[PS]Working toward a Stable Stratigraphic Reference Framework for Oligo-Miocene Fluvial Sequences in Cook Inlet, Alaska: Hemostratigraphic Characterization and Correlation of the Hemlock, Starichkof and Tyonek Formations*

Ken Ratcliffe[1], Amelia Wright[1], Meg Kremer[3], Michael C. Dix[4], Simon N. Hughes[4], Tim Reed[2] and Tavia Jackson[2]

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[1]Chemostrat Inc, Houston, TX. (kenratcliffe@chemostrat.co.uk)
[2]Pioneer Natural Resources, Anchorage, AK.
[3]Alaska Department of Natural Resources, Division of Oil and Gas, Anchorage, AK.
[4]Halliburton - Sperry Drilling Services, Houston, TX.

Abstract

Cook Inlet is a prolific gas-prone hydrocarbon basin that has been the subject of exploration efforts since the 1950s. Despite decades of study, the complexity of the Oligocene-Miocene, fluvial-dominated depositional systems have prevented the establishment of a stable reference stratigraphic framework. Traditionally, for petroleum basins, such frameworks rely on lithostratigraphic principals or derivatives thereof, such as wireline log correlation. In Cook Inlet, however, the thick, homogeneous and fluvial-dominated nature the basin-fill has resulted in several, often apparently conflicting, lithostratigraphic schemes. This lack of a stable reference stratigraphic framework hampers effective hydrocarbon exploration and exploitation.

Here, variations in whole-rock elemental (inorganic) composition of cuttings samples are used to construct a chemostratigraphic-based characterization for the Hemlock, Starichkof, and Tyonek formations in four wells located in the Cosmopolitan Unit. Based on changes in values of K/Al, Cs/Al, Nb/Al, Nb/Na, Fe/Ti, Ti/Nb, and U, seven chemostratigraphic packages are defined and correlated between the four wells, thereby providing a robust stratigraphic reference framework within the Cosmopolitan Unit. These elements and element ratios are controlled by changes through time in the composition of sand-size detritus (quartz, feldspar, rock fragments and some mica), heavy mineral species and clay mineral assemblages. Initial work elsewhere in Cook Inlet suggests that it may be possible to extend this framework over much of the 200 X 70 mile inlet area, thereby providing a means to correlate on a basin-wide scale.

Although a geochemical analysis of sediment provenance indicates a mixing from several terranes throughout Hemlock-Starichkof-Tyonek deposition, variations in values of K/Al, Rb/Al, Zr/Sc, Th/Sc, Th/Co, and REE/Al, imply an overall change in the dominant sediment provenance through time. Understanding provenance changes in space and time has important implications for sand dispersal patterns, diagenetic pathways, and therefore reservoir quality.

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Working Toward a Stable Stratigraphic Reference Framework for Oligo-Miocene Fluvial Sequences in Cook Inlet, Alaska: Chemostratigraphic Characterization and Correlation of the Hemlock, Starichkof and Tyonek Formations in the Cosmopolitan Unit

KEN RATCLIFFE, MILLY WRIGHT, Chemostrat Inc., 5850 San Felipe, Suite 500, Houston, Texas,
TIM REED, Pioneer Natural Resources, Anchorage, Alaska,
MEG C. KREMER, DNR-Division of Oil and Gas, 550 W. 7th Suite 800, Anchorage, Alaska,
MICHAEL C. DIX, SIMON HUGHES, Halliburton – Sperry Drilling Services, Houston, Texas.

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POSTER 1

ABSTRACT

Cook Inlet is a prolific gas-prone hydrocarbon basin that has been the subject of exploration efforts since the 1950s. Despite decades of study, the complexity of the Oligocene-Miocene, fluvial-dominated depositional systems have hampered the establishment of a stable reference stratigraphic framework. Traditionally, for petroleum basins, such frameworks rely on lithostratigraphic principals or derivatives thereof, such as wireline log correlation. In Cook Inlet, however, the thick, homogeneous and fluvial-dominated nature the basin-fill has resulted in several, often apparently conflicting, lithostratigraphic schemes and localised unit nomeclature. This lack of a stable reference stratigraphic framework hampers effective hydrocarbon exploration and exploitation.

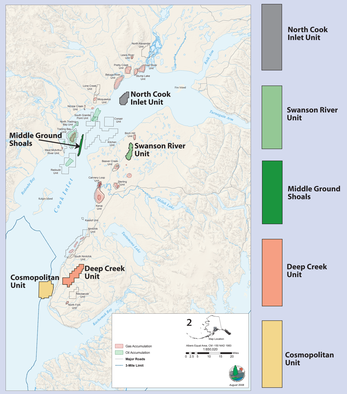
The Hemlock Formation, Tyonek Formation, Beluga Formation and Cook Inlet Member each have a unique whole-rock elemental (inorganic) composition. The composition of the Hemlock and Tyonek formations appears to be consistent over Cook Inlet. Further well penetrations are required to test the lateral persistence of the geochemical composition of the Beluga Formation and Cook Inlet Member. Each of the lithostratigraphic units can be considered a first order chemostratigraphic division termed a chemostratigraphic package, where Package 1 = Hemlock Formation, Package 2 = Tyonek Formation, Package 3 = Beluga Formation and Package 4 = Cook Inlet Member). The Starichkof Formation in the Cosmopolitan Unit is geochemically somewhat similar to the Tyonek Formation and is therefore placed within chemostratigraphic Package 2. However, more subtle changes in geochemistry allows the Starichkof Formation to be differentiated from the Tyonek Formation in this unit, therefore it can be considerd a second order chemostratigraphic division within Package 2, i.e. a geochemical unit. The Middle Ground Shoals Member is geochemically similar to the Hemlock Formation and is therefore placed within Package 1.

Within the four closely spaced well of the Cosmopolitan Unit, an 8-fold chemostratigraphic correlation is defined, providing a detailed reservoir zonation for the Hemlock and Tyonek formations, which can be used to help understand the relationship between well-bore pathway and stratigraphy in horizontal wells.

Although mixing from several terranes throughout Hemlock-Starichkof-Tyonek deposition is evident, geochemical variations imply an overall change in the dominant sediment provenance through time. Understanding provenance changes in space and time has important implications for sand dispersal patterns, diagenetic pathways, and therefore reservoir quality.

INTRODUCTION

Location Map



Study Material

North Cook Inlet Unit

Well	Study Interval	Cuttings samples	Core samples	Claystones	Sandstones
North Cook Inlet A-02	4400-5100'	0	19	4	15

Swanson River Unit

Well	Study Interval	Cuttings samples	Core samples	Claystones	Sandstones
Swanson River Unit 34-10	4700-11700'	0	75	19	56

Middle Ground Shoals

Well	Study Interval	Cuttings samples	Core samples	Claystones	Sandstones
Middle Ground Shoal A33-11	8600-9400'	0	4	0	4
Middle Ground Shoal A13-01	4100-8600'	0	23	10	13
Middle Ground Shoal C31-26	8400-9100	0	4	0	4

Deep Creek Unit

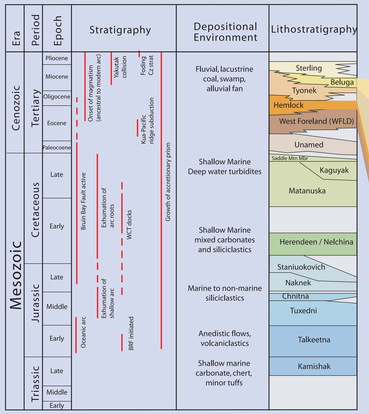
Well	Study Interval	Cuttings samples	Core samples	Claystones	Sandstones
Deep Creek Unit 1RD	1000-13700'	0	23	17	5

Cosmopolitan Unit

Well	Study Interval	Cuttings samples	Core samples	Claystones	Sandstones
Hansen-1	16000-19000'*	151	0	0	151
Hansen-1a	16900-20800' *	132	0	0	132
Starichkof ST-1	6300-7500'	68	0	0	68
Starichkof State Unoion-1	6900-7400'	14	0	0	14

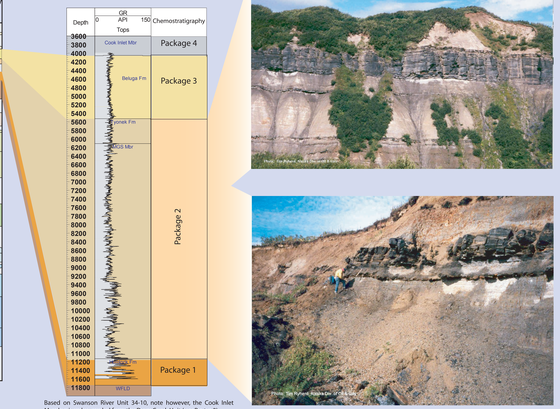
* Hansen-1 TVD study interval = 6250-7300', Hansen-1a TVD study interval = 6500-6900'

Stratigraphy of Study Intervals



Redrawn from Curry et al (1993) and Swanson (2003): additional information from Plafker et al (1989) and Nokleberg et al (2004).

Typical Log Response



Based on Swanson River Unit 34-10, note however, the Cook Inlet Member is only sampled from the Deep Creek Unit (see Poster 2).

THE TECHNIQUE

Chemostratigraphy is a methodology that involves the use of major and trace element geochemistry for the characterisation and correlation of strata. As such, it provides a method of correlation that is independent of other, more traditional, stratigraphic tools. Data for 10 major elements, 23 trace elements and 14 rare earth elements are acquired using ICP-OES and MS (inductively-coupled plasma - optical emission spectrometry and mass spectrometry) following a Li-metaborate fusion preprartion. The sample preparation and analytical procedures used in this study are the same as those detailed in Pearce et al. (1999) and Jarvis and Jarvis (1995).

STUDY RATIONALE

Initially, wells from the Cosmopolitan Unit (Hansen-1, Hansen-1a, Starichkof ST-1 and Starichkof State Union -1) were analysed in order to provide a robust stratigraphic framework within that unit. This work was carried out on cuttings samples from the four wells and allowed 8 chemostratigraphic packages and units to be defined within the Oligo-Miocene successions. The stratigraphic framework allowed the well-bore pathways of Hansen-1 and 1a to be related to stratigraphy and provided the basis for a successfull well-site deployment (REFS).

A major change in geochemistry takes place between the Hemlock and Starichkof (Tyonek) formations in the Cosmopolitan Unit. In order to test the lateral peristence of this change, core samples were analysed from wells in the Deep Creek Unit, Swanson River Unit, Middle Ground Shoals Field and the North Cook Inlet Unit. This initial work suggests that the change in geochemistry between the Hemlock and the Tyonek formations is consistent throughout the Inlet, thereby providing the starting point for a stable stratigraphic reference framework. Petrographic work is underway at State of Alaska Department of Natural Resources , Division of Oil and Gas on the core samples analyed here that will provide a better understanding of the mineralogical controls on the geochemistry.

ACKNOWLEDGEMENTS

The authors are greatful to Pioneer Natural Resources and ConocoPhillips for allowing us publish the results from the Cosmopolitan Unit. We are also greatful to the State of Alaska Department of Natural Resources , Division of Oil and Gas for providing samples from the other study areas. We are grateful to Chemostrat for providing support that has enabled the poster to be published. We would also like to thank Lorna Dyer at the University of Greenwhich for preparing and analysing the samples.

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POSTER 2

KEN RATCLIFFE, MILLY WRIGHT, Chemostrat Inc., 5850 San Felipe, Suite 500, Houston, Texas,
TIM REED, Pioneer Natural Resources, Anchorage, Alaska,
MEG C. KREMER, DNR-Division of Oil and Gas, 550 W. 7th Suite 800, Anchorage, Alaska,
MICHAEL C. DIX, SIMON HUGHES, Halliburton – Sperry Drilling Services, Houston, Texas.

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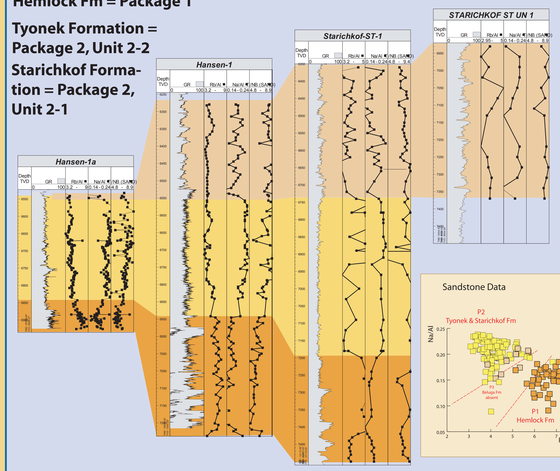
Cosmopolitan Unit

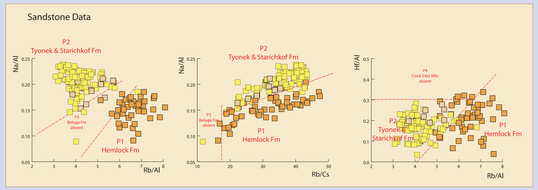
Hemlock Fm = Package 1

Tyonek Formation = Package 2, Unit 2-2

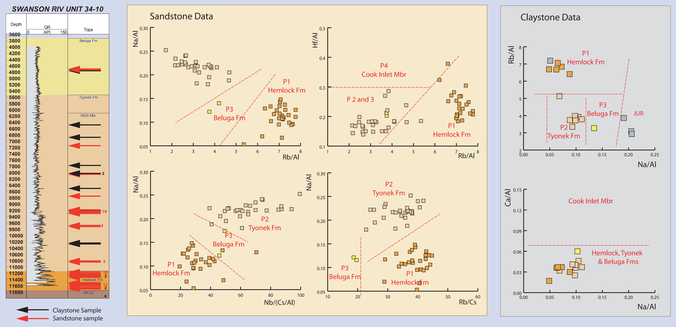
Starichkof Formation = Package 2, Unit 2-1



Samples from the Hemlock Formation, the Starichkof Formation and the Tyonek Formation, have been analysed from the Cosmopolitan Unit. Each formation has a distinctive geochemical signature as displayed by the geochemical logs on the left and on Panel 3. The binary diagrams displayed below for the Cosmopolitan Unit and Swanson River Unit 34-10 show that chemostratigraphically, the Starichkof Formation is similar to the Tyonek Formation, indicating that the Hemlock Formation is one chemostratigraphic package and the Starichkof and Tyonek formations together are a second chemostratigraphic package. The Starichkof and the Tyonek formations can be considered geochemical units within a single package.



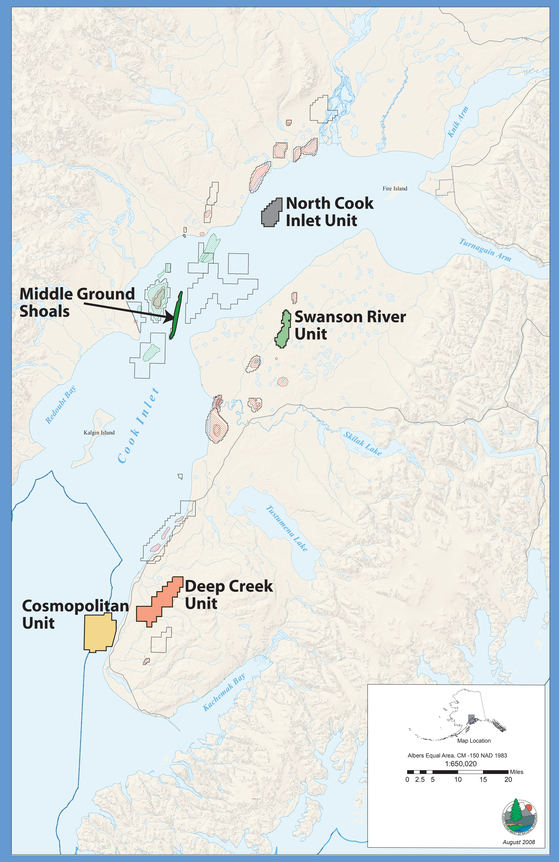
Swanson River Unit



Samples from the Beluga Formation, the Tyonek Formation, the Hemlock Formation and the underlying Jurassic sediments have been analysed from Swanson River Unit 34-10. The binary diagrams on the left demonstrate that the geochemistry of each lithostratigraphic unit is unique. By using these binary diagrams as a template, samples from the less densely sampled wells on the right of this panel can be placed within a chemostratigraphic package.

Hemlock Fm = Package 1, Tyonek Formation = Package 2, Beluga Formation = Package 3

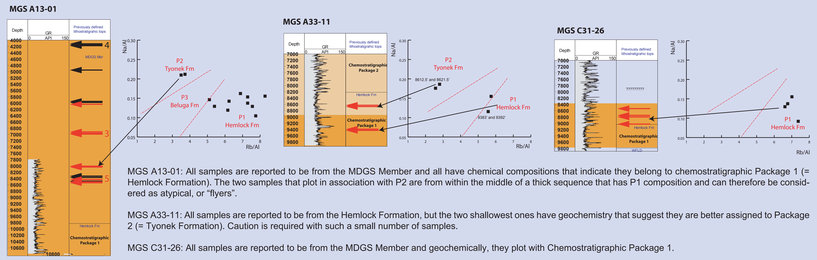
Location Map



Cosmopolitan Unit · **Deep Creek Unit** · **Middle Ground Shoals** · **Swanson River Unit** · **North Cook Inlet Unit**

Middle Ground Shoals

Using the binary diagram templates shown on the left of this panel, the sandstone and claystone samples analysed from North Cook Inlet Unit, the MGS Field and the Deep Creek Unit are placed into a chemostratigraphic package.

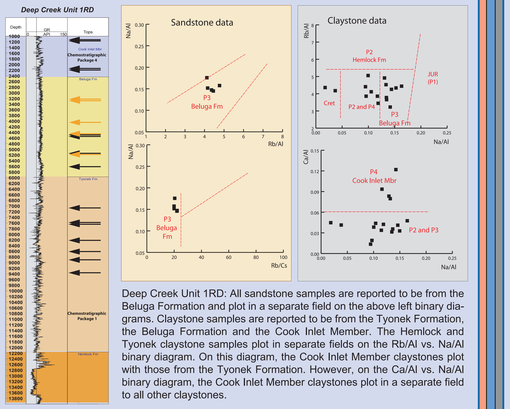


MGS A13-01: All samples are reported to be from the MDGS Member and all have chemical compositions that indicate they belong to chemostratigraphic Package 1 (= Hemlock Formation). The two samples that plot in association with P2 are from within the middle of a thick sequence that has P1 composition and can therefore be considered as atypical, or "flyers".

MGS A33-11: All samples are reported to be from the Hemlock Formation, but the two shallowest ones have geochemistry that suggest they are better assigned to Package 2 (= Tyonek Formation). Caution is required with such a small number of samples.

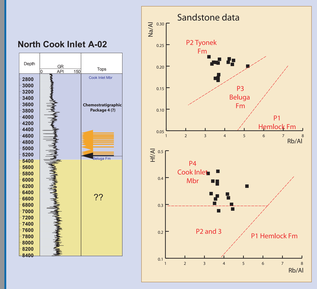
MGS C31-26: All samples are reported to be from the MDGS Member and geochemically, they plot with Chemostratigraphic Package 1.

Deep Creek Unit



Deep Creek Unit 1RD: All sandstone samples are reported to be from the Beluga Formation and plot in a separate field on the above left binary diagrams. Claystone samples are reported to be from the Tyonek Formation, the Beluga Formation and the Cook Inlet Member. The Hemlock and Tyonek claystone samples plot in separate fields on the Rb/Al vs. Na/Al binary diagram. On this diagram, the Cook Inlet Member claystones plot with those from the Tyonek Formation. However, on the Ca/Al vs. Na/Al binary diagram, the Cook Inlet Member claystones plot in a separate field to all other claystones.

North Cook Inlet Unit



Northern Cook Inlet A-02: All samples are reported to be from the Cook Inlet Member. On the upper Binary diagram, they plot in association with samples from the Tyonek Formation, but on the lower binary, they plot as a separate group, suggesting that they may belong to s fourth package. This, however, is the only well in which the Cook Inlet Member has been sampled. Additional well penetration would be needed to confirm that this lithostratigraphic uniot has a unique geochemical fingerprint.

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POSTER 3

KEN RATCLIFFE, MILLY WRIGHT, Chemostrat Inc., 5850 San Felipe, Suite 500, Houston, Texas,
TIM REED, Pioneer Natural Resources, Anchorage, Alaska,
MEG C. KREMER, DNR-Division of Oil and Gas, 550 W. 7th Suite 800, Anchorage, Alaska,
MICHAEL C. DIX, SIMON HUGHES, Halliburton – Sperry Drilling Services, Houston, Texas.

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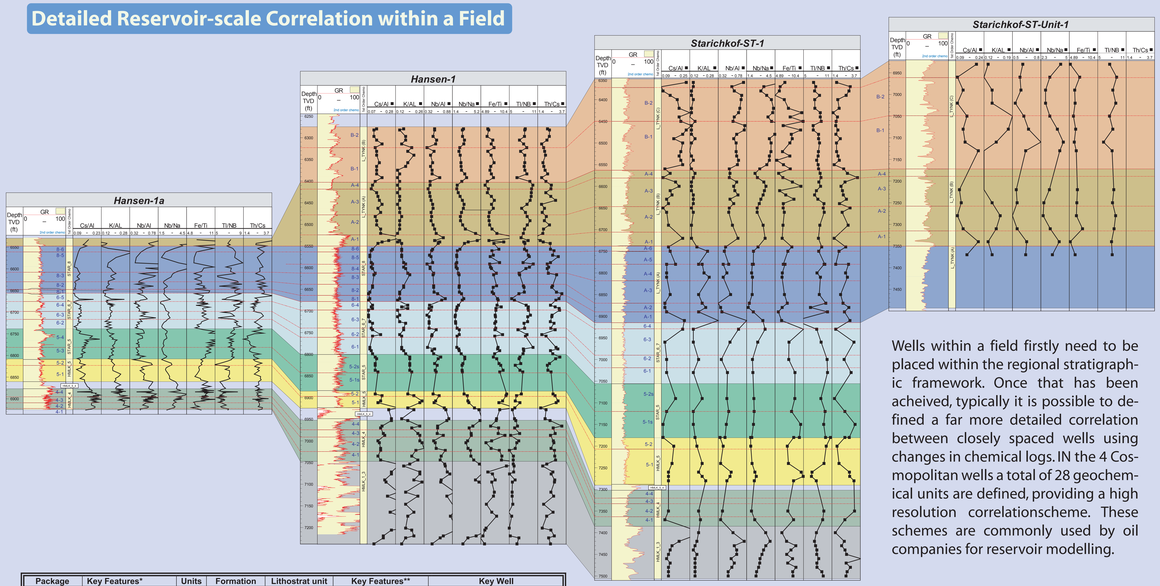
APPLICATIONS OF A CHEMOSTRATIGRAPHIC STABLE REFERENCE FRAMEWORK IN THE COSMOPOLITAN UNIT

Detailed Reservoir-scale Correlation within a Field



Wells within a field firstly need to be placed within the regional stratigraphic framework. Once that has been acheived, typically it is possible to defined a far more detailed correlation between closely spaced wells using changes in chemical logs. IN the 4 Cosmopolitan wells a total of 28 geochemical units are defined, providing a high resolution correlationscheme. These schemes are commonly used by oil companies for reservoir modelling.

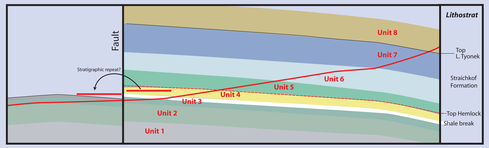
Package	Key Features*	Units	Formation	Lithostrat unit	Key Features**	Key Well
Package 10	b) high Cs/Al + Nb/Na + low Th/Cs values	10.3	Tyonek	L_TYONEK	upwardly decreasing Fe/Ti values	Starichkof State 1 Hansen-1
		10.2			high Fe/Ti values	
		10.1			upwardly increasing Fe/Ti values	
Package 9	a) low Cs/Al + high Th/Cs values b) low K/Al + high Nb/Na + Nb/Al values	9.4			low Nb/Na values	Starichkof State 1 Hansen-1
		9.3			high Fe/Ti values	
		9.2			high Ti/Nb values	
		9.1			high Cs/Al values	
Package 8	a) high K/Al + low Nb/Na + Nb/Al values b) high Nb/Al + Th/Cs values	8.6	Starichkof	STAR_8		Starichkof State 1 Hansen-1a
		8.5			high K/Al values	
		8.4			high Nb/Na values	
		8.3			high Ti/Nb values	
		8.2			low Th/Cs values	
		8.1			high Ti/Nb values	
Package 6-7	a)low Nb/Al + Th/Cs values b)low Cs/Al, K/Al + Fe/Ti + high Ti/Nb values	6-7.5		STAR 6_7	low Th/Cs values	Hansen-1a
		6-7.4			high Nb/Na values	
		6-7.3			low Fe/Ti values	
		6-7.2			high Fe/Ti values	
		6-7.1				
Package 5	a) high Cs/Al, K/Al + Fe/Ti values + low Ti/Nb values b) low Cs/Al, Nb/Al + Nb/Na + high Ti/Nb values	5.4		STAR_5		Hansen-1a
		5.3			high Cs/Al values	
		5.2	Hemlock	HMLK_5	upwardly increasing Fe/Ti values	
		5.1			low Fe/Ti values	
Package 4	a) high Cs/Al, Nb/Al + Nb/Na + low Ti/Nb values b) low Cs/Al + Nb/Na values + high Th/Cs values	4.5		HMLK_5_4		Hansen-1a
		4.4				
		4.3		HMLK_4	low Cs/Al values	
		4.2			high Nb/Na values	
		4.1			low Fe/Ti values	
Package 1	a)gh Cs/Al+ Nb/Na + low Nb/Al values					Hansen-1

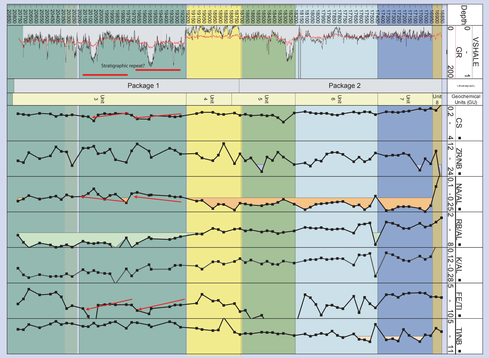
* geochemical features used to differentiate the packages
a) these features differentiate the specific package from the overlying packages
b) these features differentiate the specific packaqe from the under lying packages

Understanding Mineralogy and Provenance Changes

Na/Al: Na has mixed affinities including plagioclase feldspar, intermediate / basic igneous lithic fragments and clay minerals. By normalising Na against Al, the influence of non-clay related components, i.e. plagioclase and intermediate / basic lithic fragments is emphasised.
Rb/Al: Records the amount of illite , although both mica and feldspar may also influence this ratio.
Ga/Rb: Ga is a preferentially substituted into kaolinite, whereas as Rb is preferentially enriched in illite. Therefore, this ratio is recording the kaolinite : illite ratio.
K/Rb: K and Rb are influenced by clay minerals, notably illite, and K-feldspar. However, the K/Rb ratio is higher in K-feldspar than in illite, therefore, this ratio should emphasise the abundance of K-feldspar.
Cr/Th: Both elements are here associated with heavy minerals. Cr is typically strongly influenced by Cr-spinels, and Th by monazite. Thus the Cr/Th ratio may be recording a change in sediment provenance.
Cr/K: This ratio is designed to reflect the relative influence of basic igneous input (Cr-Spinel) and acidic igneous input (K).
K/Na: Both K and Na are controlled by a variety of Al-silicate minerals (e.g. plagioclase, clay minerals, mica), but the ratio of the two elements should be recording the proportion of plagioclase feldspar vs. K-feldspar.
Ti/Nb: Both these elements are associated with Ti-oxide heavy minerals and a marked excursion in the Ti/Nb ratio almost always reflects a change in sediment provenance, but the exact nature of that change cannot yet be determined in this study.
Nb/(Cs/Al): Nb is related to Ti-oxide heavy minerals and Cs/Al to the amount of mica (?).

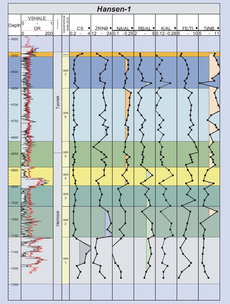
Understanding Horizontal Wells





A detailed chemostratigraphic zonation can be used in horizontal wells to understand the well-bore pathway reltive to stratigraphy. The well on the left is from the Cosmopolitan Unit and is low angle to horizontal between 16850-20850ft MD. By looking at changes in the chemical logs along the well-bore and comparing them to the chemical logs in Hansen-1 (above), it can be shown that the horizontal well:

- Penetrate Units 8 - 3 in a normal stratigraphic successtion. Run sub-parallel to bedding in Unit 3.
- Cross a small fault at c. 19750' MD
- Penetrate the top of Unit 2 at 23050' MD
- TD'd in Unit 3



CONCLUSIONS

- Using whole rock geochemical data, it is possible to define 4 chemostratigraphic packages that have markedly different compositions. Each of the packages can be related to a lithostratigraphic unit and can be recognised regioanlly
  - Package 4 (= Cook Inlet Member): Sandstones have high Hf/Al values, claystones have high Ca/Al values
  - Package 3 (=Beluga Formation): Sandstones have low Rb/Cs values and intermediate Na/Al values, claystones have low Rb/Al and high Na/Al values
  - Package 2 (=Tyonek and Starichkof Formations): Sandstones have low Rb/Al and high Na/Al values, claystones have low Rb/Al and Na/Al values
  - Package 1 (=Hemlock Fm and MDGS Member): Sandstone have high Rb/Al and low Na/Al values, claystones have high Rb/Al and low Na/Al values
- With the current dataset, these chemostratigraphic packages appear to have consistent geochemistry accross Cook Inlet, thereby providing the basis of establishing a stable reference stratigraphic framework, although additional well penetrations in additional units and fields are required to confirm this supposition
- In the closely spaced wells of the Cosmopolitan Unit, high resolution correlation is possible, within the basin-wide stable reference chemostratigraphic framework. A total of 28 geochemical units are defined within the Cosmopolitan Unit
- The geochemical changes used to define the chemostratigraphic packages relate to changes through time in sediment provenance and paleoclimate
- Using the high resolution framework, it is possible to determine the well-bore pathway with respect to stratigraphy in deviated wells, both historical and real-time.