Using Geophysical Logs to Estimate Relative Uplift in Cook Inlet Basin, Alaska

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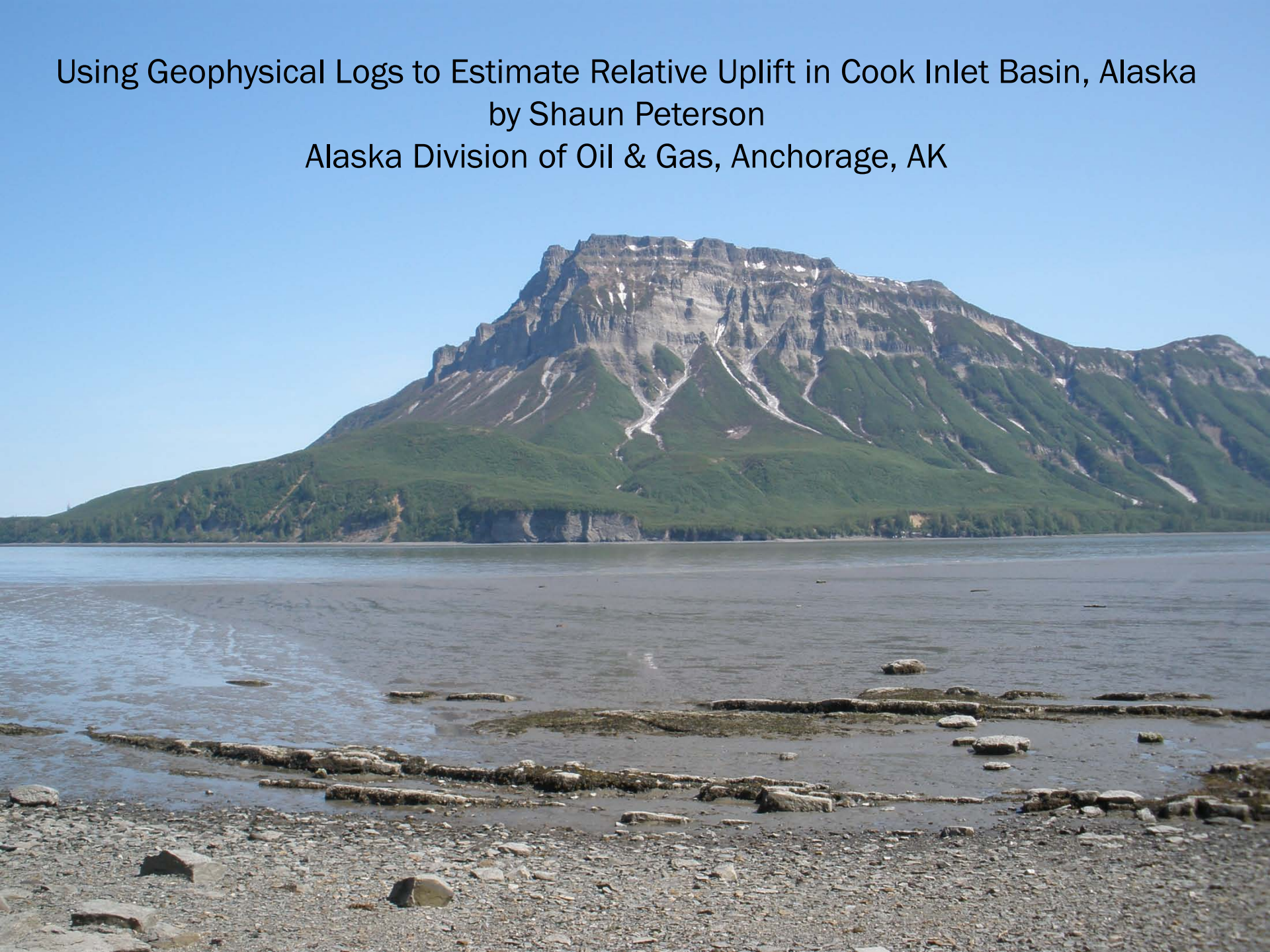

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Purposes of this Study

- To understand regional relative differences in Cook Inlet basin uplift history.
- To attempt, using public data sources, a Cook Inlet basin relative uplift model similar to other proprietary evaluations done in the past.
- To develop a model for better understanding Tertiary-aged surface outcrop distribution.
- To provide a check on vitrinite reflectance- and bottom hole temperature-based geothermal gradient estimates.

Premises

- By use of shale compaction data (sonic logs) thicknesses of sedimentary sequences removed by erosion (i.e. uplift) can be estimated (Magara, 1976 & 1978).
- Compaction in sediments is a one-way street. Rebound does not occur when overburden is removed or pressure is reduced. The sonic log thus records the maximum compaction achieved at typically the greatest depth.

Primary references

Magara, 1976, Thickness of removed sedimentary rocks, paleopore pressure, and paleotemperature, southwestern part of Western Canada Basin, AAPG Bulletin, v. 60, p. 554-565.

Magara, 1978, Compaction and fluid migration, practical petroleum geology, Elsevier, Amsterdam, The Netherlands, 329 p.
(Chapter 2: Shale compaction and estimation of erosion and structural timing)

Johnsson, Howell, and Bird, 1993, Thermal maturity patterns in Alaska: implications for tectonic evolution and hydrocarbon potential, AAPG Bulletin, v. 77, p. 1874-1903.

Dumitru, 1988, Subnormal geothermal gradients in the Great Valley forearc basin, California, during Franciscan subduction: a fission track study, Tectonics, v. 7, p. 1201-1221.

Preface to governing equations

- Porosity decreases with increasing depth.
- Rate of porosity decrease is exponential (faster at shallower depths, slower at greater depths).
- Porosity can be influenced by anomalously high subsurface fluid pressure (i.e. greater porosities than expected can occur).
- Caution: Higher than expected porosity values at depth are therefore likely the result of associated higher than normal fluid pressure.

(Magara, 1978)

Equation 1

Sonic log/porosity/depth relationship (at hydrostatic fluid pressure)

$$\varphi = \varphi_o e^{-cZ} \qquad (1)$$

where φ = shale porosity at depth (Z)

φ_o = shale porosity at surface (Z=0)

e = base of the natural log

c = constant (ft^{-1}) indicating slope of the normal compaction trend

Z = depth

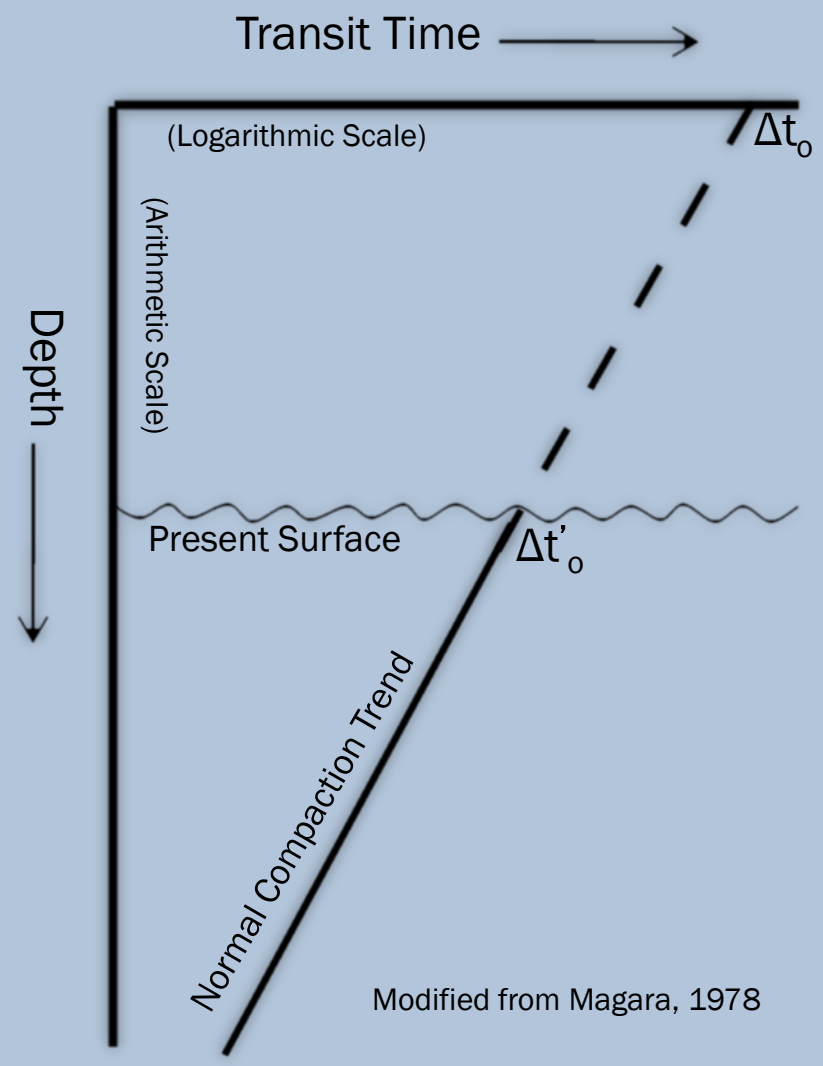
Because shale porosity (φ) at depth is difficult to obtain, sonic log transit time (Δt) may act as a proxy for φ. Therefore substituting Δt for φ in (1) above yields:

$$\Delta t = \Delta t'_o e^{-cZ} \qquad (1a)$$

where Δt = sonic log transit time (μs/ft) at depth (Z)

$\Delta t'_o$ = extrapolated transit time (μs/ft) at surface (Z=0)

(Magara, 1978)



Relationship of Δt_{log}, Δt_o, and $\Delta t'_o$

Δt_{log} = sonic log transit time (μs/ft) from which normal compaction trend is plotted.

Δt_o = extrapolated surface transit time (μs/ft) at original surface when significant erosion has not occurred.

$\Delta t'_o$ = extrapolated surface transit time (μs/ft) at present surface when erosion has occurred.

Equation 2

Transit-time/porosity relationship for shale

$$\Delta t_{log} = (\Delta t_{water} - \Delta t_{matrix})\varphi + \Delta t_{matrix} \qquad (2)$$

where Δt_{log} = sonic log transit time (μs/ft)

Δt_{water} = formation water transit time (μs/ft)

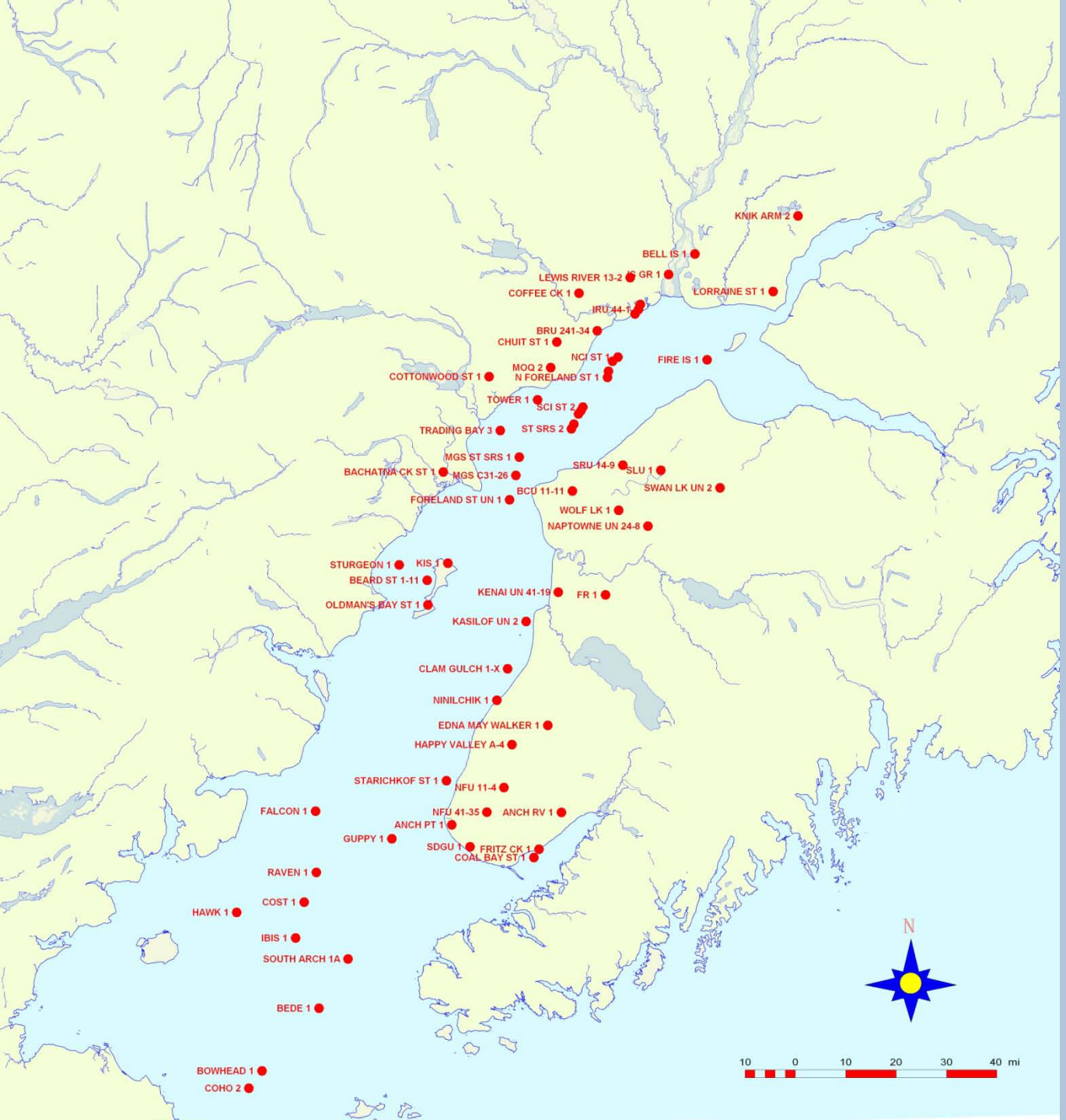
Δt_{matrix} = rock matrix transit time (μs/ft)

φ = shale porosity

Because shale porosity (φ) at depth is difficult to obtain, Δt_{log} may act as a proxy for φ. Therefore substituting Δt_{log} for φ in (2) above yields:

$$\Delta t_{log} = \Delta t_{matrix} - (\Delta t_{matrix}/\Delta t_{water}) + 1 \qquad (2a)$$

(Magara, 1978)



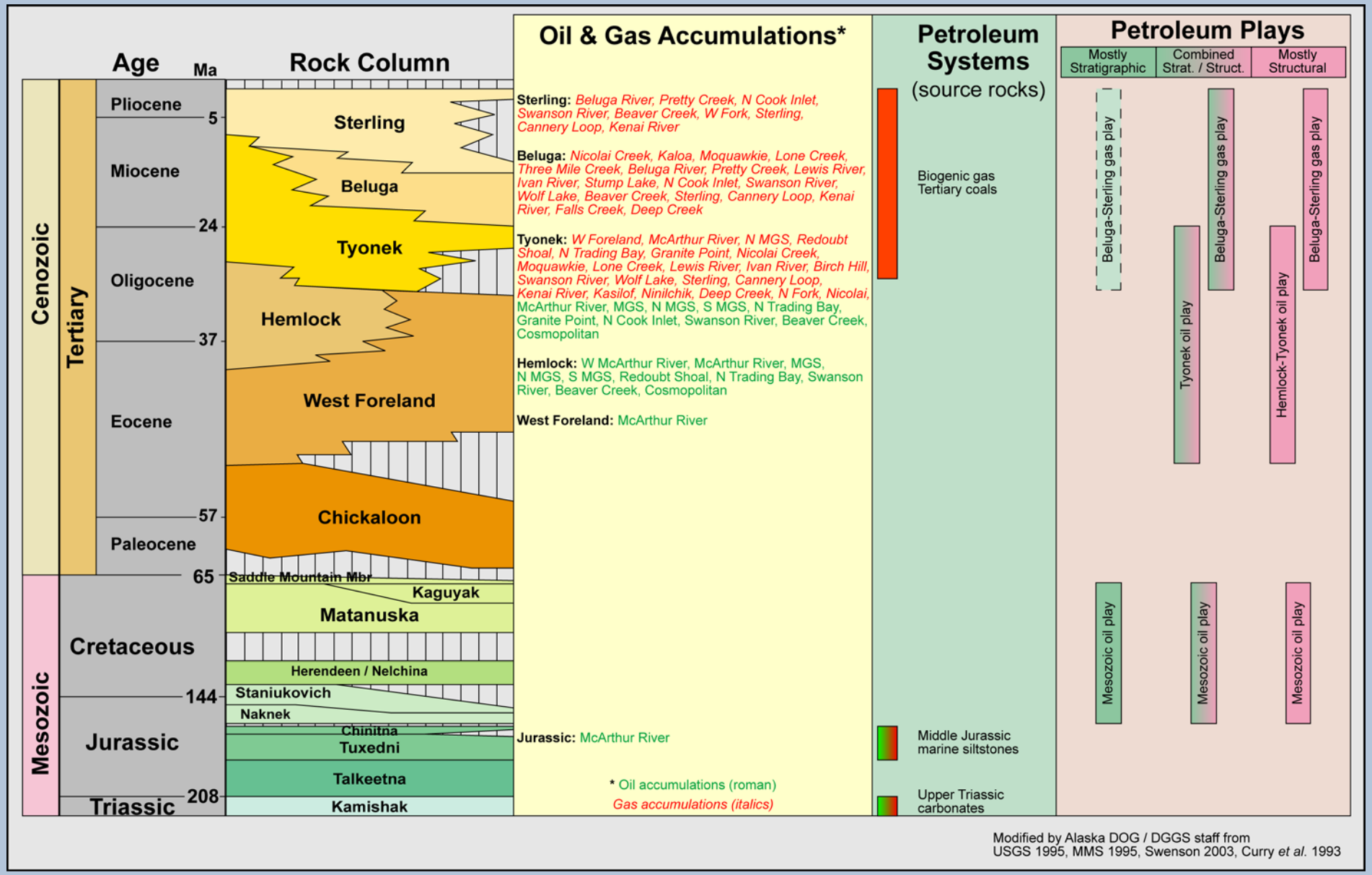
Well Distribution

64 Upper Cook Inlet wells analyzed

47 wells retained for further analysis

17 wells dropped due to data integrity problems

Cook Inlet Stratigraphy and Petroleum Plays

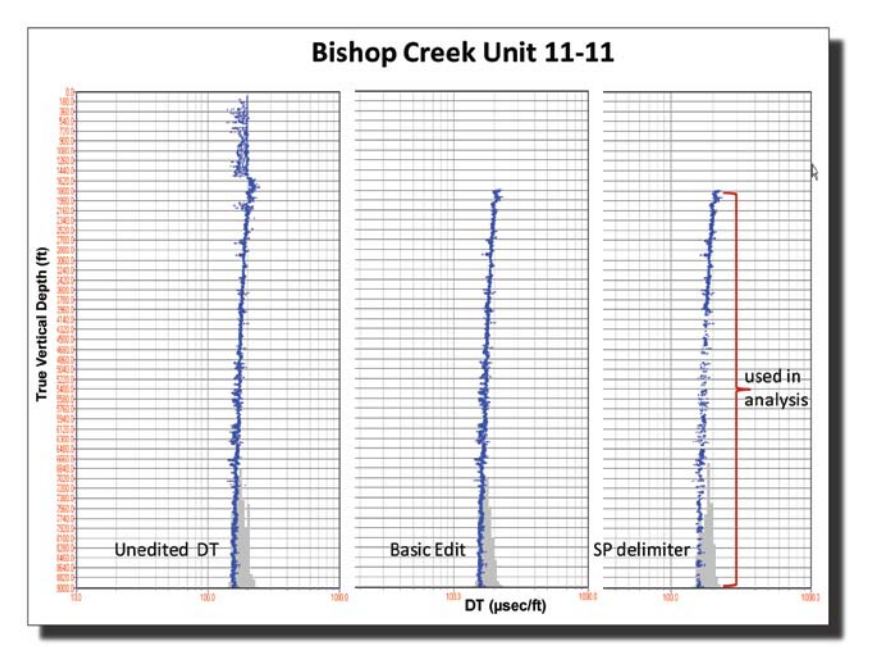


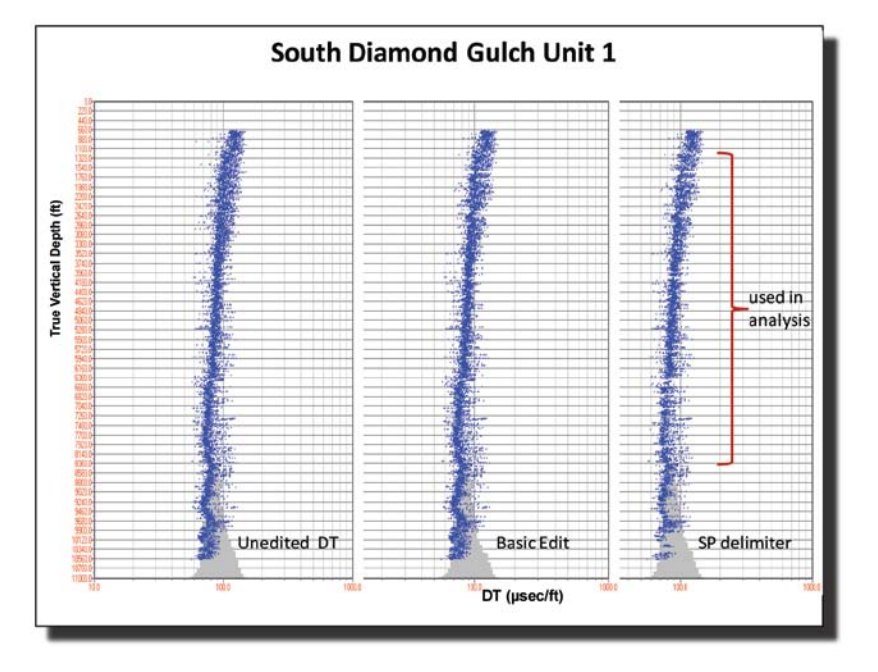
Modified by Alaska DOG / DGGS staff from
USGS 1995, MMS 1995, Swenson 2003, Curry *et al.* 1993

Methods

Sonic log editing workflow

- Edit DT logs: Remove poor data quality zones, cycle skips, and coals.
- Apply Spontaneous Potential (SP) delimiter: Select only those DT/Depth values where SP baseline shifted values are 95-100mv in an attempt to capture data representing only the shaliest lithologies.
- Edit DT trends: Ignore remnant non-shale lithologies (conglomerates, volcanics etc.) not successfully removed using the SP delimiter. Extract data affected by obvious fluid effects (i.e. known gas fields). Ignore over pressured zones.



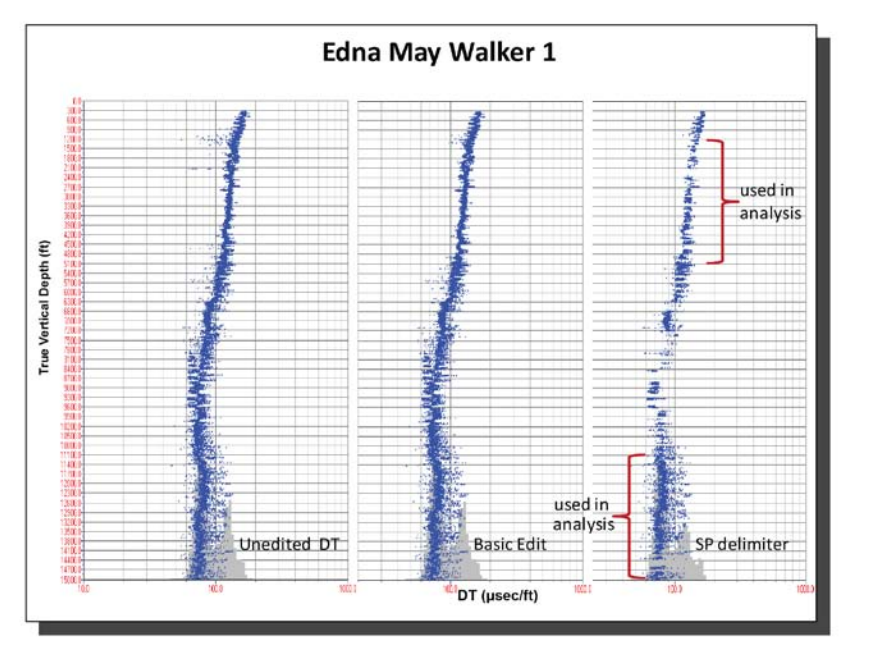


Sonic Log vs Depth Plots

Basic Edit
- Erroneous data removed.
- Obvious cycle skips removed.

SP delimiter
- Data cloud narrowed (and segmented).

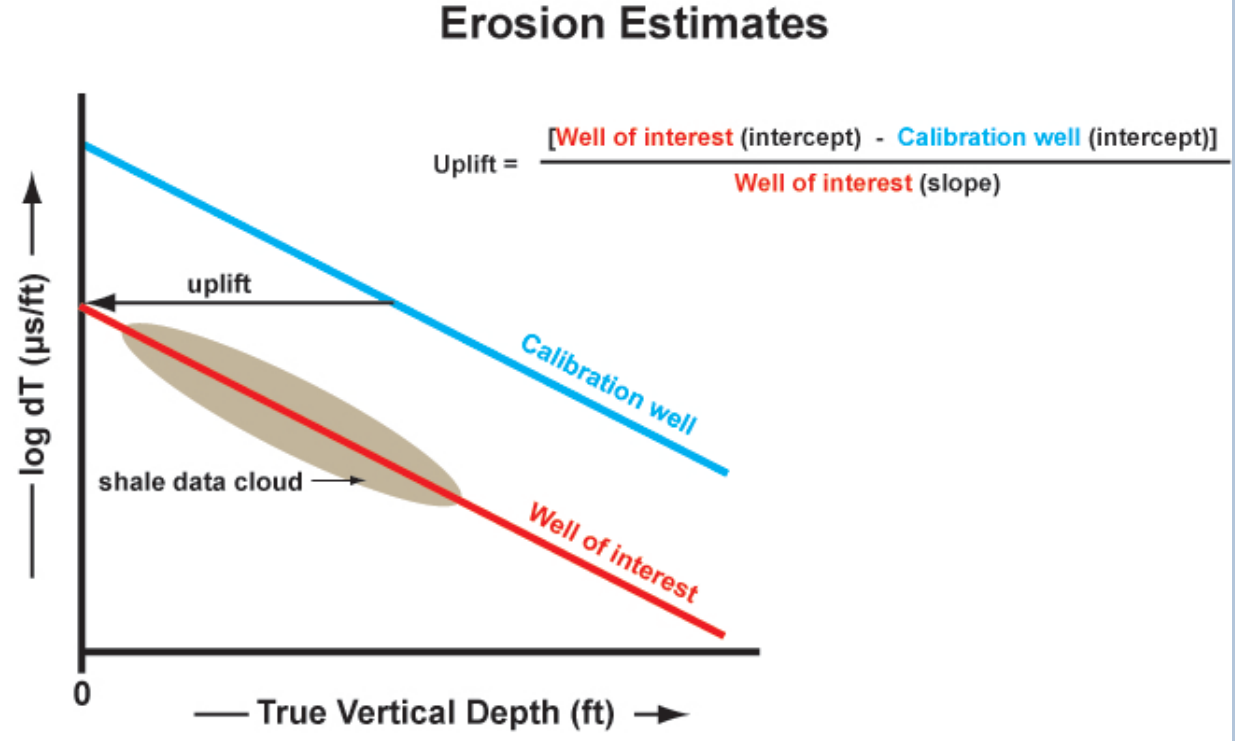
In general
- Non-shale lithologies ignored.
- Over pressured zones ignored.



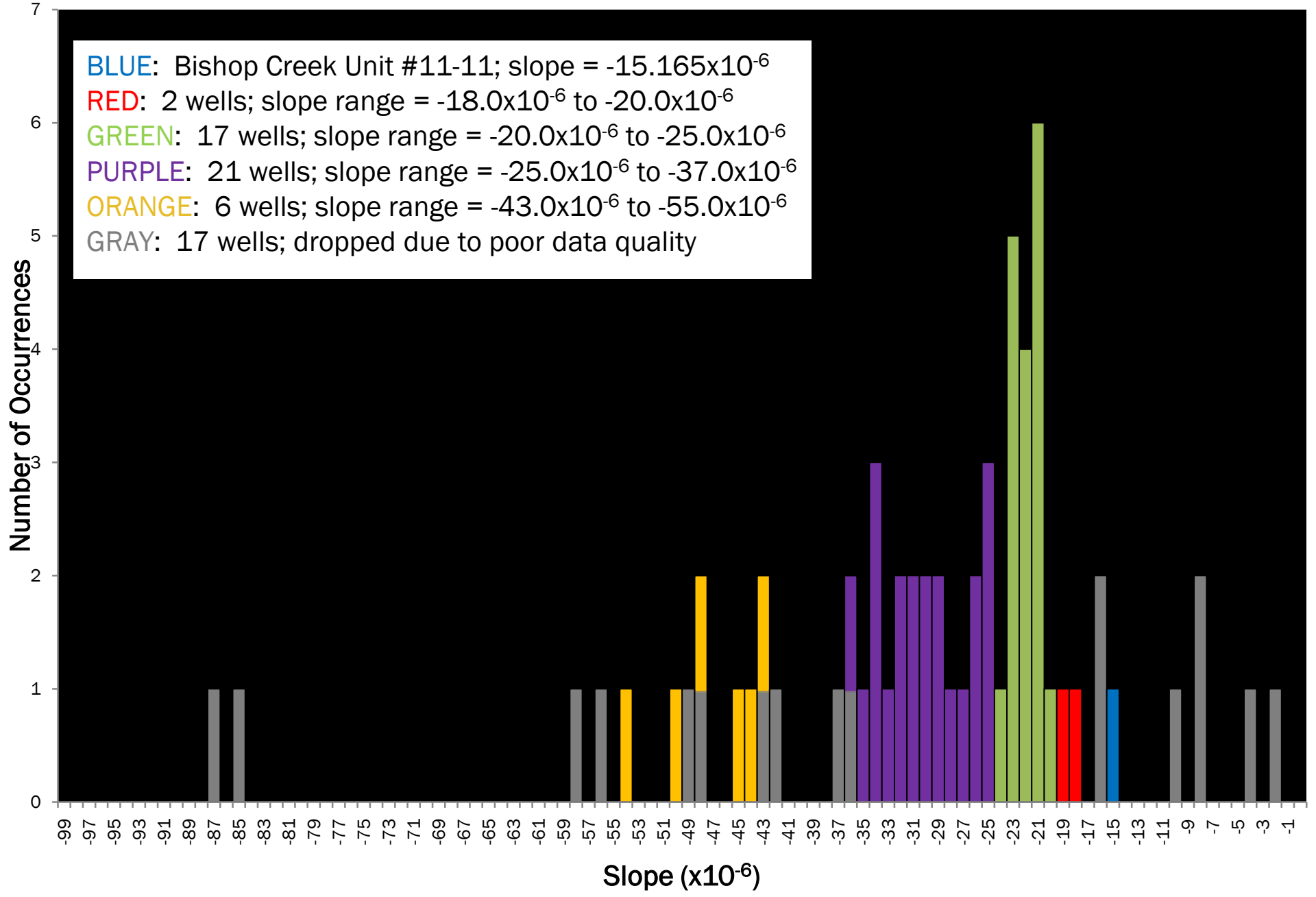
Methods cont.

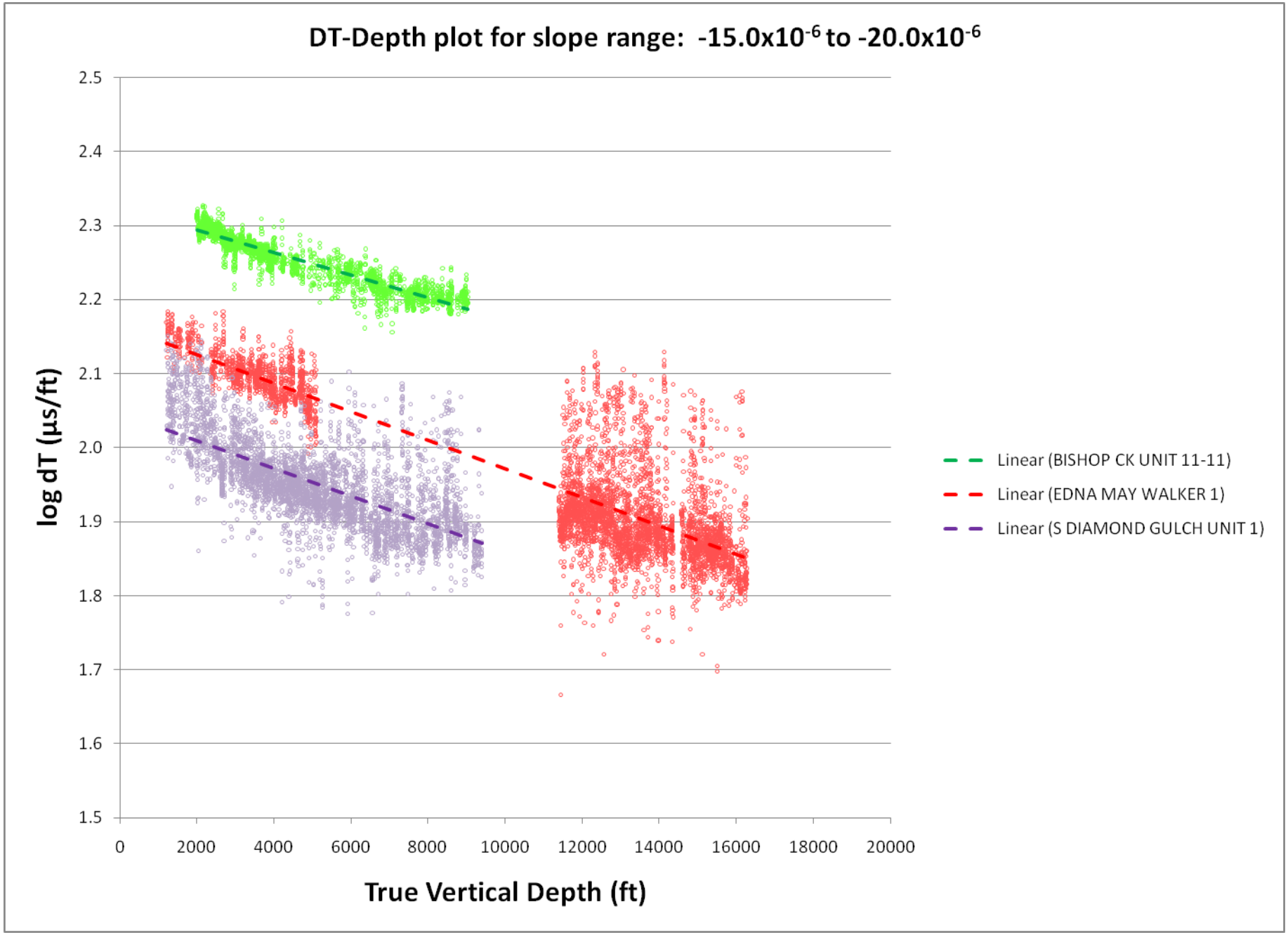
Determine normal compaction trends for 64 Cook Inlet wells

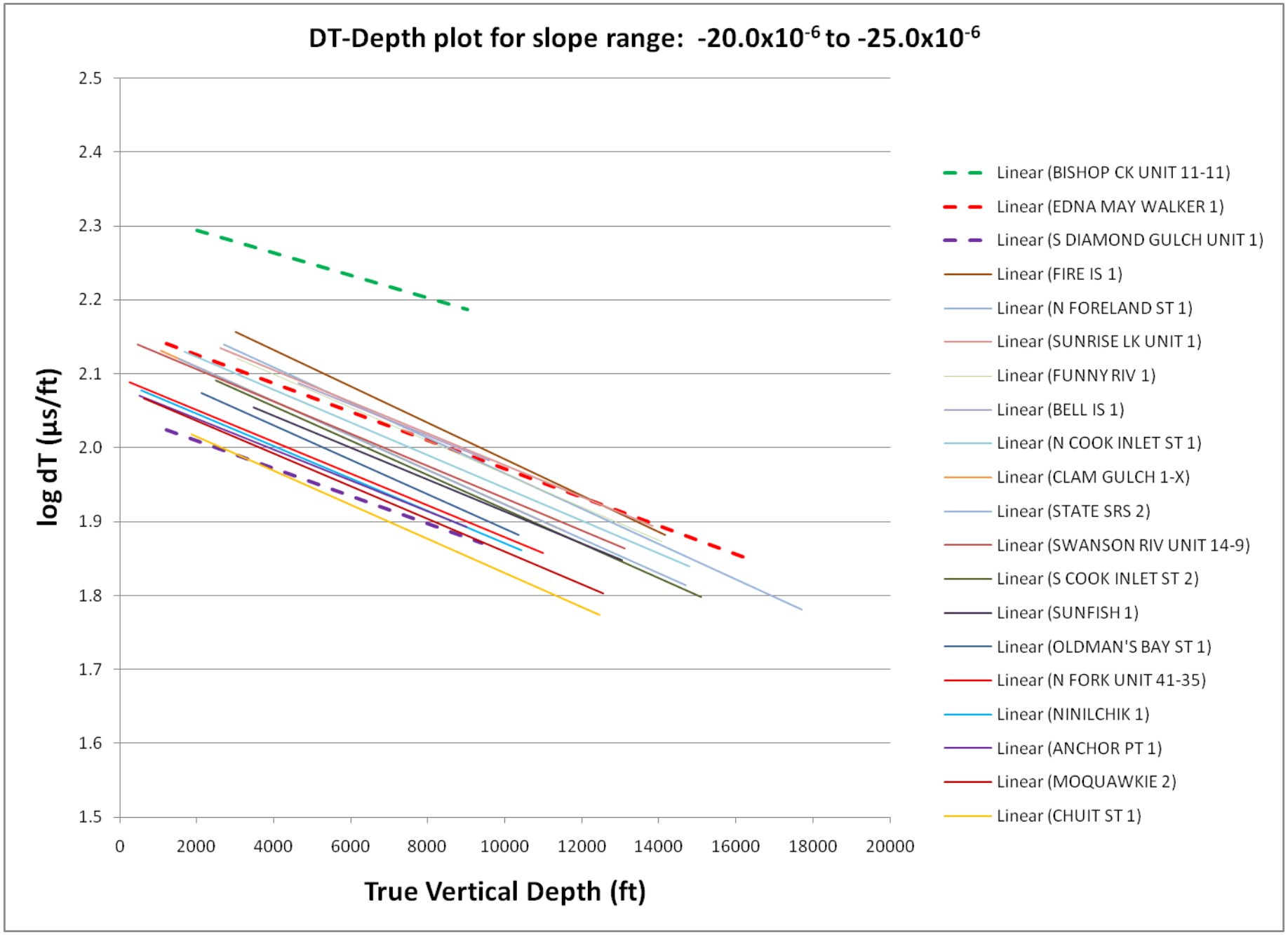
1) Plot Δt_{log} (sonic log) vs. TVD.
2) Extrapolate these trends back to surface (depth=0) to determine $\Delta t'_o$ (with erosion).
3) Of these trends max $\Delta t'_o$ is defined as the value closest to Δt_o (without significant erosion).
4) The well with the max $\Delta t'_o$ will serve as the "calibration well" against which all other wells will be measured for "relative" uplift.

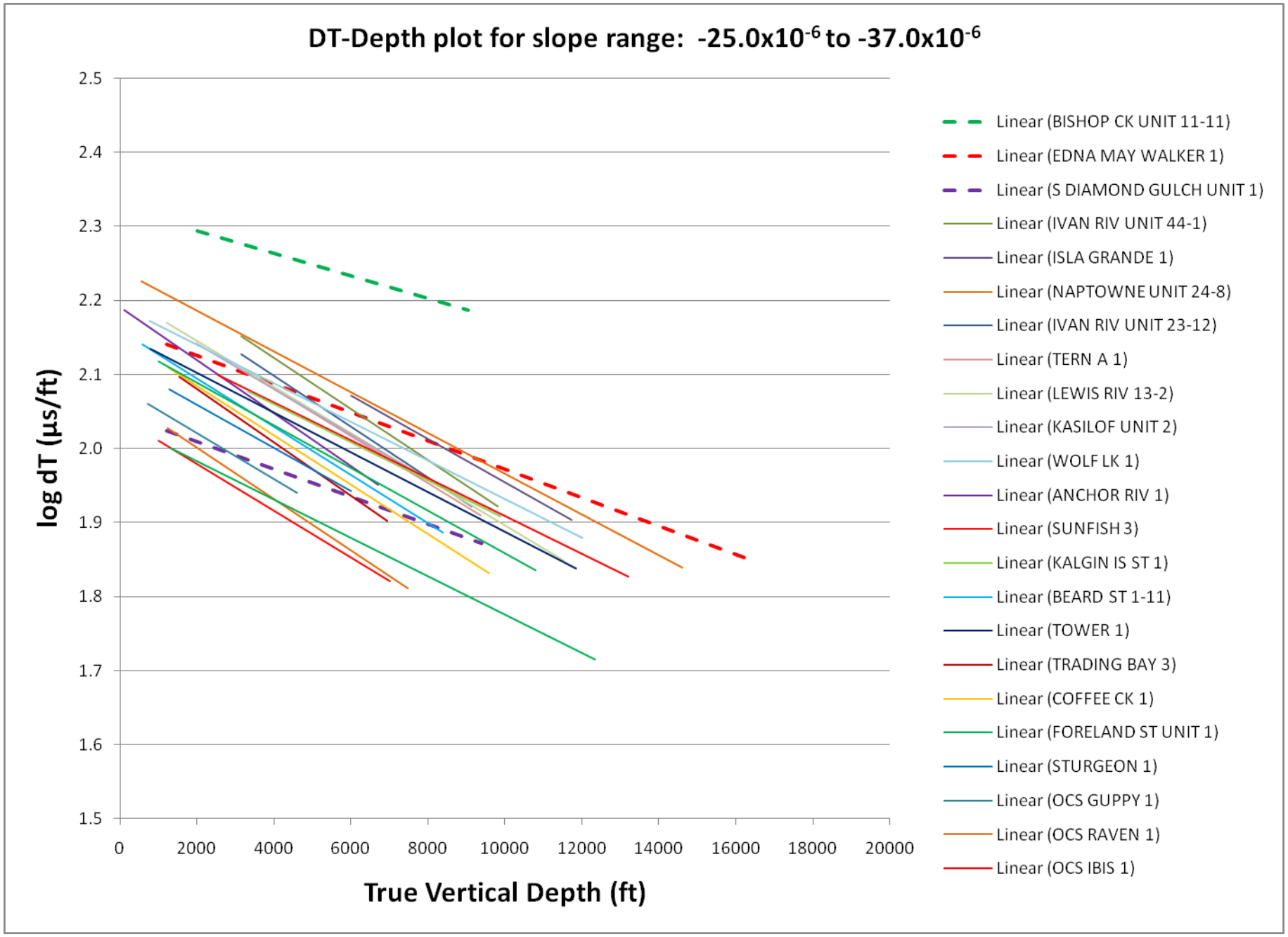


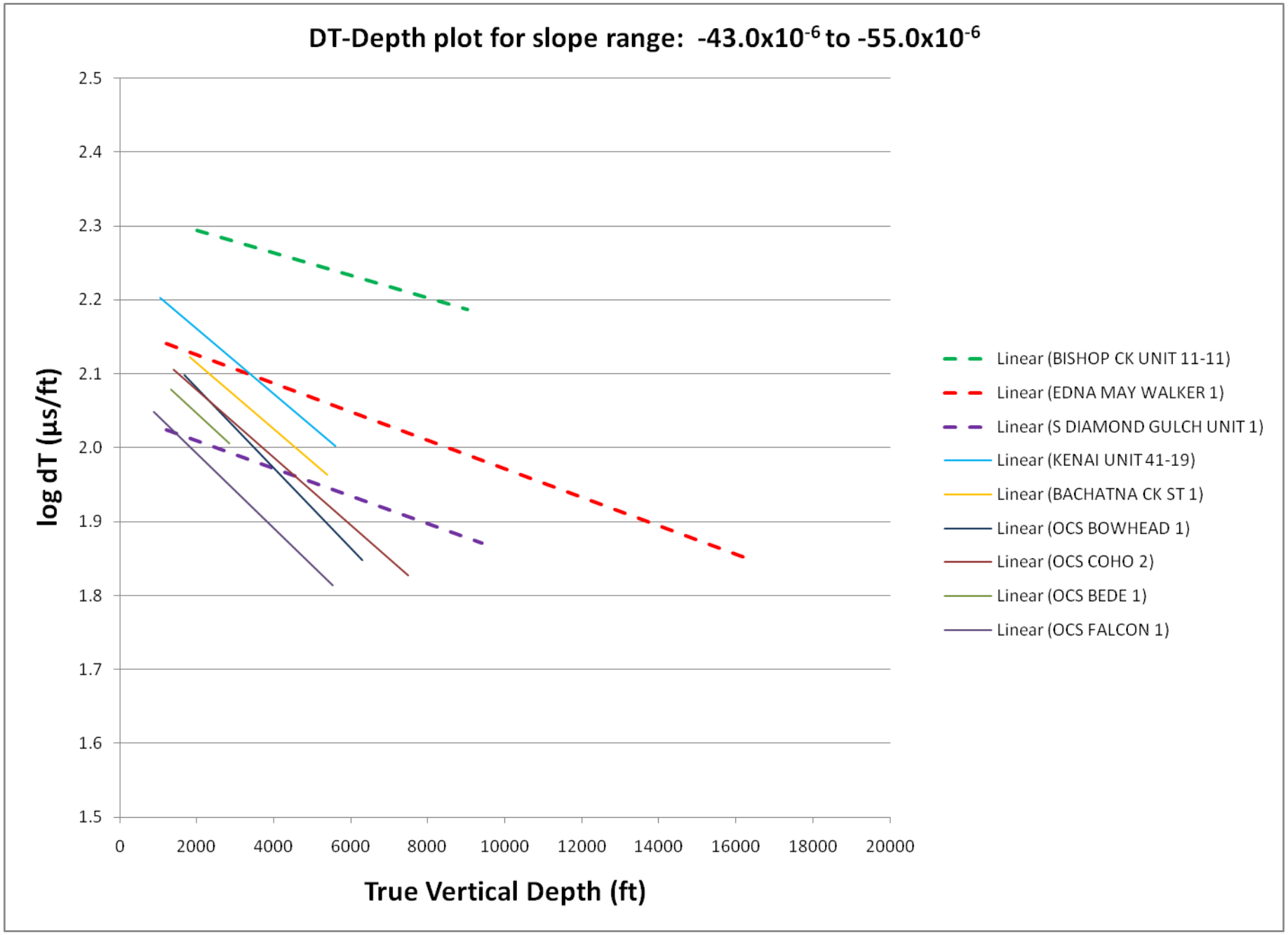
SLOPE COMPARISON FOR 64 UPPER COOK INLET WELLS

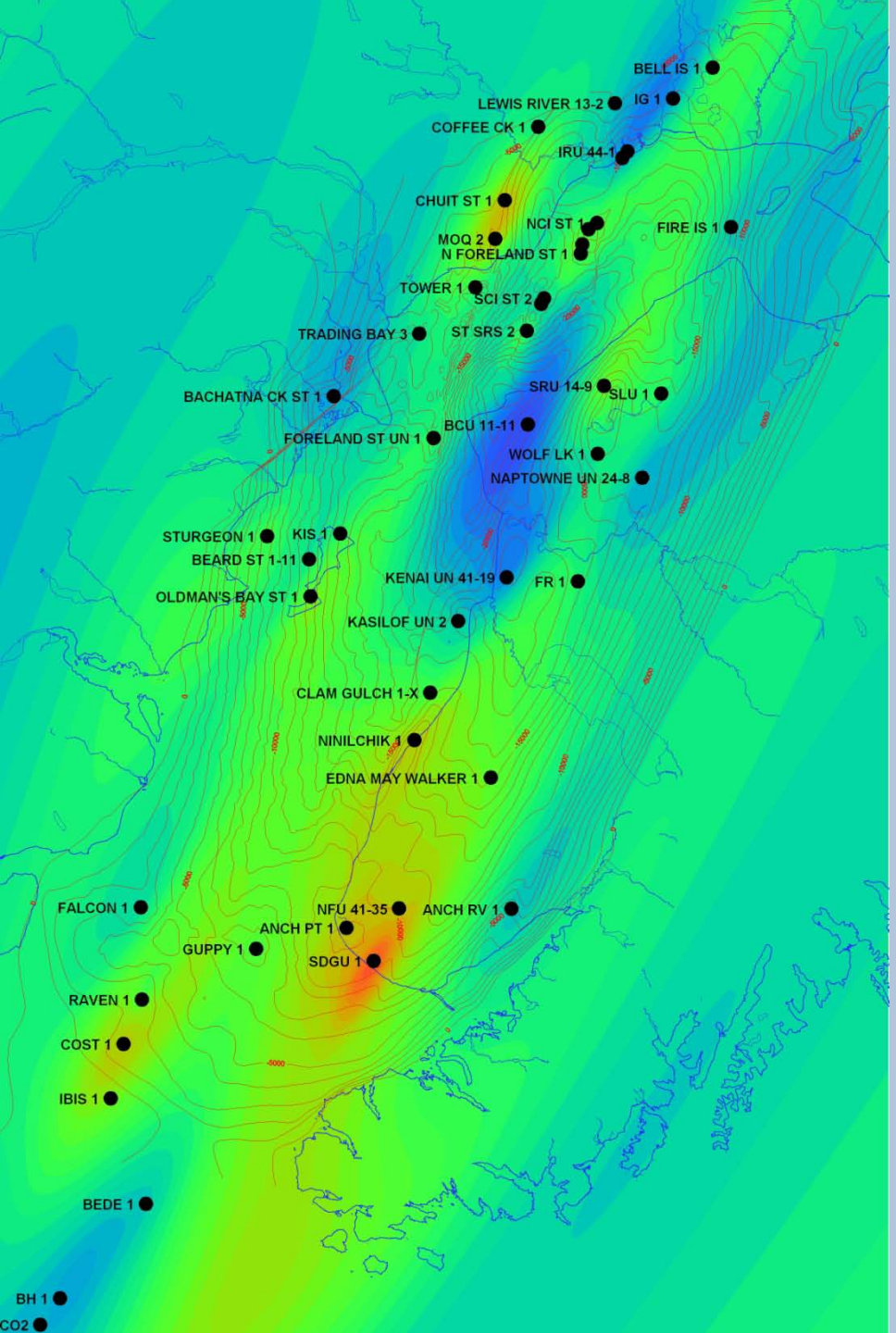



DT-Depth plot for slope range: -15.0x10-6 to -20.0x10-6
log dT (µs/ft)
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
True Vertical Depth (ft)
Linear (BISHOP CK UNIT 11-11)
Linear (EDNA MAY WALKER 1)
Linear (S DIAMOND GULCH UNIT 1)


DT-Depth plot for slope range: -20.0x10-6 to -25.0x10-6
log dT (µs/ft)
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
True Vertical Depth (ft)
Linear (BISHOP CK UNIT 11-11)
Linear (EDNA MAY WALKER 1)
Linear (S DIAMOND GULCH UNIT 1)
Linear (FIRE IS 1)
Linear (N FORELAND ST 1)
Linear (SUNRISE LK UNIT 1)
Linear (FUNNY RIV 1)
Linear (BELL IS 1)
Linear (N COOK INLET ST 1)
Linear (CLAM GULCH 1-X)
Linear (STATE SRS 2)
Linear (SWANSON RIV UNIT 14-9)
Linear (S COOK INLET ST 2)
Linear (SUNFISH 1)
Linear (OLDMAN'S BAY ST 1)
Linear (N FORK UNIT 41-35)
Linear (NINILCHIK 1)
Linear (ANCHOR PT 1)
Linear (MOQUAWKIE 2)
Linear (CHUIT ST 1)


DT-Depth plot for slope range: -25.0x10-6 to -37.0x10-6
log dT (µs/ft)
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
True Vertical Depth (ft)
Linear (BISHOP CK UNIT 11-11)
Linear (EDNA MAY WALKER 1)
Linear (S DIAMOND GULCH UNIT 1)
Linear (IVAN RIV UNIT 44-1)
Linear (ISLA GRANDE 1)
Linear (NAPTOWNE UNIT 24-8)
Linear (IVAN RIV UNIT 23-12)
Linear (TERN A 1)
Linear (LEWIS RIV 13-2)
Linear (KASILOF UNIT 2)
Linear (WOLF LK 1)
Linear (ANCHOR RIV 1)
Linear (SUNFISH 3)
Linear (KALGIN IS ST 1)
Linear (BEARD ST 1-11)
Linear (TOWER 1)
Linear (TRADING BAY 3)
Linear (COFFEE CK 1)
Linear (FORELAND ST UNIT 1)
Linear (STURGEON 1)
Linear (OCS GUPPY 1)
Linear (OCS RAVEN 1)
Linear (OCS IBIS 1)


DT-Depth plot for slope range: -43.0x10-6 to -55.0x10-6
log dT (µs/ft)
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
True Vertical Depth (ft)
Linear (BISHOP CK UNIT 11-11)
Linear (EDNA MAY WALKER 1)
Linear (S DIAMOND GULCH UNIT 1)
Linear (KENAI UNIT 41-19)
Linear (BACHATNA CK ST 1)
Linear (OCS BOWHEAD 1)
Linear (OCS COHO 2)
Linear (OCS BEDE 1)
Linear (OCS FALCON 1)



Uplift contour map based on 47 wells

Pseudo-calibration well:
Well: Bishop Creek Unit 11-11
Relative uplift: 0 ft
Slope: -15.165×10^{-6}

Largest relative uplift:
Well: South Diamond Gulch Unit 1
Relative uplift: 14,896 ft (± 100 ft)
Slope: -18.617×10^{-6}
Δslope: 3.452×10^{-6}

Smallest relative uplift:
Well: Kenai Unit 41-19
Relative uplift: 1,708 ft (± 100 ft)
Slope: -43.915×10^{-6}
ΔSlope: 2.875×10^{-5}

Note: Similarities between relative uplift contours (colors) and Mesozoic subcrop contours (lines) suggests a possible link between relative uplift and base Tertiary depth.

Results

Bottom line

1) Bishop Creek Unit 11-11 (BCU 11-11) has experienced the least amount of uplift in the 64 well dataset. As such it serves as the "calibration well" against which the other wells were measured for relative uplift.

2) South Diamond Gulch Unit 1 (SDGU 1) well experienced the most (14,896 ft) relative uplift.

3) Kenai Unit 41-19 (KU 41-19) well experienced the least (1,708 ft) relative uplift, although the difference in slope when compared to BCU 11-11 could be large enough to be outside acceptable limits.

4) The average uplift of the 46 wells analyzed relative to BCU 11-11 is 6,343 ft.

DATA CORRELATION

Cook Inlet Data to attempt correlation with:

Vitrinite Reflectance (VR) – Johnsson et al., 1993 provided subsurface VR data for 30 Cook Inlet wells.

Bottom-hole temperature (BHT) – Compiled BHT dataset for the 64 wells in this study in order to compare with VR-derived geothermal gradients and geothermal gradients derived from merging DT/Depth data with VR data.

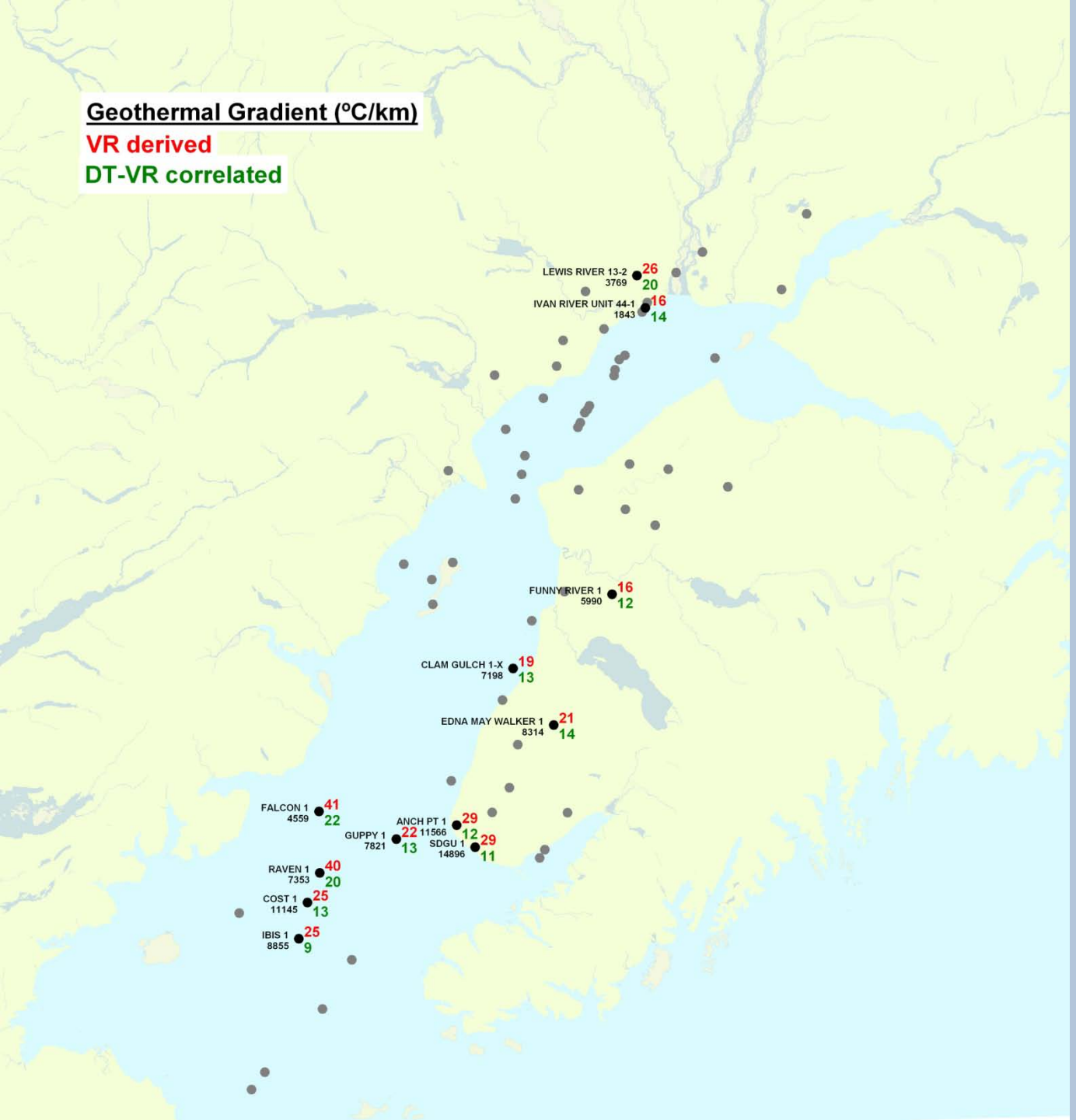
Geothermal Gradient calculation

$$GG = \frac{FT - ST}{TVD - (KB - GL)}$$

where GG = geothermal gradient (°C/km)
FT = formation temperature (°C)
ST = surface temperature (°C)
TVD = true vertical depth of BHT measurement (km)
KB = kelly bushing elevation (km)
GL = ground level elevation (km)

Relating temperature and vitrinite reflectance using Barker (1988) equation:

$$T\ (°C) = 104(\ln R_o) + 148$$



Geothermal Gradients determined with VR data

VR indicates highest temperature attained (i.e. deepest burial), not uplift.

Cook Inlet VR values are low (<1.0% R_o). Why is that??

DT-VR correlation combines VR sampling depth with DT/Depth uplift estimate for the TVD value used in the geothermal gradient calculation.

Example

SDGU 1 geothermal gradients:
VR derived = 29ºC/km
(TVD = 9,230').
DT-VR correlated = 11ºC/km
(TVD = 9,230' + 14,896')

Could VR samples have acquired their temperature signatures at much greater depths during periods of subnormal geothermal gradient in the Cook Inlet forearc basin??

Dumitru, 1988 synopsis:

Forearc basins commonly have subnormal geothermal gradients due to relatively cold lithosphere subduction occurring beneath them.

In the Great Valley forearc basin of CA during early Tertiary time geothermal gradients of about 9°C/km were calculated based on fission track studies. The data permit gradients no greater than 15°C/km at 90 Ma and no greater than 9°C/km at 65 Ma.

In the presence of active subduction in an area where the overriding plate is about 30 km thick, modeling indicates gradients would take 10-30 Ma to approach equilibrium low levels.

In the absence of active subduction, geothermal gradients will increase toward normal values. A period of non-subduction of greater than about 5-20 m.y. should cause detectable thermal effects in the forearc basin area. In the accretionary wedge much shorter periods of non-subduction are necessary to begin to increase the geothermal gradient.

It is plausible that Cook Inlet basin VR samples acquired their temperature signatures at much greater depths during a period of subnormal geothermal gradient in a forearc basin. If this were the case, then the uplift estimates presented in this report could correlate with VR data.

Geothermal Gradients determined with BHT data

BHT data provide an estimate of undisturbed formation temperature.

Difficulties arise due to:
-temperature re-equilibration issues: months to years needed.

-well BHT data being reported as "Max BHT" with no indication of associated depth.

On average:
BHT-derived gradients are 5ºC/km lower than VR-derived gradients for the 12 VR gradients shown previously.

Exceptions:
Funny Rv 1 and EMW 1 have BHT gradients higher than VR gradients.

Conclusions

1) Differential uplift throughout upper Cook Inlet basin has occurred.

2) Bishop Creek Unit 11-11 appears to be the area of least uplift (corroborated by base Tertiary map which suggests a similar conclusion).

3) South Diamond Gulch Unit 1 appears to have experienced the greatest amount of relative uplift (~15,000 ft).

4) Kenai Unit 41-19 appears to have experienced the least amount of relative uplift and is spatially the closest well to BCU 11-11. However reliability of data is suspect due to extreme differences in slope.

5) Roughly 15,000' of uplift has occurred in SDGU 1 relative to BCU 11-11. Approximately 8,900 ft (unconsolidated, SRLG, & some BLUG) is missing from SDGU 1
SDGU 1: BLUG top 455' tvd, TYNK top 2863' tvd.
BCU 11-11: SRLG top 4,476' tvd, BLUG top 8,918' tvd.

6) Uplift values determined in this study are plausible if subnormal geothermal gradients existed in the geologic past in the Cook Inlet forearc basin.

Next steps

Fission-track (FT) analysis

Identify 1-2 wells from this study for fission track analysis.

Problematic due to the amount of core needed over an adequate interval.

If successful this will provide additional indication of uplift/thermal history.

Construct burial histories for Cook Inlet wells

Utilize uplift estimates calculated here.

The End