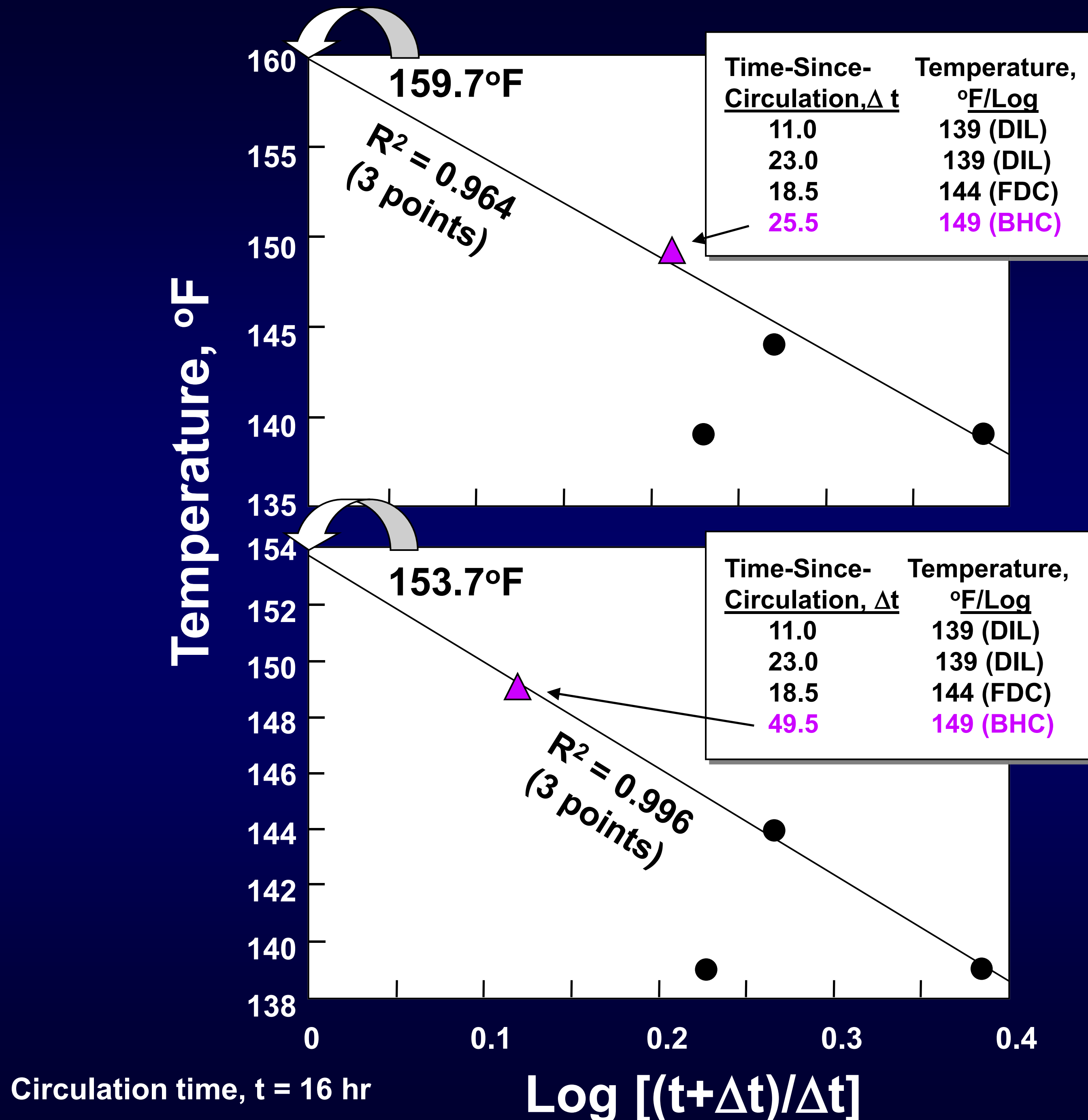



| | | | | | | |
|---|---|---|---|---|---|---|
| Date | 6/15/78 | 8/4/78 | 9/15/78 | 2/14/79 | 4/27/79 | 5/13/79 |
| Run No. | ONE | TWO | THREE | FOUR | FIVE | SIX |
| Depth—Driller | 2625 | 8315 | 12311 | 17571 | 19273 | 20091 |
| Depth—Logger (Schl.) | 2596 | 8311 | 12285 | SEE REMARKS | 19250 | 20061 |
| Btm. Log Interval | 2590 | 8306 | 12279 | 16938 | 19243 | 20055 |
| Top Log Interval | 50 | | | | | |
| Casing—Driller | 30" @ 508" | | | | | |
| Casing—Logger | 508" | | | | | |
| Bit Size | 17½ | | | | | |
| Type Fluid in Hole | FGM/BENEX | | | | | |
| Dens. / Visc. | 9.9 / 73 | | | | | |
| pH / Fluid Loss | 7.5 / 5.8 ml | | | | | |
| Source of Sample | CIRCULATED | | | | | |
| Rm @ Meas. Temp. | 4.5 @ 52 °F | | | | | |
| Rmf @ Meas. Temp. | 3.8 @ 50 °F | | | | | |
| Rmc @ Meas. Temp. | 3.3 @ 52 °F | | | | | |
| Source: Rmf / Rmc | SEE REMARKS | M / M | M / M | M / M | M / - | M / - |
| Rm @ BHT | 2.4 @ 94 °F | .096 @ 149 °F | .057 @ 192 °F | .04 @ 342 °F | .06 @ 350 | .05 @ 360 °F |
| Time: Circulation Stopped | 1400 6/14 | 1100 8/3 | 1500 9/15 | 1745 2/13 | 4/27 0000 | 1300 5/13 |
| Time: Logger on Bottom | 0400 6/15 | 1230 8/5 | 2115 9/15 | 1030 2/14 | 4/27 1300 | 0200 5/14 |
| Max. Rec. Temp. | 94 °F | 149 °F | SEE REMARKS | 342 °F | 350 °F | 369 °F |
| Equip. / Location | 3440 / 4614 | 3440 / 4614 | 3440 / 4614 | 3440 / 4614 | 3440 / 4614 | 3440 / 4614 |
| Recorded By | BRAGG | PATTEN | LIPPINCOTT | CHAFFEY/PAI | EN /RATHERT/ | BOND/RATHERT |
| Witnessed By Mr. | A. EHM | KANE | KANE | KANE | KANE | KANE |

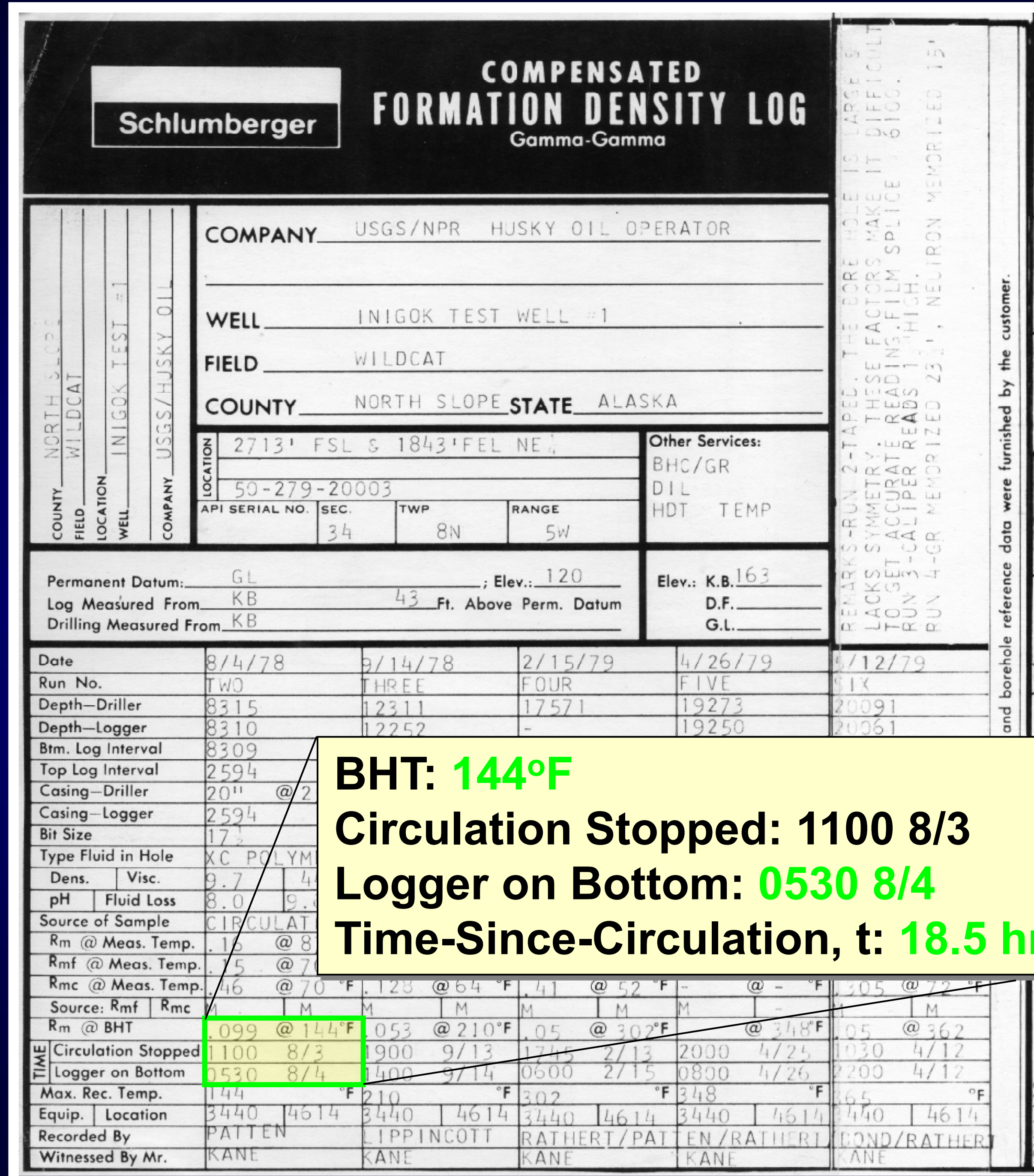


Time-since-circulation, t (or warming time), is calculated as the difference between "circulation stopped" and "logger on bottom" from the log headers. Circulation time (cooling time) must be obtained from the drilling report.

# Horner Plots Predict True Formation Temperature



# FDC Log Header for Husky Oil Inigok-1 Well Has BHT Data



Schlumberger

**COMPENSATED FORMATION DENSITY LOG**
Gamma-Gamma

COMPANY: USGS/NPR HUSKY OIL OPERATOR
WELL: INIGOK TEST WELL #1
FIELD: WILDCAT
COUNTY: NORTH SLOPE STATE: ALASKA

COUNTY: NORTH SLOPE
FIELD: WILDCAT
LOCATION:
WELL: INIGOK TEST #1
COMPANY: USGS/HUSKY OIL

LOCATION: 2713' FSL & 1843' FEL NE¼
50-279-20003

API SERIAL NO. | SEC. 34 | TWP 8N | RANGE 5W

Other Services:
BHC/GR
DIL
HDT TEMP

Permanent Datum: GL ; Elev.: 120
Log Measured From KB 43 Ft. Above Perm. Datum
Drilling Measured From KB

Elev.: K.B. 163
D.F.
G.L.

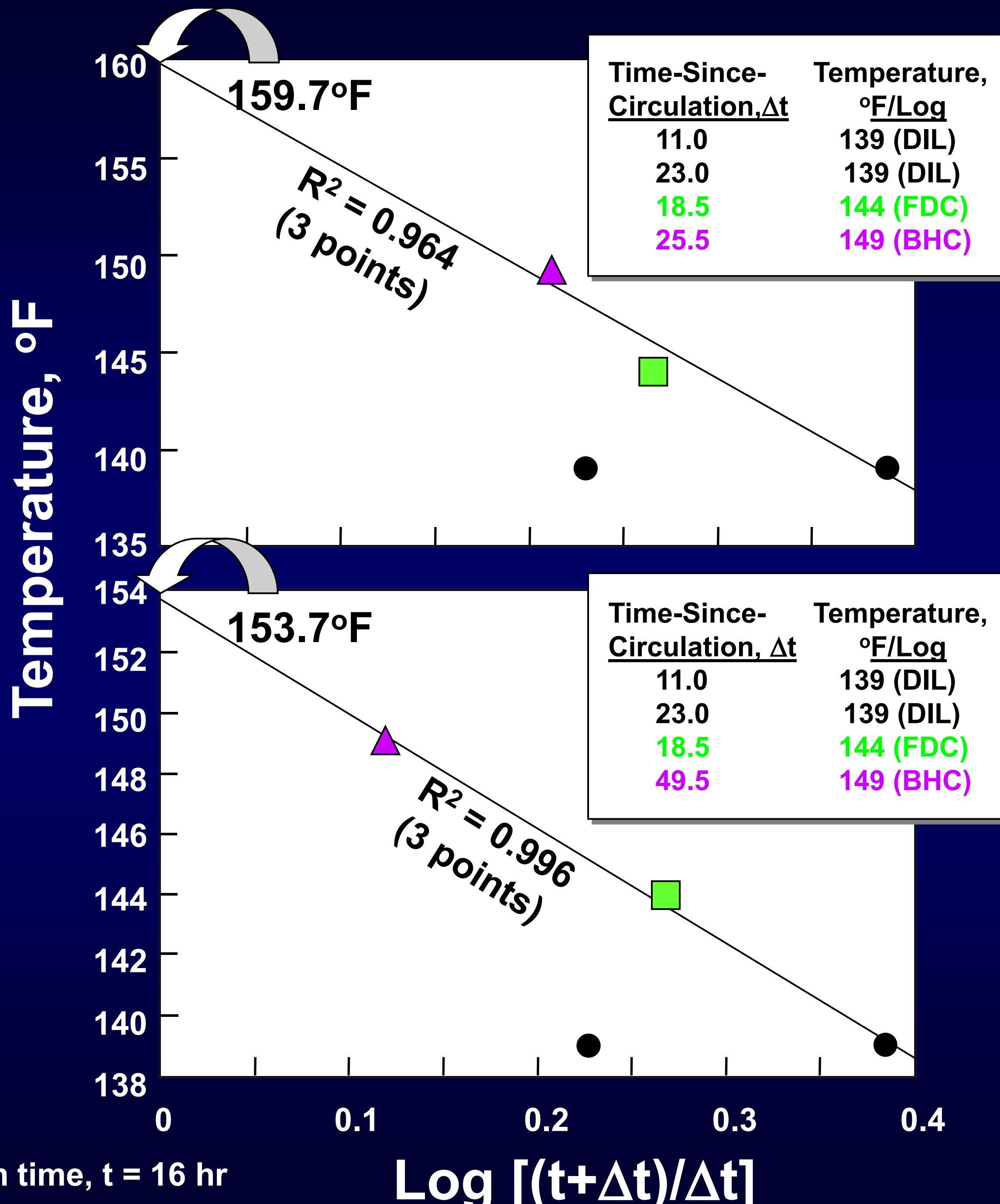
REMARKS-RUN 2-TAPED. THE BORE HOLE IS LARGE & LACKS SYMMETRY. THESE FACTORS MAKE IT DIFFICULT TO GET ACCURATE READING. FILM SPLICE 6100.
RUN 3-CALIPER READS 1½" HIGH.
RUN 4-GR MEMORIZED 23½', NEUTRON MEMORIZED 15'.

| | | | | | |
|---|---|---|---|---|---|
| Date | 8/4/78 | 9/14/78 | 2/15/79 | 4/26/79 | 5/12/79 |
| Run No. | TWO | THREE | FOUR | FIVE | SIX |
| Depth—Driller | 8315 | 12311 | 17571 | 19273 | 20091 |
| Depth—Logger | 8310 | 12252 | - | 19250 | 20061 |
| Btm. Log Interval | 8309 | | | | |
| Top Log Interval | 2594 | | | | |
| Casing—Driller | 20" @ 2 | | | | |
| Casing—Logger | 2594 | | | | |
| Bit Size | 17½ | | | | |
| Type Fluid in Hole | XC POLYM | | | | |
| Dens. / Visc. | 9.7 / 4 | | | | |
| pH / Fluid Loss | 8.0 / 9. | | | | |
| Source of Sample | CIRCULAT | | | | |
| Rm @ Meas. Temp. | .16 @ 8 | | | | |
| Rmf @ Meas. Temp. | .15 @ 7 | | | | |
| Rmc @ Meas. Temp. | .46 @ 70 °F | .128 @ 64 °F | .41 @ 52 °F | - @ - °F | .305 @ 72 °F |
| Source: Rmf / Rmc | M / M | M / M | M / M | M / - | M / M |
| Rm @ BHT | .099 @ 144°F | .053 @ 210°F | .05 @ 302°F | @ 348°F | .05 @ 362 |
| TIME Circulation Stopped | 1100 8/3 | 1900 9/13 | 1745 2/13 | 2000 4/25 | 1030 4/12 |
| TIME Logger on Bottom | 0530 8/4 | 1400 9/14 | 0600 2/15 | 0800 4/26 | 2200 4/12 |
| Max. Rec. Temp. | 144 °F | 210 °F | 302 °F | 348 °F | 365 °F |
| Equip. / Location | 3440 / 4614 | 3440 / 4614 | 3440 / 4614 | 3440 / 4614 | 3440 / 4614 |
| Recorded By | PATTEN | LIPPINCOTT | RATHERT/PATTEN | /RATHERT | BOND/RATHERT |
| Witnessed By Mr. | KANE | KANE | KANE | KANE | KANE |

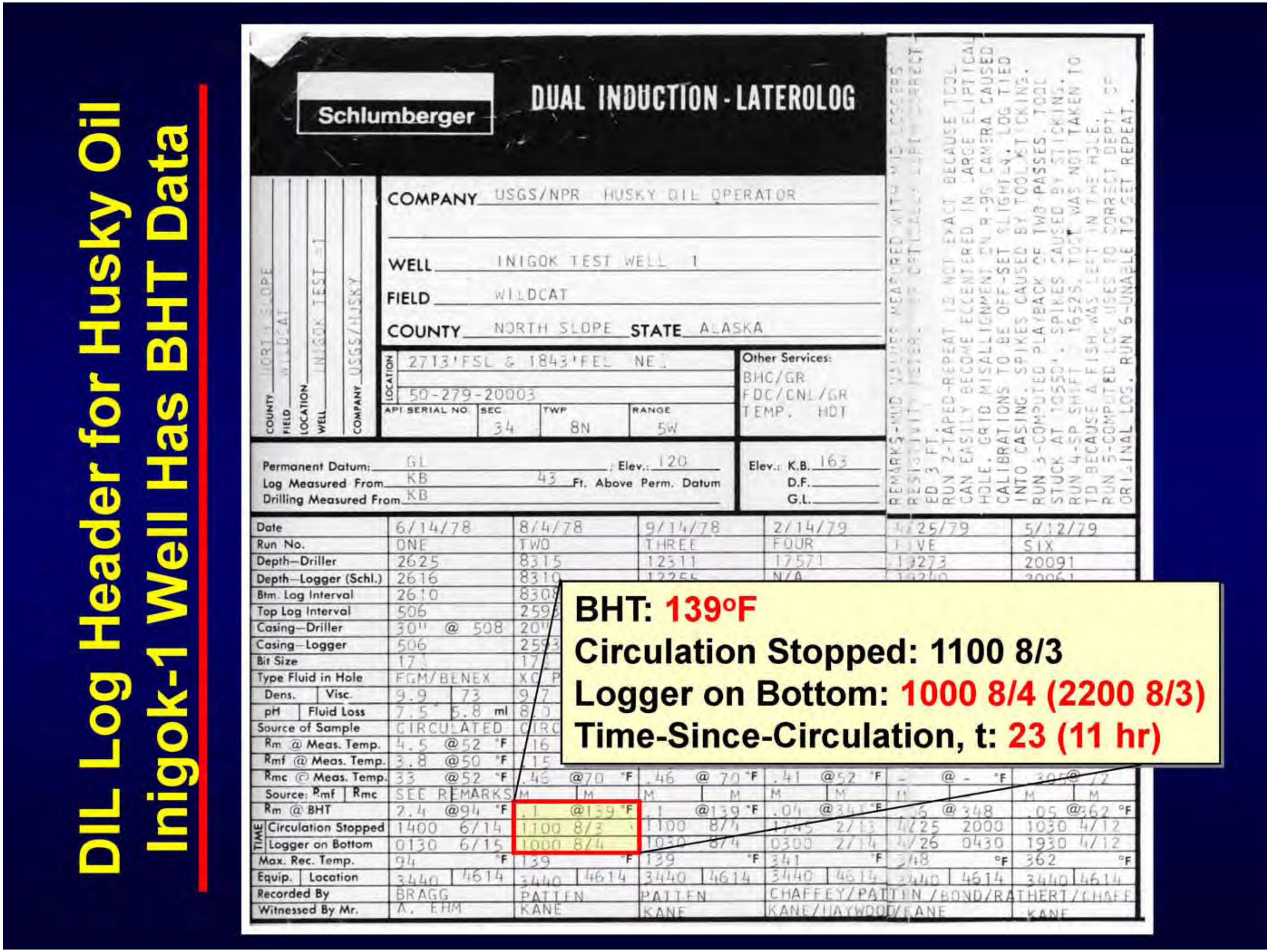
...and borehole reference data were furnished by the customer.

**BHT: 144°F**
**Circulation Stopped: 1100 8/3**
**Logger on Bottom: 0530 8/4**
**Time-Since-Circulation, t: 18.5 hr**

# Horner Plots Predict True Formation Temperature



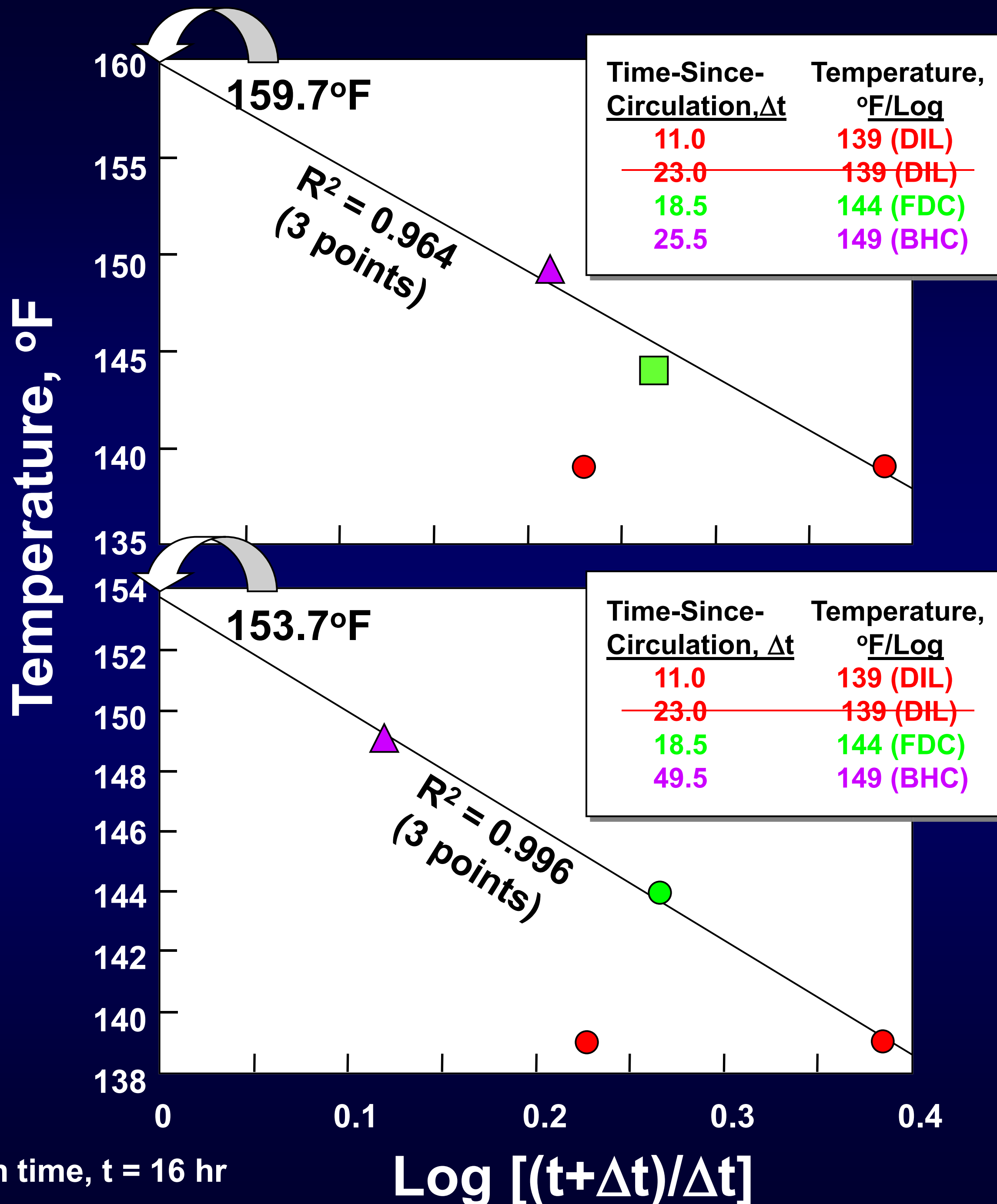

Circulation time, t = 16 hr




| | | | | | | |
|---|---|---|---|---|---|---|
| Date | 6/14/78 | 8/4/78 | 9/14/78 | 2/14/79 | 4/25/79 | 5/12/79 |
| Run No. | ONE | TWO | THREE | FOUR | FIVE | SIX |
| Depth—Driller | 2625 | 8315 | 12311 | 17571 | 19273 | 20091 |
| Depth—Logger (Schl.) | 2616 | 8310 | | N/A | | |
| Btm. Log Interval | 2610 | 8308 | | | | |
| Top Log Interval | 506 | 259 | | | | |
| Casing—Driller | 30" @ 508 | 20" | | | | |
| Casing—Logger | 506 | 259 | | | | |
| Bit Size | 17 | 17 | | | | |
| Type Fluid in Hole | FGM/BENEX | XC P | | | | |
| Dens. / Visc. | 9.9 / 73 | 9.7 | | | | |
| pH / Fluid Loss | 7.5 / 5.8 ml | 8.0 | | | | |
| Source of Sample | CIRCULATED | CIRC | | | | |
| Rm @ Meas. Temp. | 4.5 @ 52 °F | .16 | | | | |
| Rmf @ Meas. Temp. | 3.8 @ 50 °F | .15 | | | | |
| Rmc @ Meas. Temp. | 3.3 @ 52 °F | .46 @ 70 °F | .46 @ 70 °F | .41 @ 52 °F | - @ - °F | @ 72 |
| Source: Rmf / Rmc | SEE REMARKS | M / M | M / M | M / M | M | M / M |
| Rm @ BHT | 2.4 @ 94 °F | .1 @ 139 °F | .1 @ 139 °F | .04 @ 341 °F | .06 @ 348 | .05 @ 362 °F |
| Circulation Stopped | 1400 6/14 | 1100 8/3 | 1100 8/4 | 1745 2/13 | 4/25 2000 | 1030 4/12 |
| Logger on Bottom | 0130 6/15 | 1000 8/4 | 1030 8/4 | 0300 2/14 | 4/26 0430 | 1930 4/12 |
| Max. Rec. Temp. | 94 °F | 139 °F | 139 °F | 341 °F | 348 °F | 362 °F |
| Equip. / Location | 3440 / 4614 | 3440 / 4614 | 3440 / 4614 | 3440 / 4614 | 3440 / 4614 | 3440 / 4614 |
| Recorded By | BRAGG | PATTEN | PATTEN | CHAFFEY/PATTEN | /BOND/RATHERT | /CHAFF |
| Witnessed By Mr. | A. EHM | KANE | KANE | KANE/HAYWOOD | /KANE | KANE |

Incorrectly recorded T and t is common, particularly when a long work shift runs past midnight. In the example, the time was recorded assuming a 12-hr rather than 24 hr clock (i.e., 10 am versus 10 pm).

# Horner Plots Predict True Formation Temperature




Circulation time, t = 16 hr

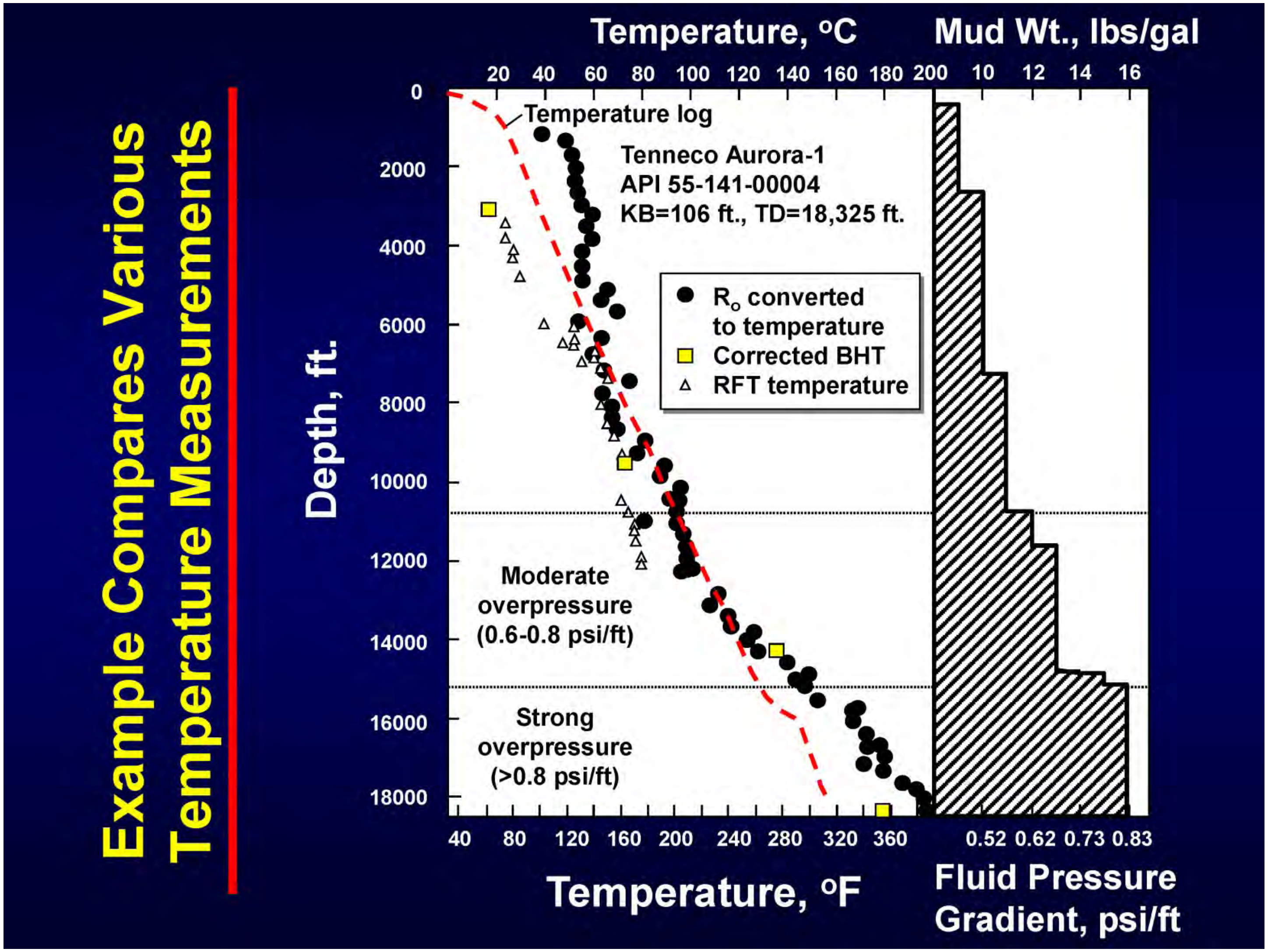
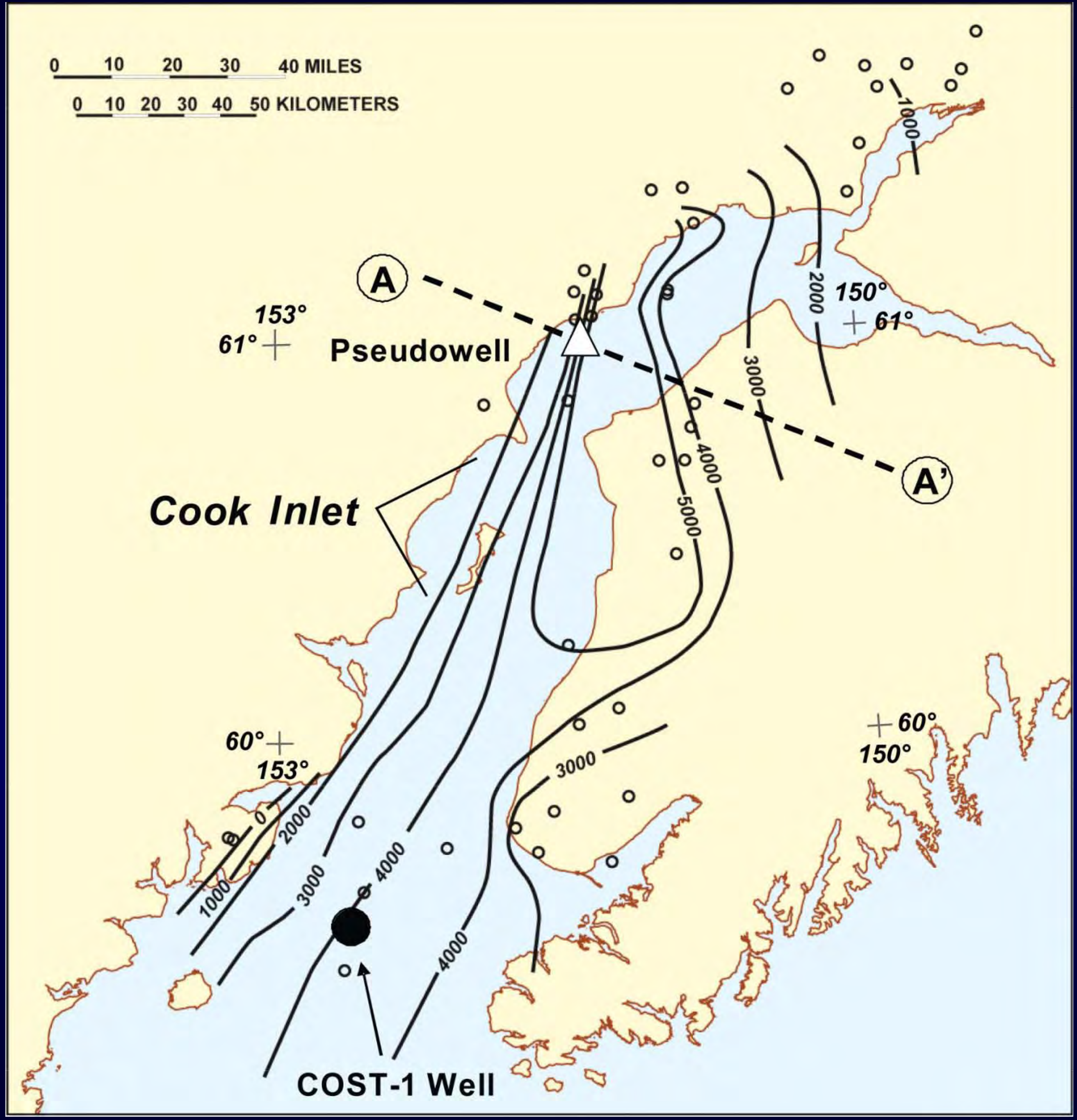
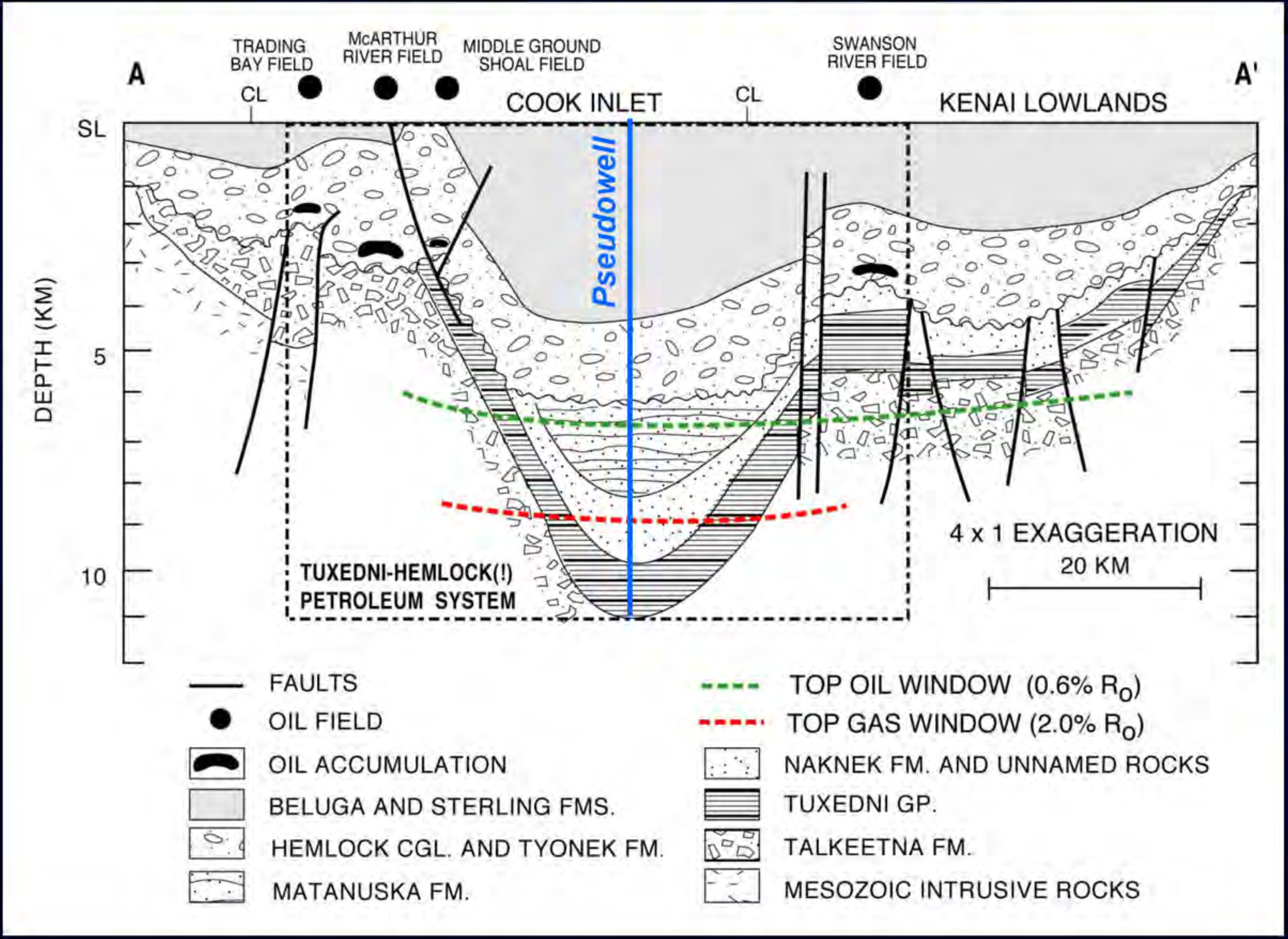



Figure the present-day log temperature curve with maximum paleotemperature inferred from vitrinite reflectance using the method of Barker and Pawlewicz (1994). The warm drilling mud had insufficient time during the temperature log run to equilibrate with the cooler formation. Therefore, the drilling mud was warmer than the formation at shallow depth (<6,000 ft, <1,829 m), resulting in higher temperature from the temperature log (measured in the mud column) compared to RFTs (uncorrected) and the corrected BHT. The maximum paleotemperature inferred from vitrinite reflectance at shallow depth (<6,000 ft, <1,829 m; solid dots) in the well is higher than that from the temperature log (dashed line) and higher than the true formation temperature, probably because of recycled vitrinite in these shallow Tertiary rocks. The dogleg in the calculated temperature profile at 6,000 ft in the well (Fig. 6) probably indicates the time when the Sadlerochit Mountains began to contribute recycled vitrinite to the coastal plain near the present-day Aurora-1 well. Apatite fission track evidence indicates that the most severe uplift and erosion events occurred in the Sadlerochit Mountains about 45 Ma and 23 Ma (Eocene and Oligocene-Miocene, respectively; O'Sullivan et al., 1993). At depths greater than 14,000 ft (4,267 m; Fig. 6), the temperature log records lower temperatures than the two corrected BHT measurements and the reflectance-converted temperatures. At these depths, the drilling mud is cooler than the formation, resulting in lower temperature from the temperature log than that from corrected BHT data at 14,400 and 18,350 ft (4,389 and 5,593 m). The higher temperature gradient is evident in the paleotemperature profile. Bird et al. (1999) postulate that overpressures and an associated 'thermal blanketing effect' related to enhanced porosity and lower thermal conductivity, typical of overpressured zones (Hunt, 1996), are responsible for the abrupt increase in vitrinite reflectance and inferred paleotemperature below 14,000 ft (4,267 m).

# Upper Cook Inlet: 1D Basin and Petroleum System Modeling



# Section A-A' Shows Oil and Gas Windows From Magoon (1994)



# Model Input Included Thickness, Eroded Thickness, Ages, Lithologies, $TOC_o$, $HI_o$

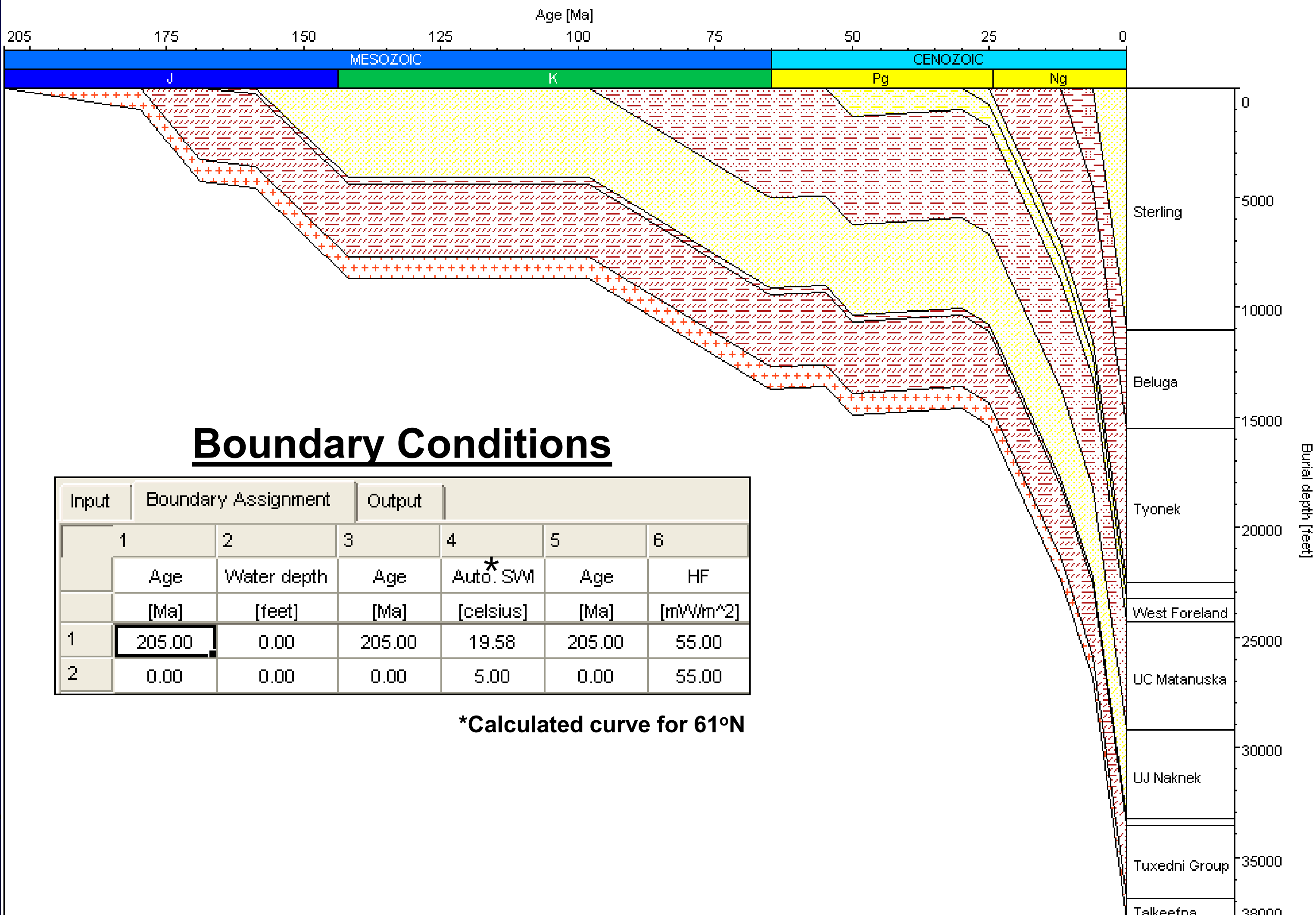
Input | Boundary Assignment | Output

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Present | Eroded | Deposition Age | | Erosion Age | | |
| | Name | Top | Bottom | Thickness | Thickness | from | to | from | to | Lithology |
| | | [feet] | [feet] | [feet] | [feet] | [Ma] | [Ma] | [Ma] | [Ma] | |
| 1 | Sediment Surface | | | 0.00 | | | | | | |
| 2 | Sterling | 0.00 | 11000.00 | 11000.00 | | 6.00 | 0.00 | | | SANDsilty |
| 3 | Beluga | 11000.00 | 15500.01 | 4500.01 | | 12.00 | 6.00 | | | SHALEsand |
| 4 | Tyonek | 15500.01 | 22500.02 | 7000.01 | | 25.00 | 12.00 | | | SHALE&SILT |
| 5 | Hemlock | 22500.02 | 23250.01 | 749.99 | | 30.00 | 25.00 | | | SANDcongl |
| 6 | West Foreland | 23250.01 | 24250.00 | 999.99 | 300.00 | 55.00 | 50.00 | 50.00 | 30.00 | SANDshaly |
| 7 | UC Matanuska | 24250.00 | 29171.99 | 4921.99 | 100.00 | 98.00 | 65.00 | 65.00 | 55.00 | SHALE&SAND |
| 8 | UJ Naknek | 29171.99 | 33272.99 | 4101.00 | | 159.00 | 142.00 | | | SANDsilty |
| 9 | Tuxedni SR | 33272.99 | 33572.99 | 300.00 | | 169.00 | 159.00 | | | SHALE |
| 10 | Tuxedni Group | 33572.99 | 36853.99 | 3281.00 | | 180.00 | 169.00 | | | SHALE&SILT |
| 11 | Talkeetna | 36853.99 | 37853.98 | 999.99 | | 205.00 | 180.00 | | | Basalt |
| 12 | | 37853.98 | | | | | | | | |

**Kinetics (Pepper & Corvi_TII(B), Tuxedni SR 2 wt.% TOC, HI = 350 mg HC/g TOC**

In subsequent lectures and exercises you will see more details on how we build the stratigraphy for PetroMod, including how to quantify missing section. You will also see how to determine the variation of the boundary conditions through time.

# Boundary Conditions: Water Depth, Sediment-Water Interface Temperature, and Heat Flow



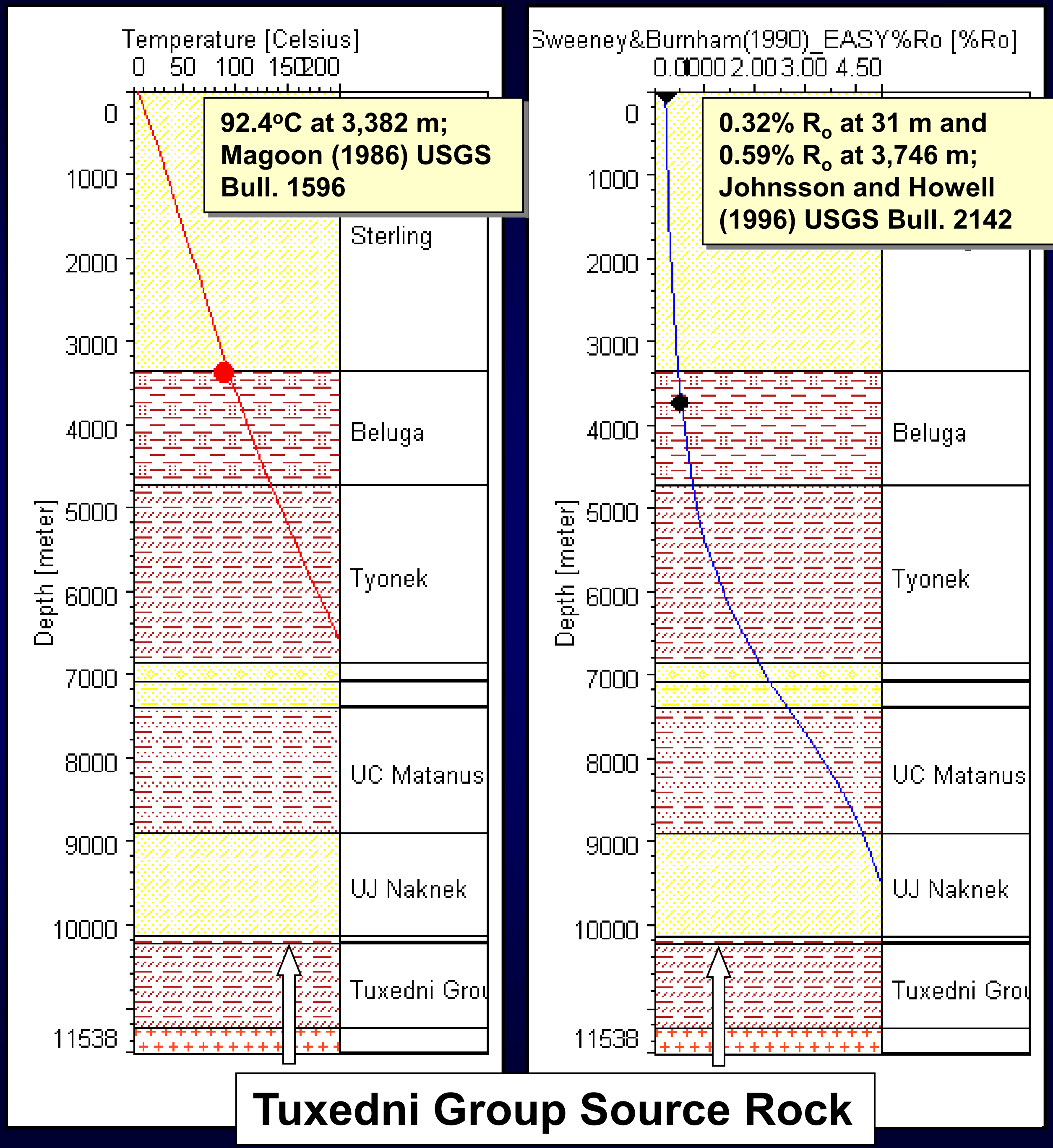

## Boundary Conditions

Input | Boundary Assignment | Output

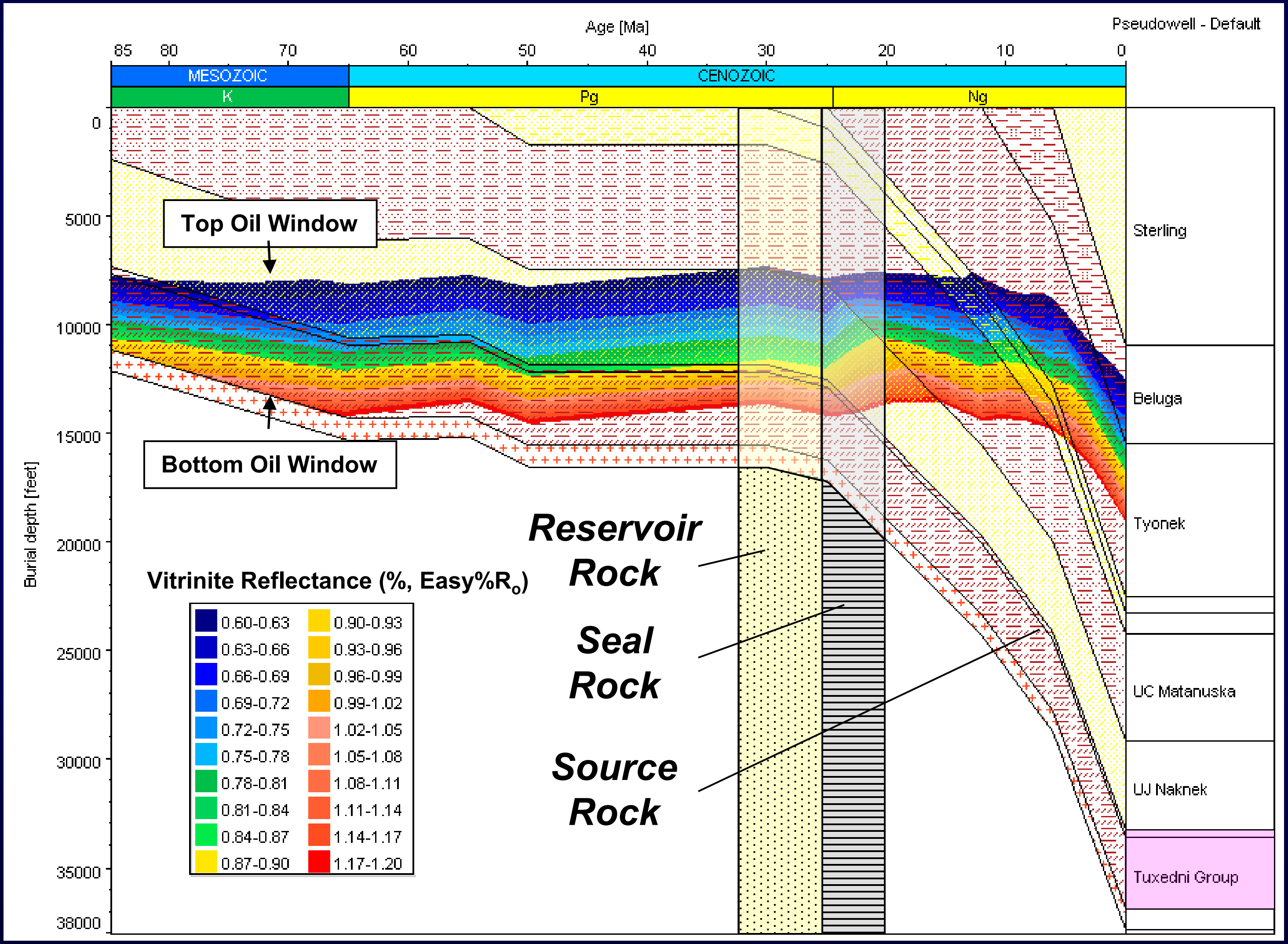
| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| | Age | Water depth | Age | Auto.* SWI | Age | HF |
| | [Ma] | [feet] | [Ma] | [celsius] | [Ma] | [mW/m^2] |
| 1 | 205.00 | 0.00 | 205.00 | 19.58 | 205.00 | 55.00 |
| 2 | 0.00 | 0.00 | 0.00 | 5.00 | 0.00 | 55.00 |

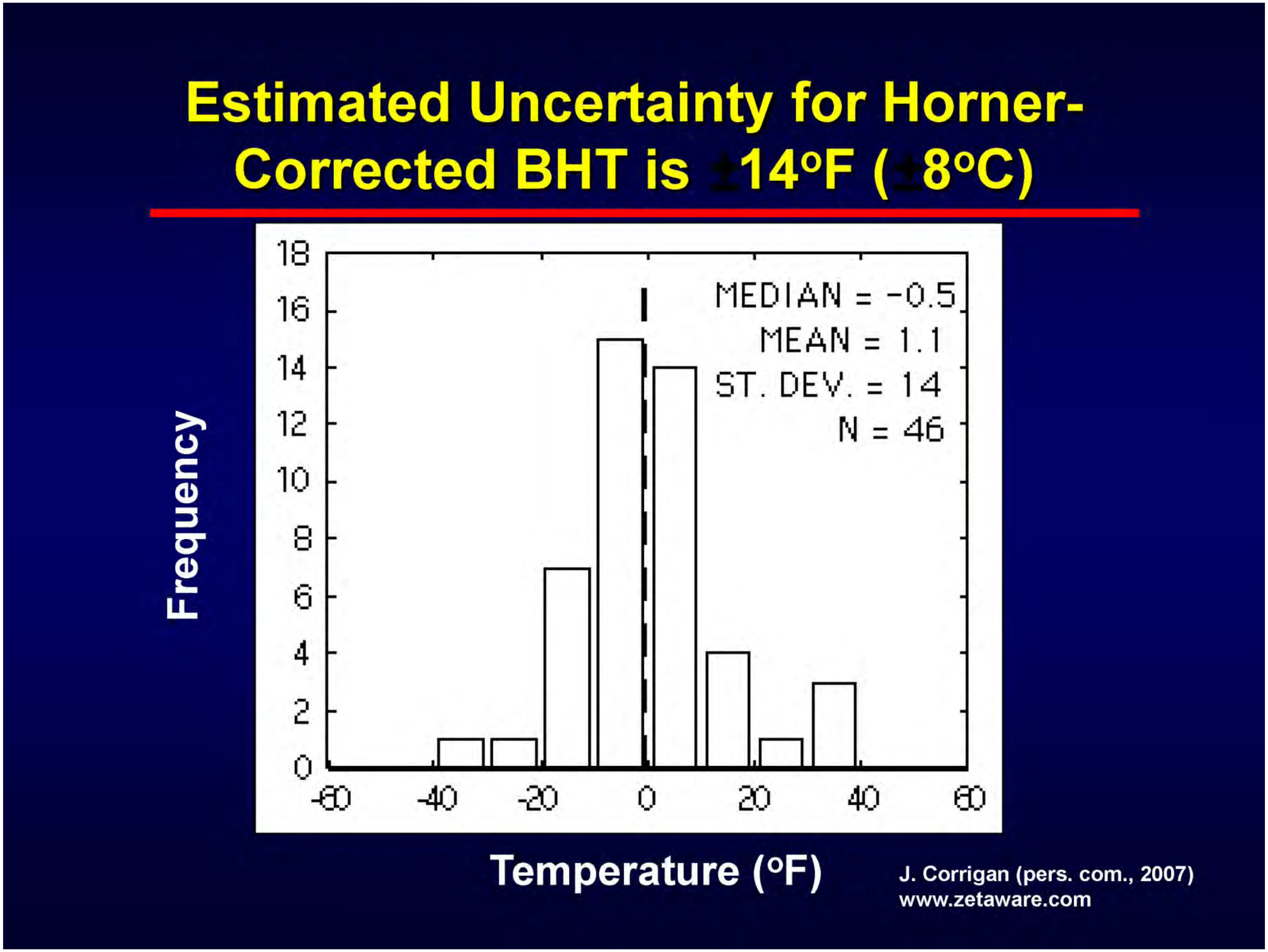
***Calculated curve for 61°N**

# Example Shows Calibration of the 1D Model at the Pseudowell



# Only High-Maturity Product Was Trapped From the Deep Tuxedni Source Rock






The histogram shows the differences between DST temperatures and adjacent (±500 ft) Horner-corrected BHTs. It provides an estimate of the uncertainty associated with a Horner-corrected temperature.

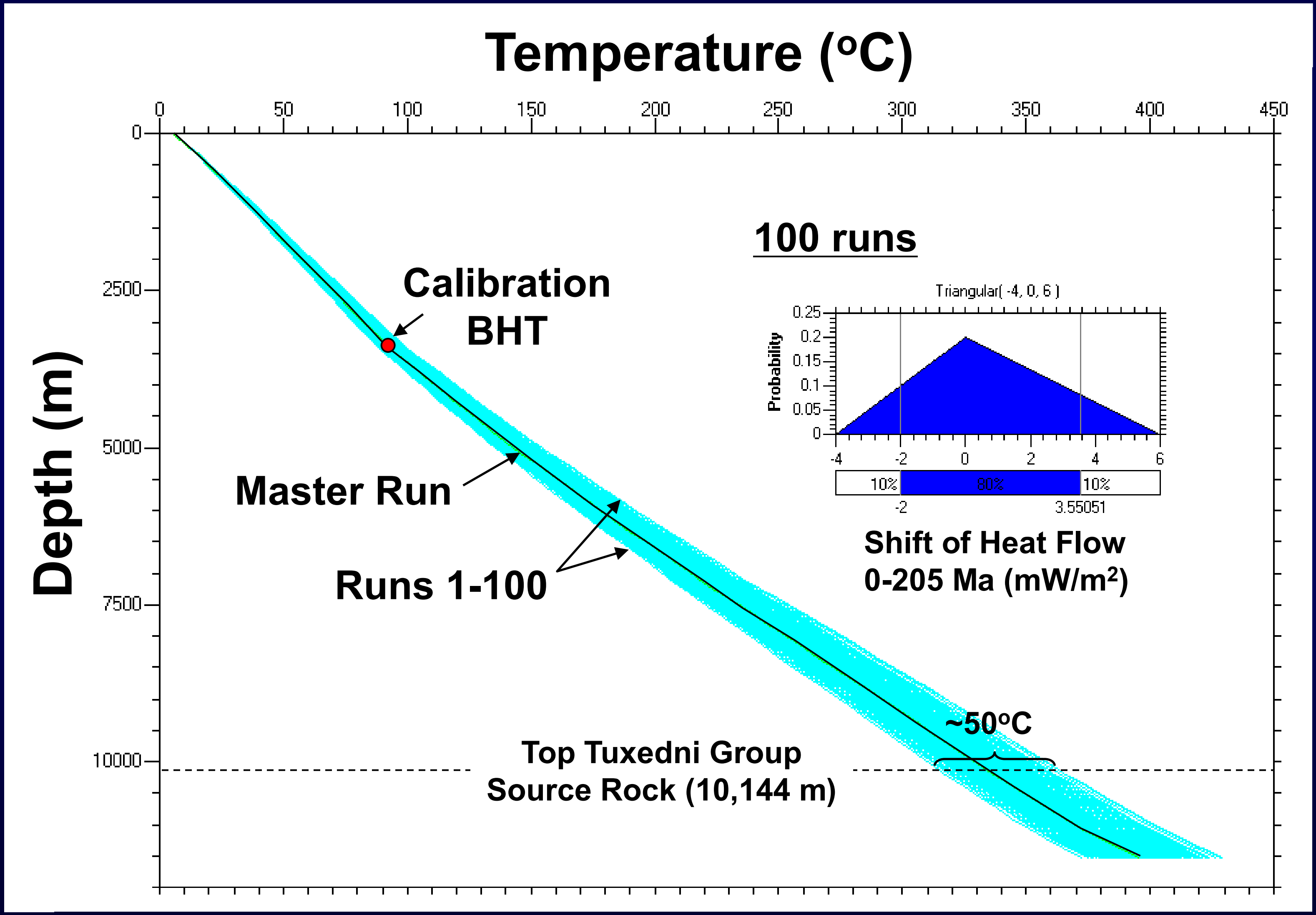
Based on a study of 983 BHT and associated equilibrium temperature estimate (Teq) pairs, the Teq uncertainty (1 sigma) using the Horner correction is ±14°F (±8°C).

# Sensitivity of 1D Model to BHT Error ( 8°C*) Spans Millions of Years

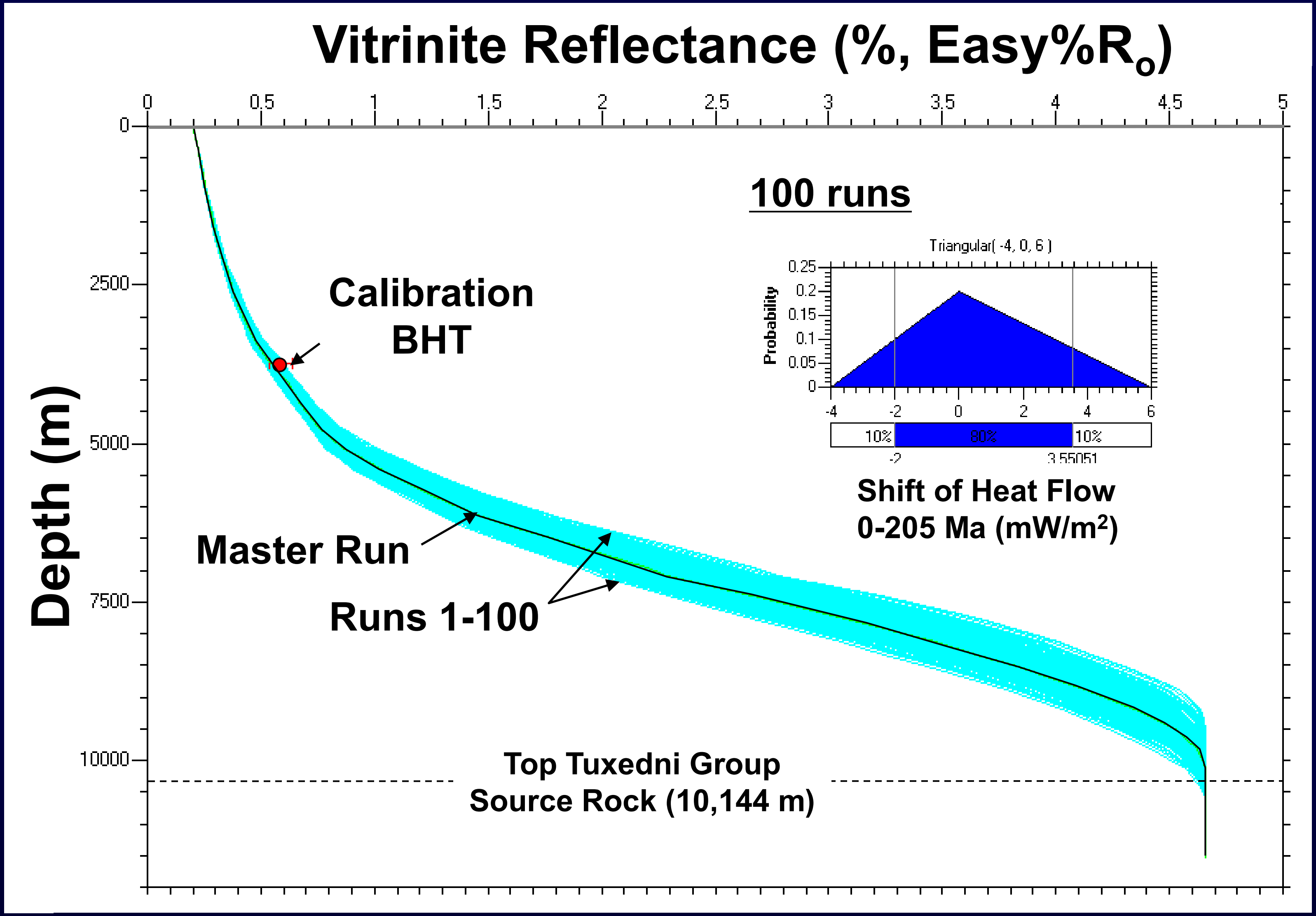
| BHT, °C | Error, °C | Adjusted HF, $mW/m^2$ | Tuxedni Group Source Rock = 0.6% $R_o$† | | Difference From Measured BHT | |
|---|---|---|---|---|---|---|
| | | | Ma | Depth, m | my | m |
| 100.4 | +8 | 73.83 | 88.73 | 2,104 | 6.23 | 305 |
| 92.4 | 0 | 67.65 | 82.50 | 2,409 | 0 | 0 |
| 84.4 | -8 | 63.04 | 77.96 | 2,640 | 4.54 | 231 |

*Hermanrud et al. (1990); J. Corrigan (pers. com., 2007)
†Top oil window at 0.6% vitrinite reflectance

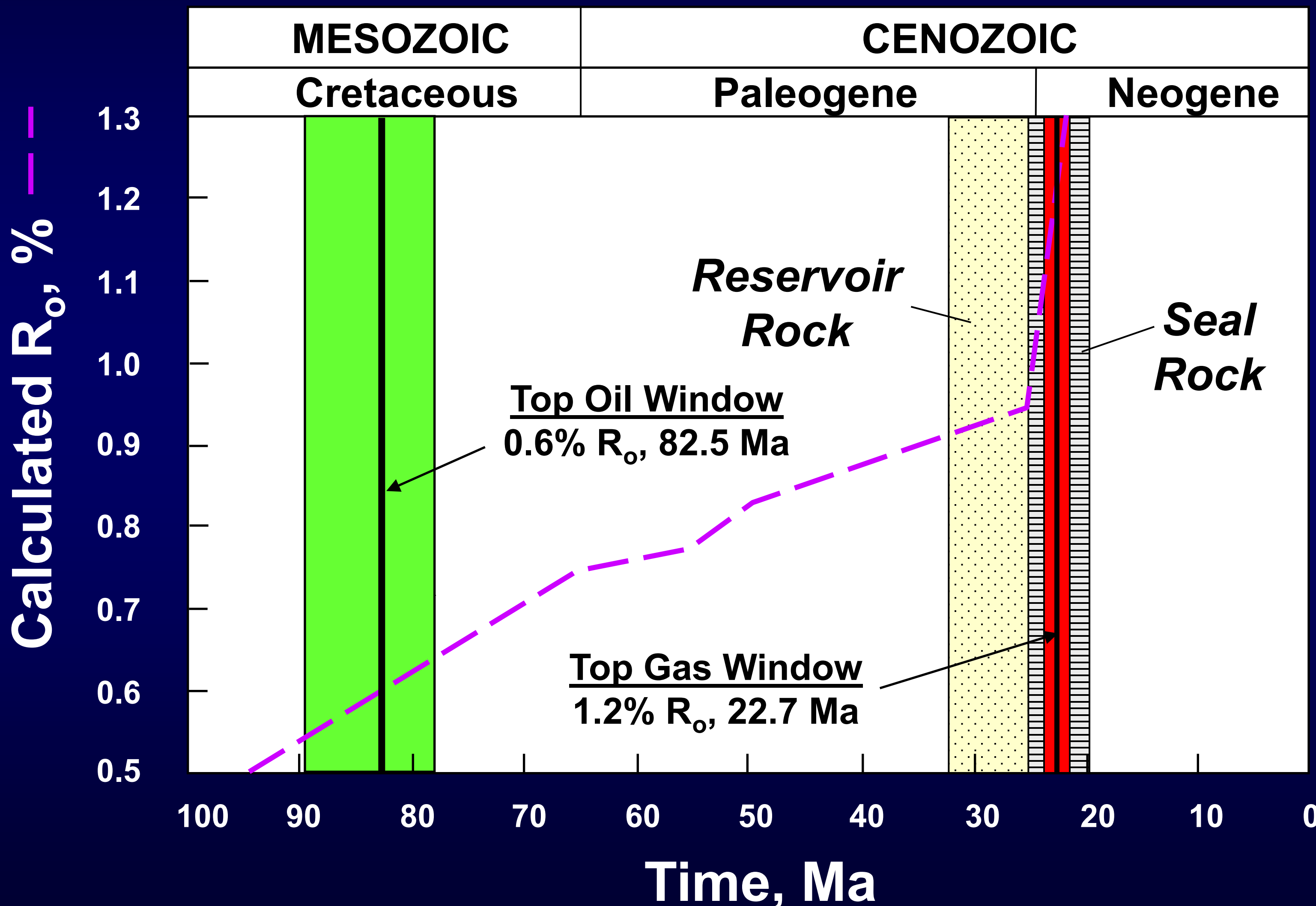
# Simulated Error in Calculated Temperature Increases with Depth



# Simulated Error in Calculated Vitrinite Reflectance Increases with Depth



# BHT Error Affects Calculated Timing of Oil and Gas Generation in U. Cook Inlet



# Conclusions: Borehole Formation Temperatures for Calibration of Models

- **Production or drillstem tests can give reliable formation T (criteria: >100 bbl, avoid gas production)**
- **BHT are common, but can be 20-30°C (36-54°F) below formation T; they must be corrected**
- **Error associated with shallow BHT (  8°C) can propagate to higher values for deep source rock**
- **A pseudowell in the Upper Cook Inlet was calibrated using one BHT  8°C and constant heat flow: 1D model predicts top oil window at 78-89 Ma (11 my) and 2104-2640 m (536 m).**