Results of new 1:63,360-scale geologic mapping and related field studies in the south-central Tyonek Quadrangle, south-central Alaska: Middle Eocene transtension and post-Oligocene inversion on the northwest periphery of the Cook Inlet forearc basin

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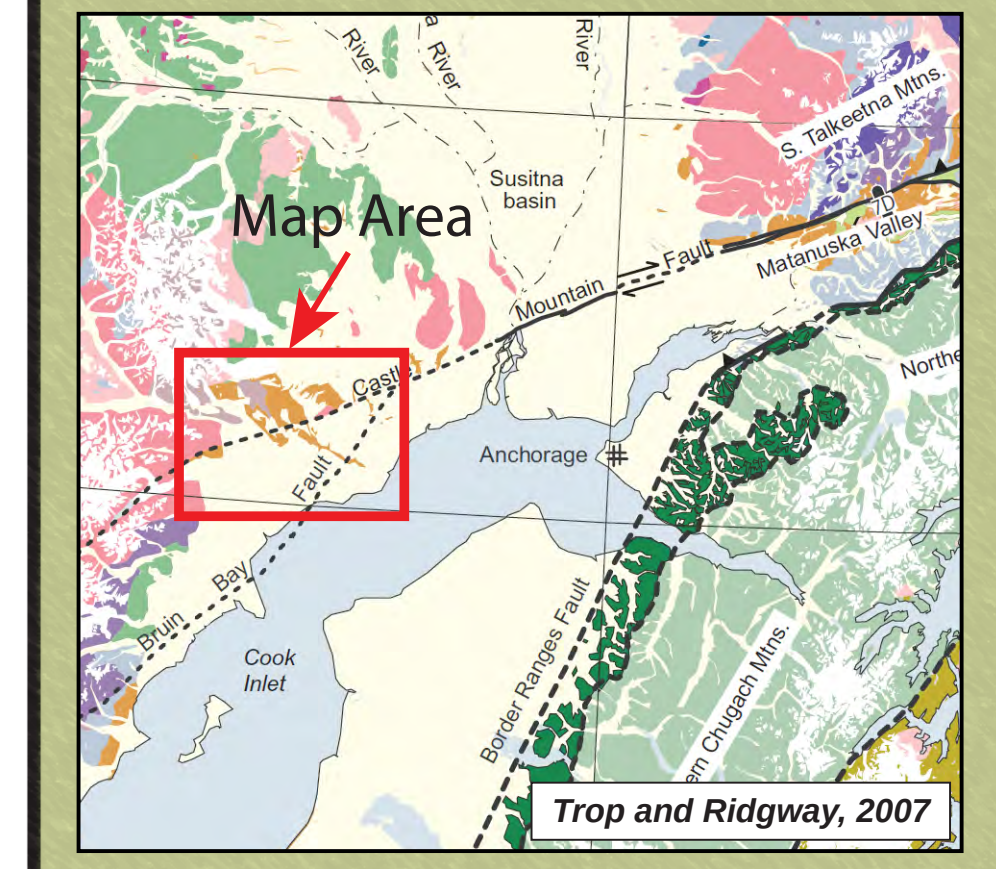
ABSTRACT

New inch-to-mile geologic mapping of approximately 875 square miles in the south-central Tyonek Quadrangle along the northwestern margin of the Cook Inlet basin include parts of the exhumed Cretaceous and Cenozoic magmatic arcs and the principal structures that define the Cenozoic arc-forearc boundary. Major results include subdivision of the earliest Cenozoic basin strata (West Foreland Formation) into three mappable subunits, and newly-recognized stratigraphic and structural relationships that define the margin as an inverted pull-apart basin. A more nuanced depositional model and better constraints on the timing of arc magmatism were guided by companion detailed descriptions of 37 measured stratigraphic sections, 84 U-Pb and ^{40}Ar/^{39}Ar geochronologic analyses of intrusive, extrusive, and sedimentary rocks, and 143 palynologic analyses from throughout the Cenozoic succession.

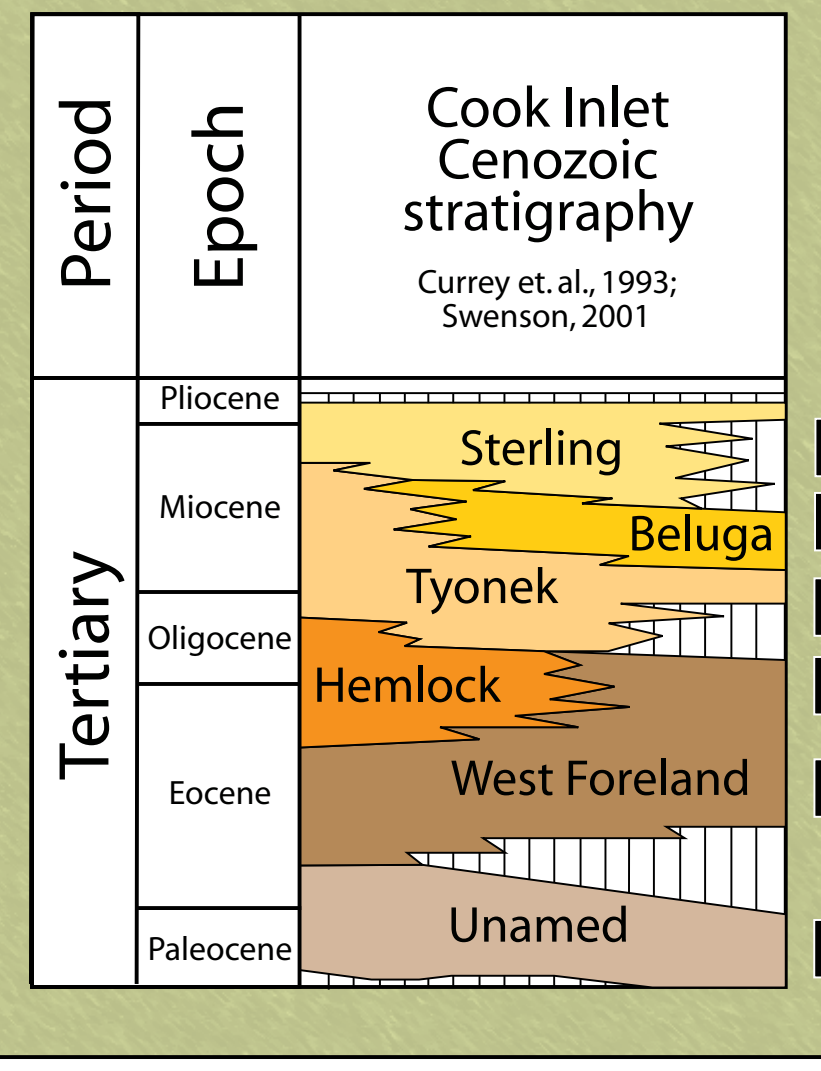
Over 1000 shear plane measurements including more than 400 slip lineation directions, numerous uni-directional kinematic indicators, and field cross cutting relationships have helped constrain the structural style, the timing of onset of deformation, and the principal stress directions during early basin formation. In regions approaching the Cook Inlet coast where exposures are relatively rare due to a surficial glacial mantle and dense vegetation, publically- and privately-held subsurface data
informed the mapping of stratigraphic contacts and major structures, redefining what has classically been called the Bruin Bay fault as a complex system of en echelon faults referred to here as the Moquawkie-Beluga River fault system (M-BRFS), adhering more closely to industry subsurface nomenclature.

Collectively, the new mapping, field observations, and supplemental data define the northwestern margin of the Cook Inlet forearc basin as a dextral, right-stepping transtensional pull-apart system initiating at 57 Ma, linking the Capps Glacier fault to the northwest with the Castle Mountain fault to the southeast. Deposition of proximal West Foreland Formation strata was syntectonic from before 47.9 to after 38.7 Ma, when the principal extension direction ranged between 189 to 215 degrees azimuth. Seismic and well log interpretation tentatively suggest local normal slip along the M-BRFS during Paleocene-Eocene time prior to regional structural inversion that likely began after Oligocene time. Dextral transtension occurred locally after middle Miocene time along the SE-dipping Lake Clark fault, which may not link directly to the Castle Mountain fault as originally mapped.

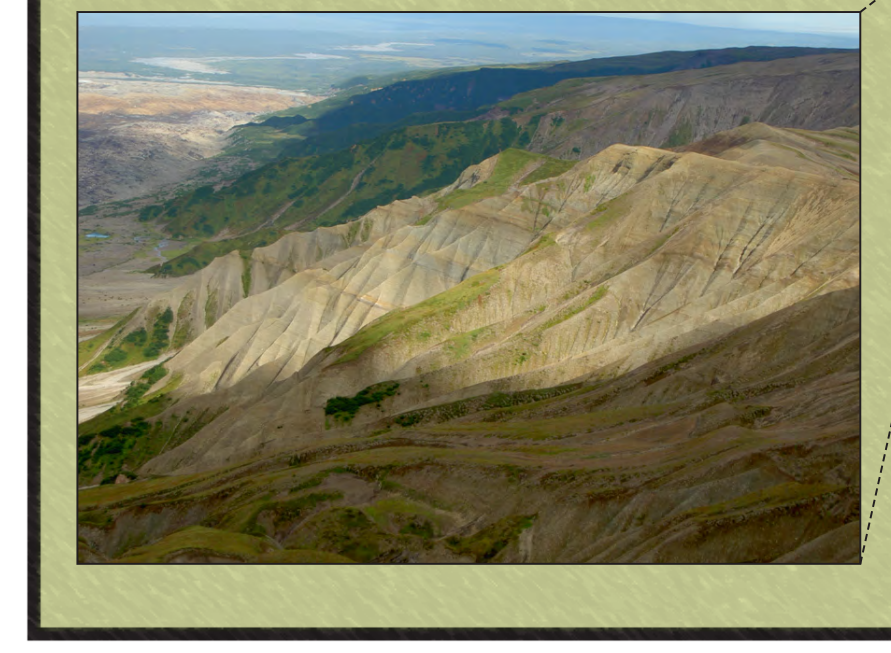
Location map


Map Area
Susitna basin
S. Talkeetna Mtns.
Matanuska Valley
Mountain
Fault
Castle
Fault
Anchorage
Bruin
Bay
Cook Inlet
Border Ranges Fault
Chugach Mtns.
North
River
Trop and Ridgway, 2007

Cook Inlet Cenozoic stratigraphy and new age constraints

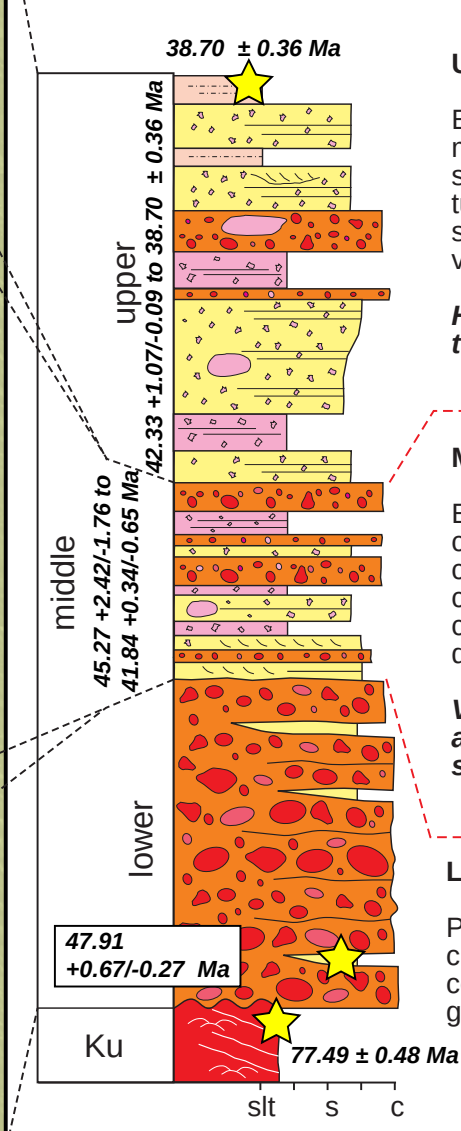

Period
Epoch
Cook Inlet Cenozoic stratigraphy
Currey et. al., 1993; Swenson, 2001
Tertiary
Pliocene
Miocene
Oligocene
Eocene
Paleocene
Sterling
Beluga
Tyonek
Hemlock
West Foreland
Unamed

Ts	latest Miocene to early Pliocene (paly)
Tb	13.4-11.8 Ma (Zr U-Pb), middle to latest Miocene (paly)
Tt	23.6(?) Ma (Ar-Ar), 15.9-15.2 Ma (Zr U-Pb), middle Miocene (paly)
Th	late Eocene to early Miocene (paly)
Twf	47.9-38.7 Ma (Zr U-Pb), middle to late Eocene (paly)
Tc	(unexposed at surface)



West Foreland Formation (47.9 to 38.7 Ma)

Capps Glacier, Straight Creek and eastern tributaries


38.70 ± 0.36 Ma
upper
42.33 +1.07/-0.09 to 38.70 ± 0.36 Ma
middle
45.27 +2.42/-1.76 to 41.84 +0.34/-0.65 Ma
lower
47.91 +0.67/-0.27 Ma
Ku
77.49 ± 0.48 Ma
slt
s
c

Upper member (>300m ?)

Brown and tan weathering poorly sorted, clast-supported conglomerate, massive and horizontal stratification; medium- to very coarse-grained, poorly sorted sandstone, horizontal stratification; airfall and reworked crystal-lithic tuffs up to 12 m thick, massive and horizontal stratification; cross-stratified sandstone and interbedded mudstone locally prominent; clasts dominantly volcanic, some granitoids

Hyperconcentrated flood flow deposits, primary airfall(?) and reworked tuffs, distal alluvial fan, and abundant dilute streamflow deposits

Middle member (0-200m)

Brown weathering, poorly sorted, clast-supported pebble to boulder conglomerate, massive and crude horizontal stratification; coarse- to very coarse-grained, very poorly sorted sandstone, horizontal stratification; crystal-lithic tuffs up to 8 m thick, massive and horizontal stratification; minor cross-stratified medium- to coarse-grained sandstone and siltstone; clasts dominantly volcanic, some granitoids

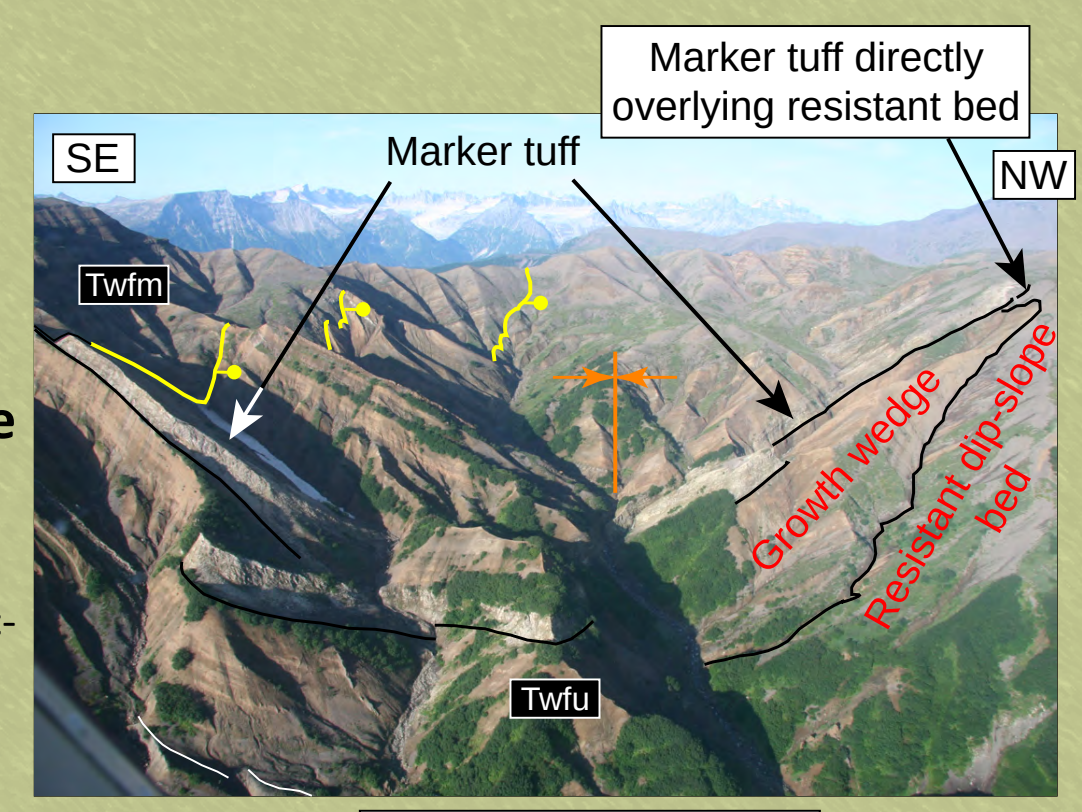
Volcanogenic hyperconcentrated flood flow deposits, primary(?) airfall and reworked tuffs, and interbedded distal alluvial fan and minor dilute streamflow deposits

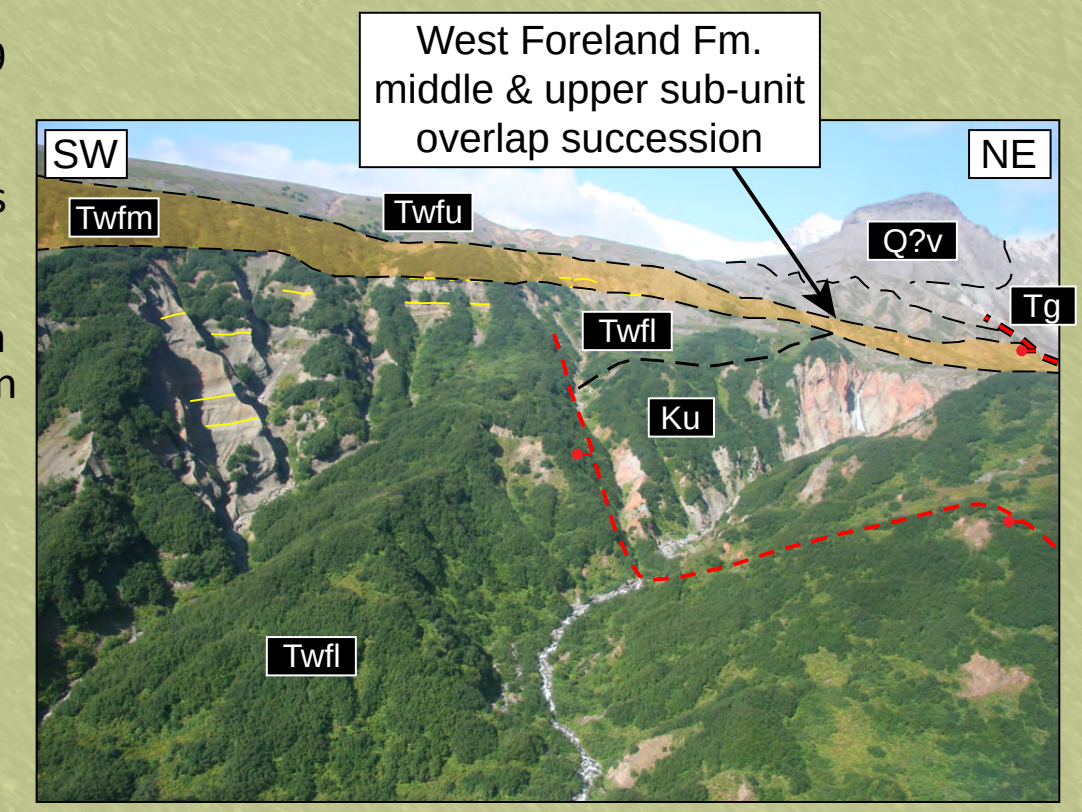
Lower member (0-300m)

Pebble, cobble, and boulder conglomerate, clast-supported, poorly sorted, crude horizontal stratification; minor lenses of poorly sorted medium- to very coarse-grained pebbly sandstone; clasts dominantly volcanic, common granitoids

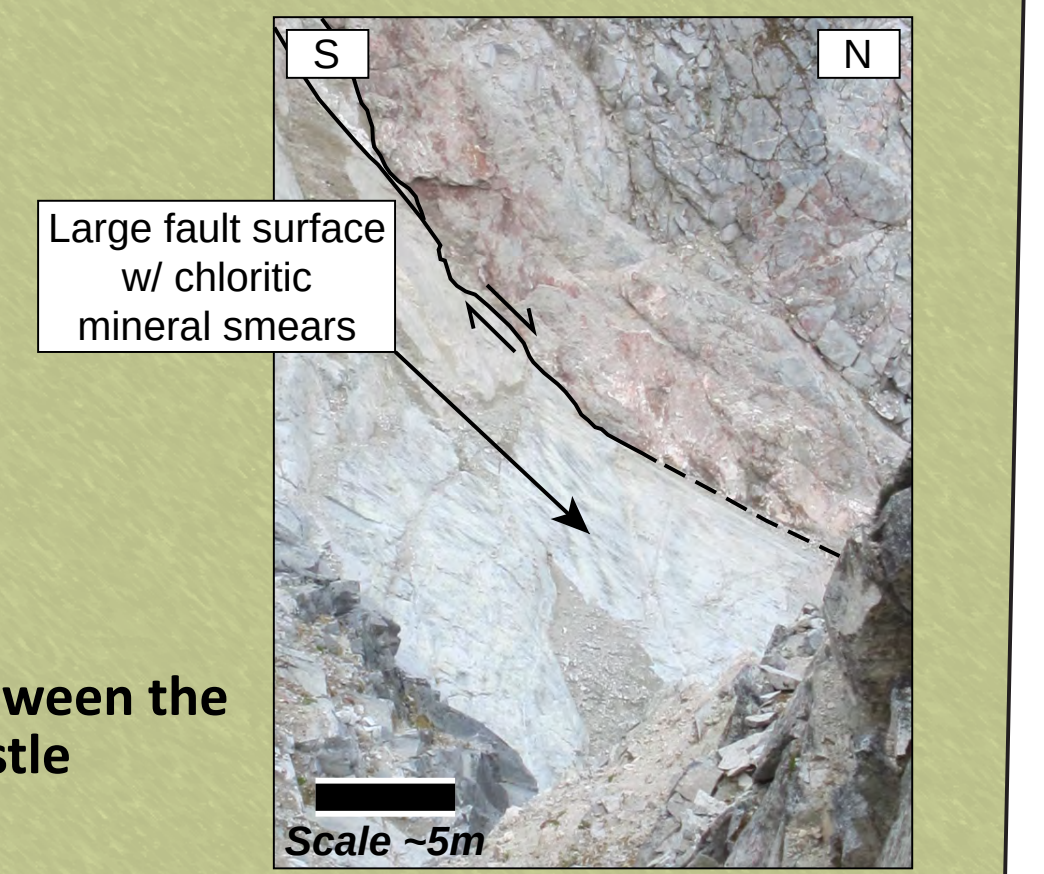
Proximal alluvial fan and feeder canyon-fill

Middle Eocene deposition in a tectonically-active basin


Marker tuff directly overlying resistant bed
SE
Marker tuff
NW
Twfm
Growth wedge
Resistant dip-slope bed
Twfu

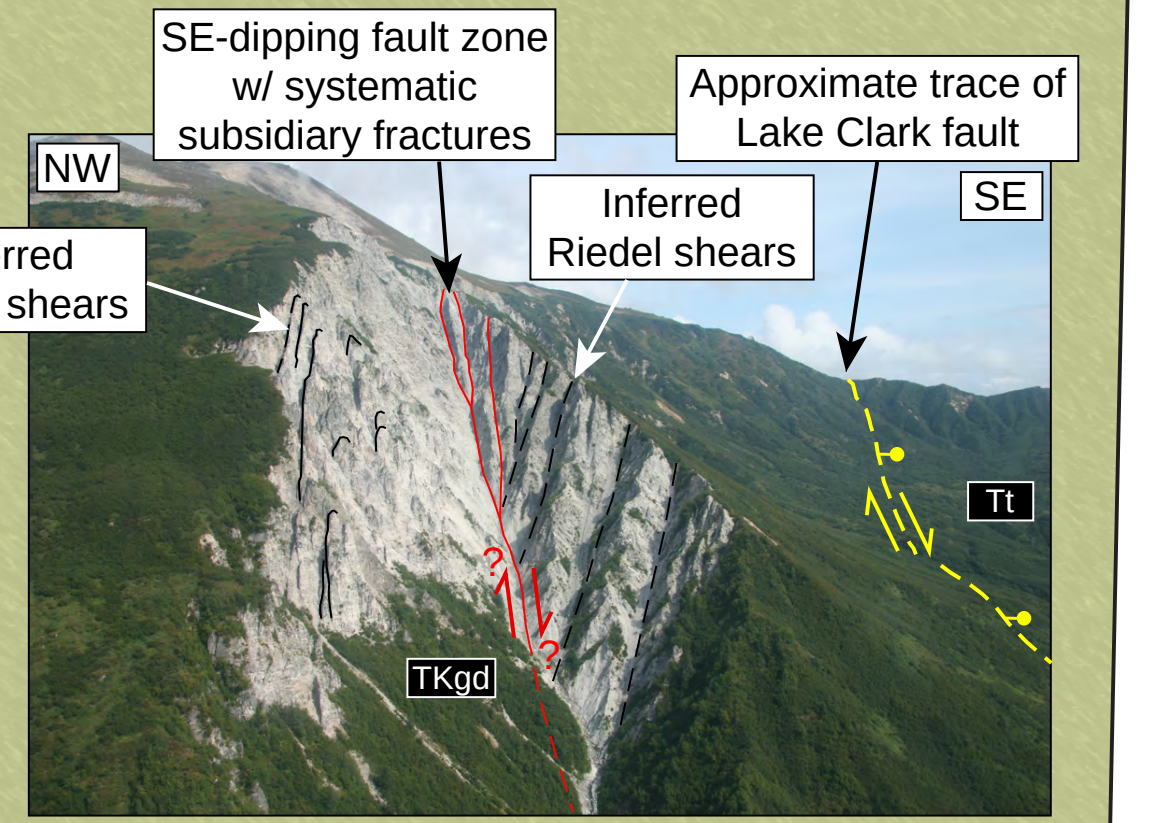

West Foreland Fm. middle & upper sub-unit overlap succession
SW
NE
Twfm
Twfu
Q?v
Tg
Twfl
Ku
Twfl

Growth strata and a prominent overlap succession indicate that West Foreland Fm. strata were deposited in a tectonically active basin from before 47.9 Ma to after 38.7 Ma. NW-striking faults cut older NE-striking faults in the Capps Glacier fault hanging-wall, potentially indicating a ~37° clockwise rotation of the stress field deforming the Capps pull-apart basin after ~45 Ma.


S
N
Large fault surface w/ chloritic mineral smears
Scale ~5m

Linking structures between the Capps Glacier and Castle Mountain faults

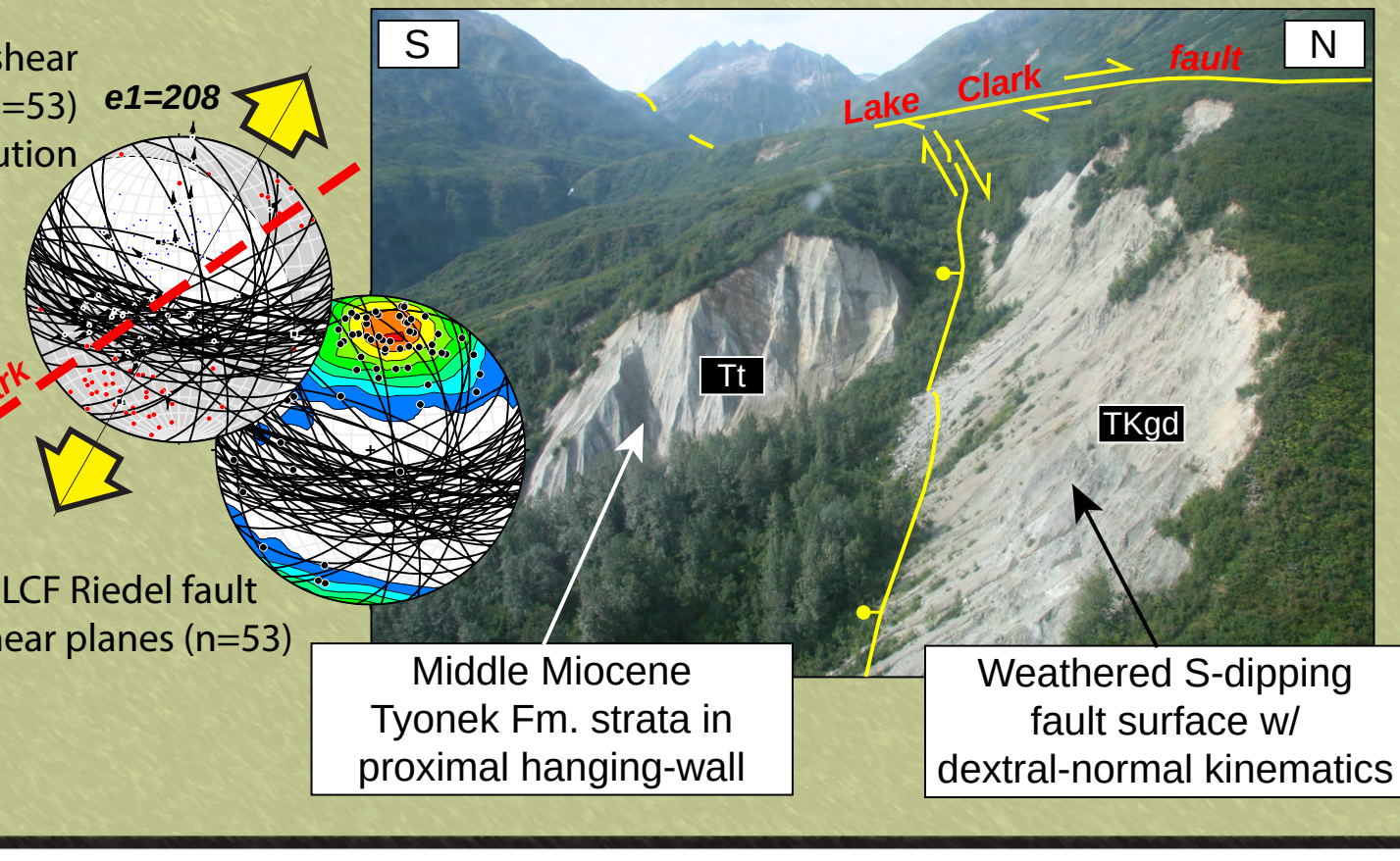
Linking structures between the Capps Glacier and Castle Mtn. faults are poorly exposed in the map area. However, a large, inaccessible north-dipping fault plane with chloritic slickensides suggest principally dip-slip motion on one such candidate. The fault faces the southeast-dipping Capps Glacier fault and a narrow basin wedge where over 1,000 m of West Foreland conglomerate has been drilled in the subsurface, suggesting faults at this location are normal slip and help to accommodate significant basin subsidence.


SE-dipping fault zone w/ systematic subsidiary fractures
Approximate trace of Lake Clark fault
NW
SE
Inferred Riedel shears
Inferred Riedel shears
Tt
TKgd

A wide, southeast-dipping fault zone sub-parallel to, and due northwest of the Lake Clark fault has prominent, well-developed subsidiary fracture sets that are consistent with Riedel shears in a dextral-normal slip system that is interpreted to be synthetic to the LCF.

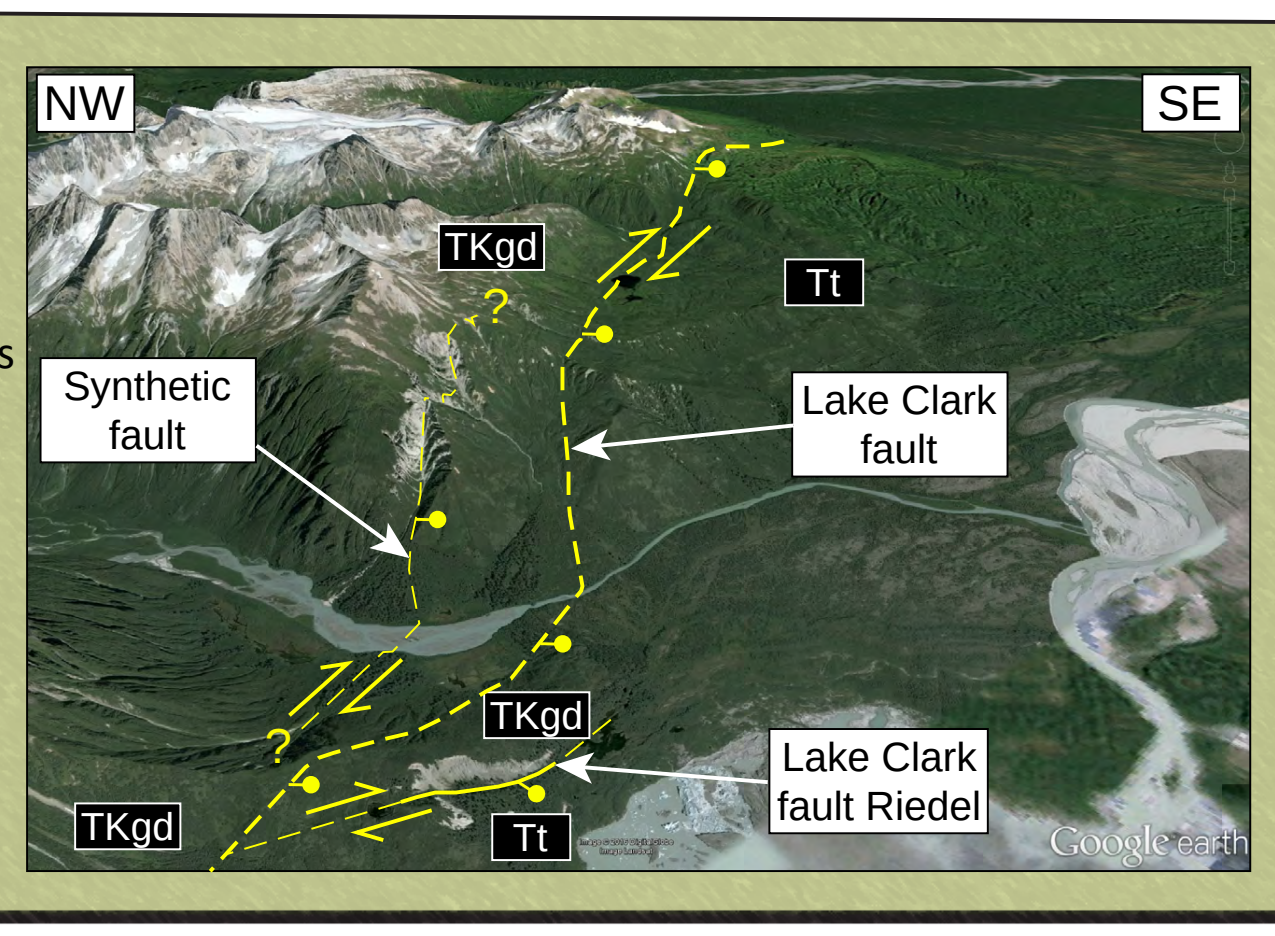
Subsidiary faults to the Lake Clark fault

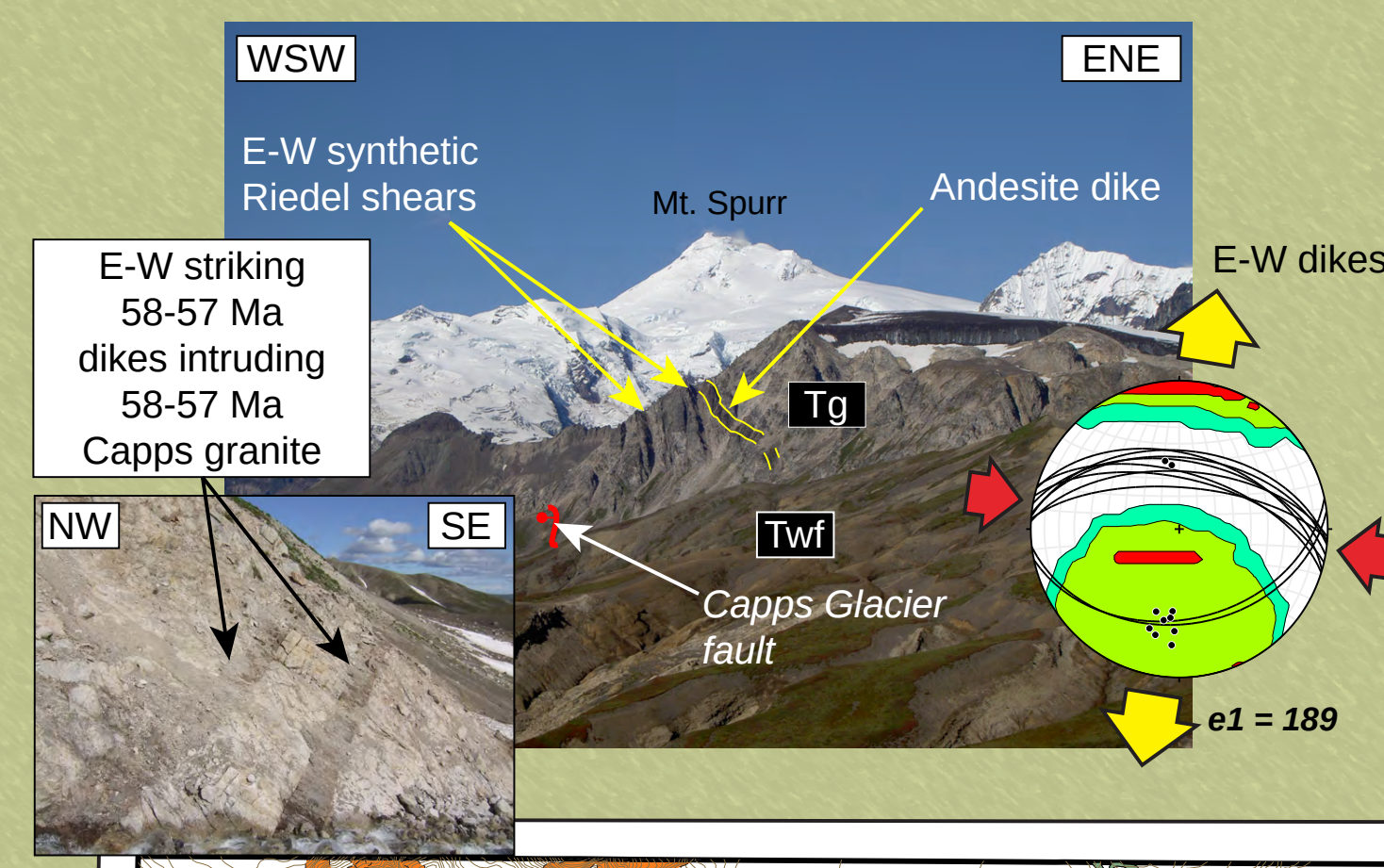
A well exposed, highly-weathered south-dipping fault plane locally preserves proximal Tyonek Fm. conglomerate directly juxtaposed against >72.5 Ma granodiorite and kinematic indicators that define dextral-normal slip. The fault's sense of slip and shallow oblique strike to the Lake Clark fault (LCF) is consistent with it being a synthetic Riedel shear to the LCF. Kinematic analysis of the fault plane data produce a SSW-striking mean extension axis and subvertical shortening axis.


LCF Riedel fault shear planes w/ kinematics (n=53)
& fault-plane solution
e1=208
Lake Clark fault
LCF Riedel fault shear planes (n=53)
S
N
Lake Clark fault
Tt
TKgd
Middle Miocene Tyonek Fm. strata in proximal hanging-wall
Weathered S-dipping fault surface w/ dextral-normal kinematics

Re-interpretation of Lake Clark fault as a dextral-normal fault system

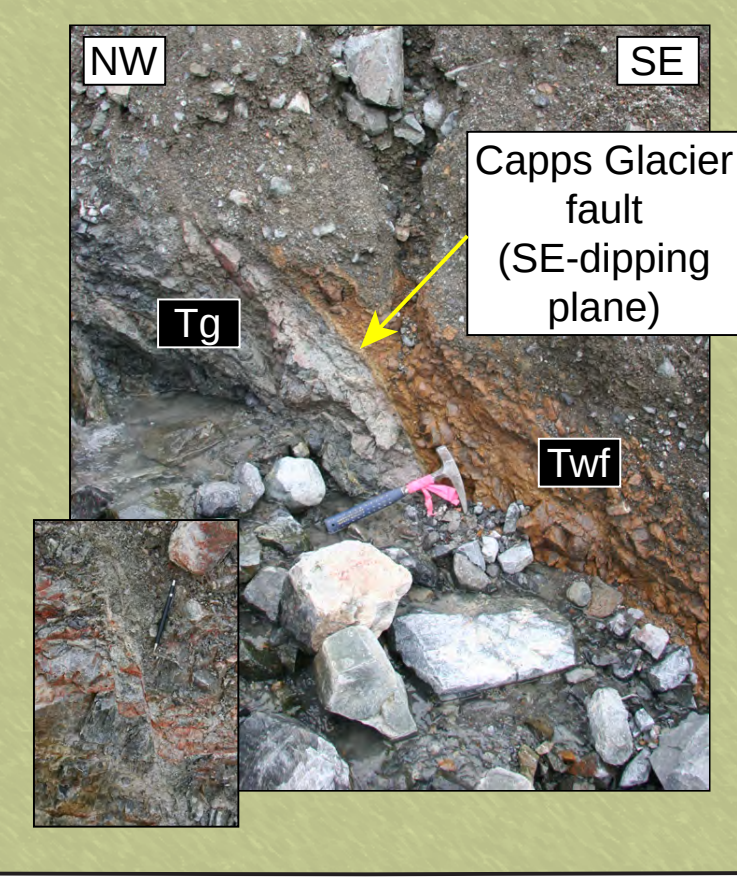
The Lake Clark fault (LCF) is not exposed in the map area, but exposed faults subsidiary to the LCF are either inferred or demonstrated to be southward dipping and transtensional. Thus, the simplest interpretation for the LCF is that it is also a southward dipping dextral-normal fault.


NW
SE
TKgd
Tt
Synthetic fault
Lake Clark fault
TKgd
TKgd
Tt
Lake Clark fault Riedel
Google earth


E-W striking 58-57 Ma dikes intruding 58-57 Ma Capps granite
NW
SE
WSW
ENE
E-W synthetic Riedel shears
Mt. Spurr
Andesite dike
Tg
Twf
Capps Glacier fault
E-W dikes
e1 = 189

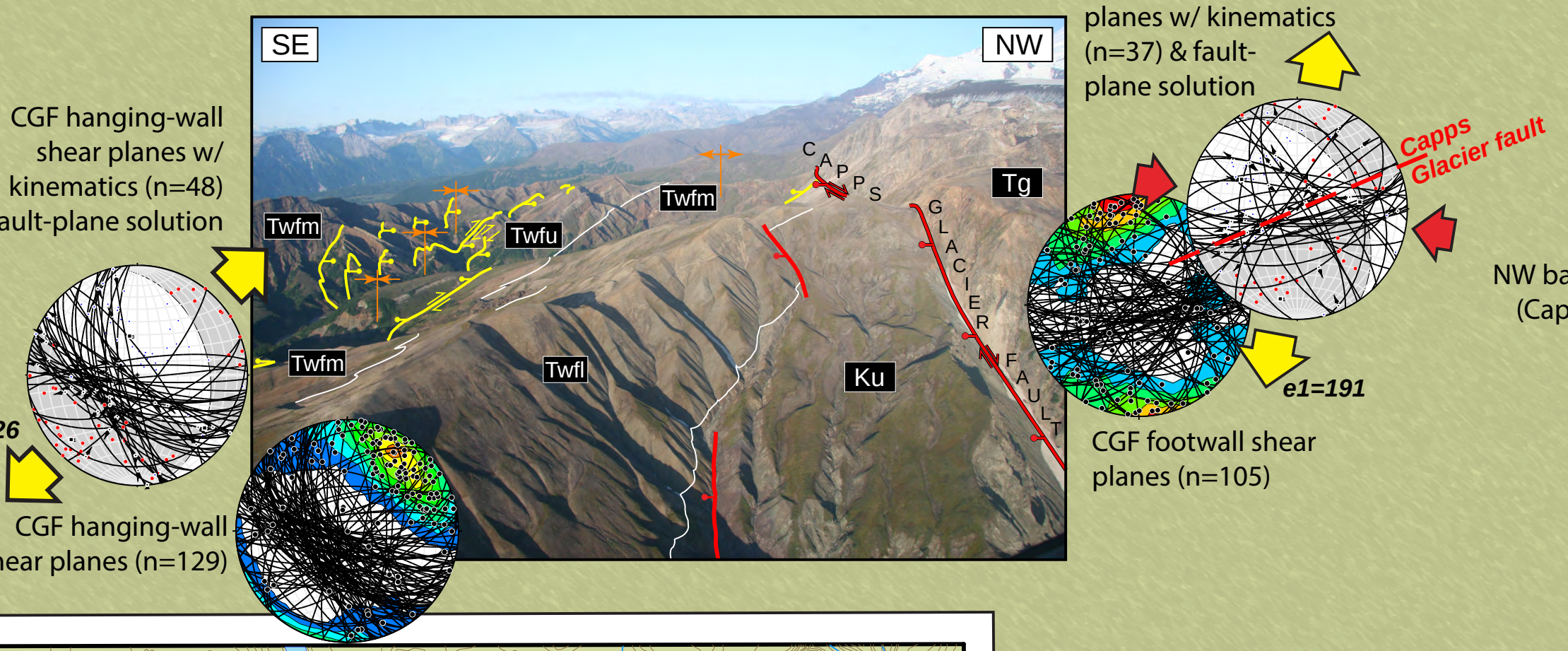
The significance of E-W dikes intruding the Capps granite

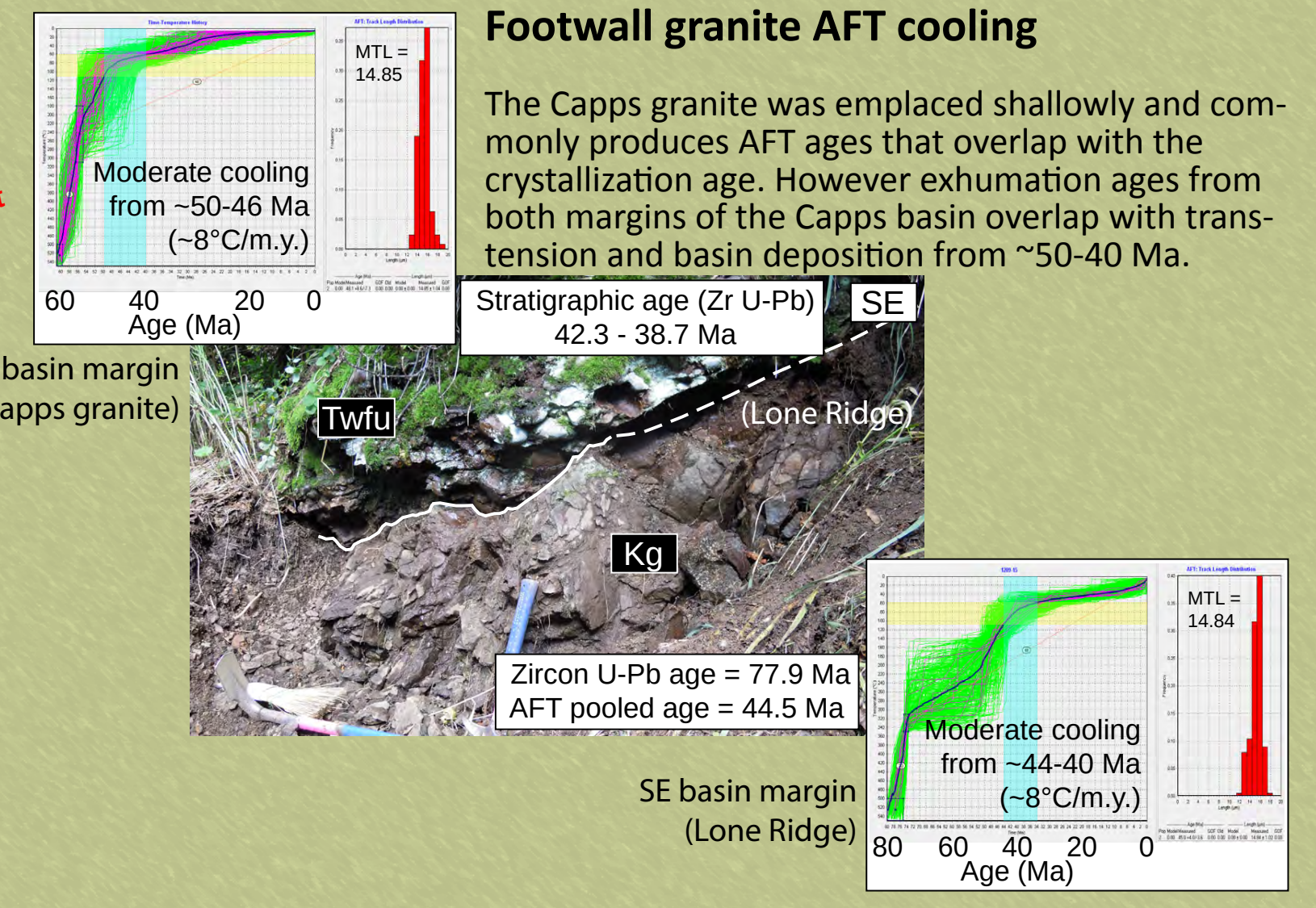
An E-W-trending dike swarm intruding the non-foliated Capps granite overlaps in age, but post-dates its emplacement. They are sub-parallel to a prominent set of transtensional Riedel shears to the Capps Glacier fault and yield a SSW extension direction that is compatible with extension directions derived from kinematics associated with the fault. Thus their ages are interpreted to represent onset of transtension immediately after emplacement of the Capps granite at 57 Ma.


NW
SE
Tg
Capps Glacier fault (SE-dipping plane)
Twf

Capps Glacier fault

The Capps Glacier fault (CGF) is a SE-dipping dextral-normal transtensional fault that linked with the Castle Mtn. fault to produce a pull-apart basin chiefly during middle Eocene time. The age of the Capps granite and systematic dike emplacement along a trend of transtensional Riedel shears to the fault, combined with well-dated syn-tectonic basin fill constrain the age of its motion, and thus transtension along the NW margin of the Cook Inlet forearc basin at ~57 Ma to <39 Ma.

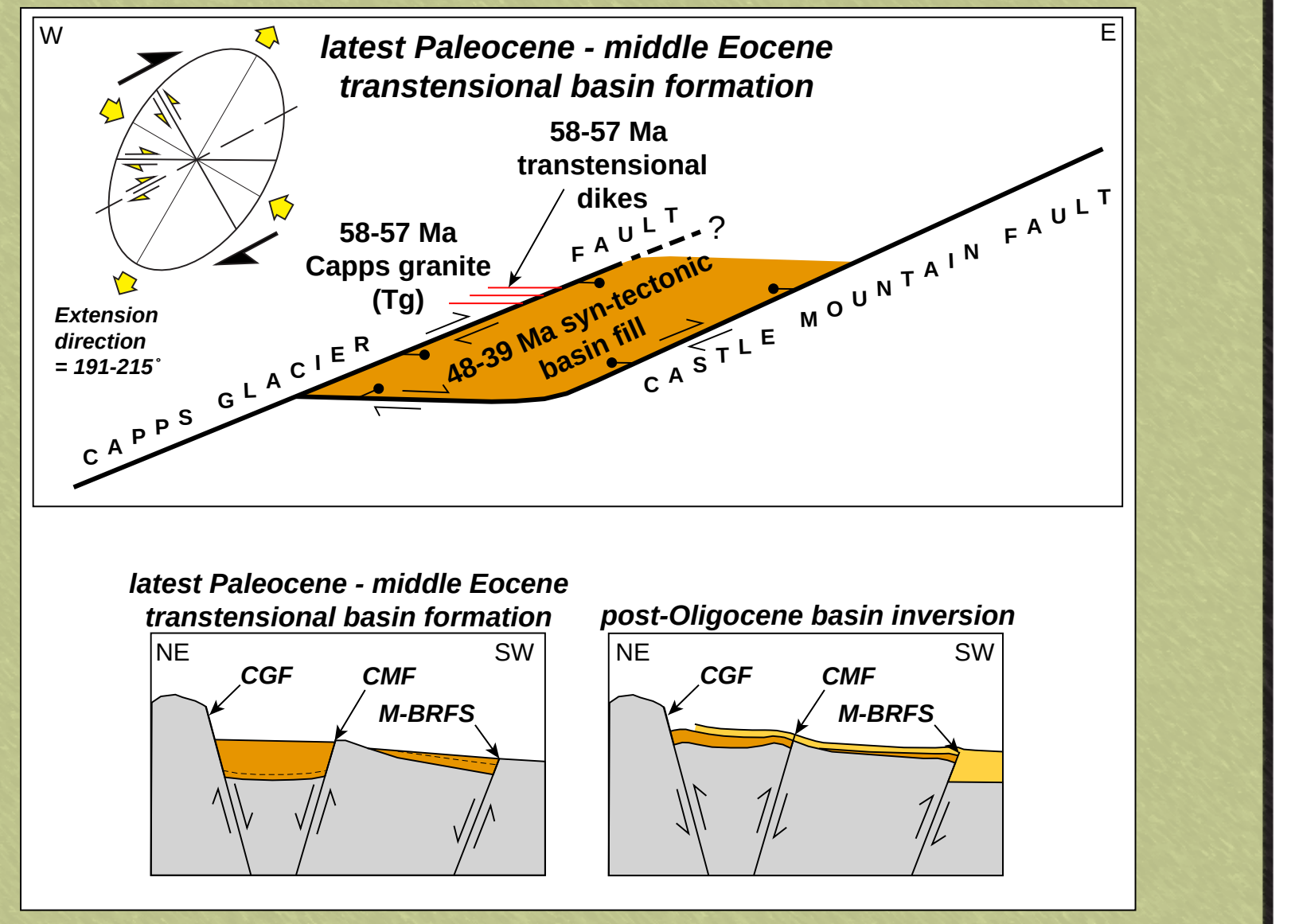

CGF hanging-wall shear planes w/ kinematics (n=48)
& fault-plane solution
e1=226
CGF hanging-wall shear planes (n=129)
SE
NW
Twfm
Twfu
Twfm
Twfl
Ku
Twfm
CAPPS GLACIER FAULT
Tg
Ku
CGF footwall shear planes w/ kinematics (n=37) & fault-plane solution
Capps Glacier fault
e1=191
CGF footwall shear planes (n=105)

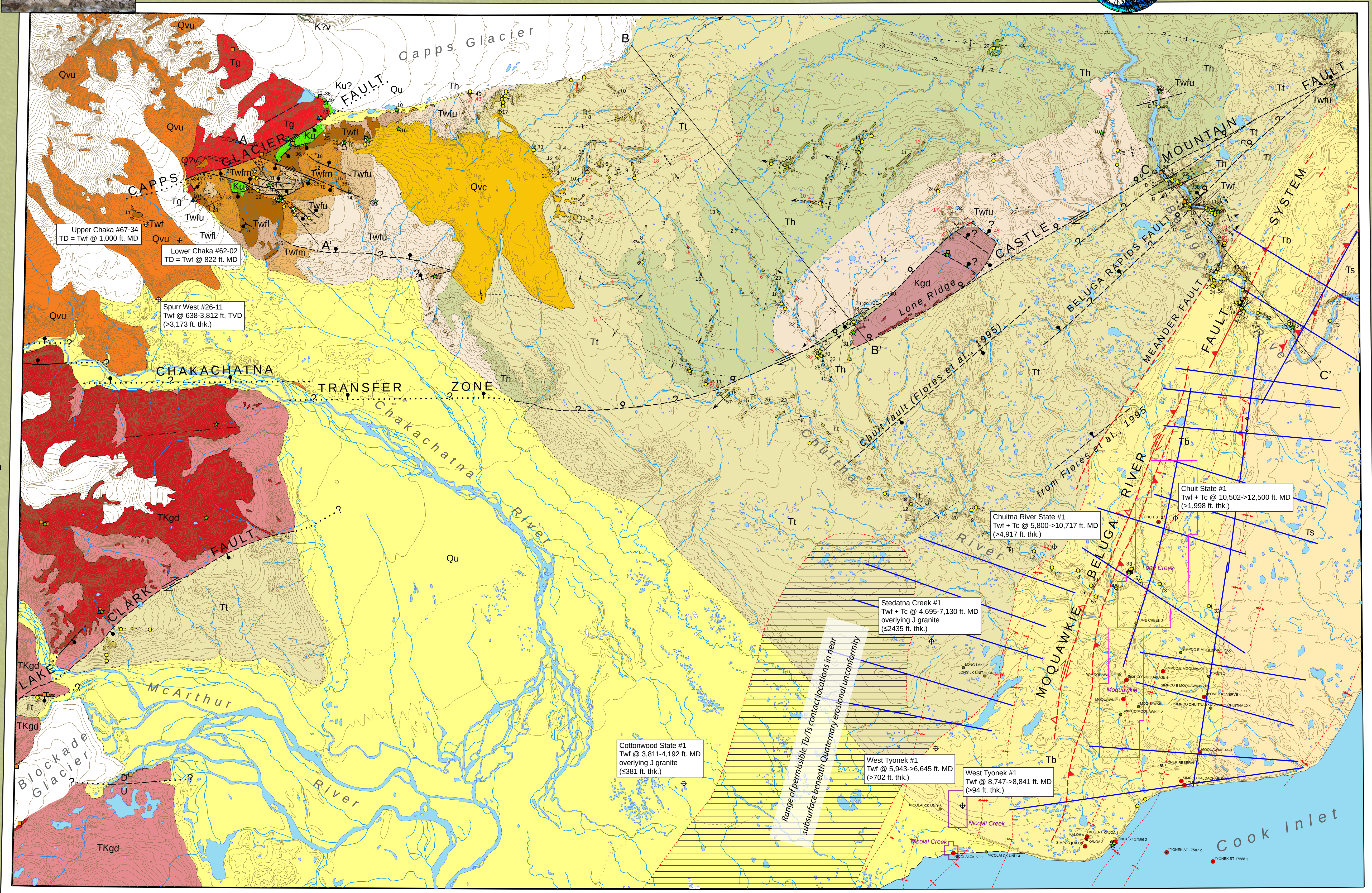


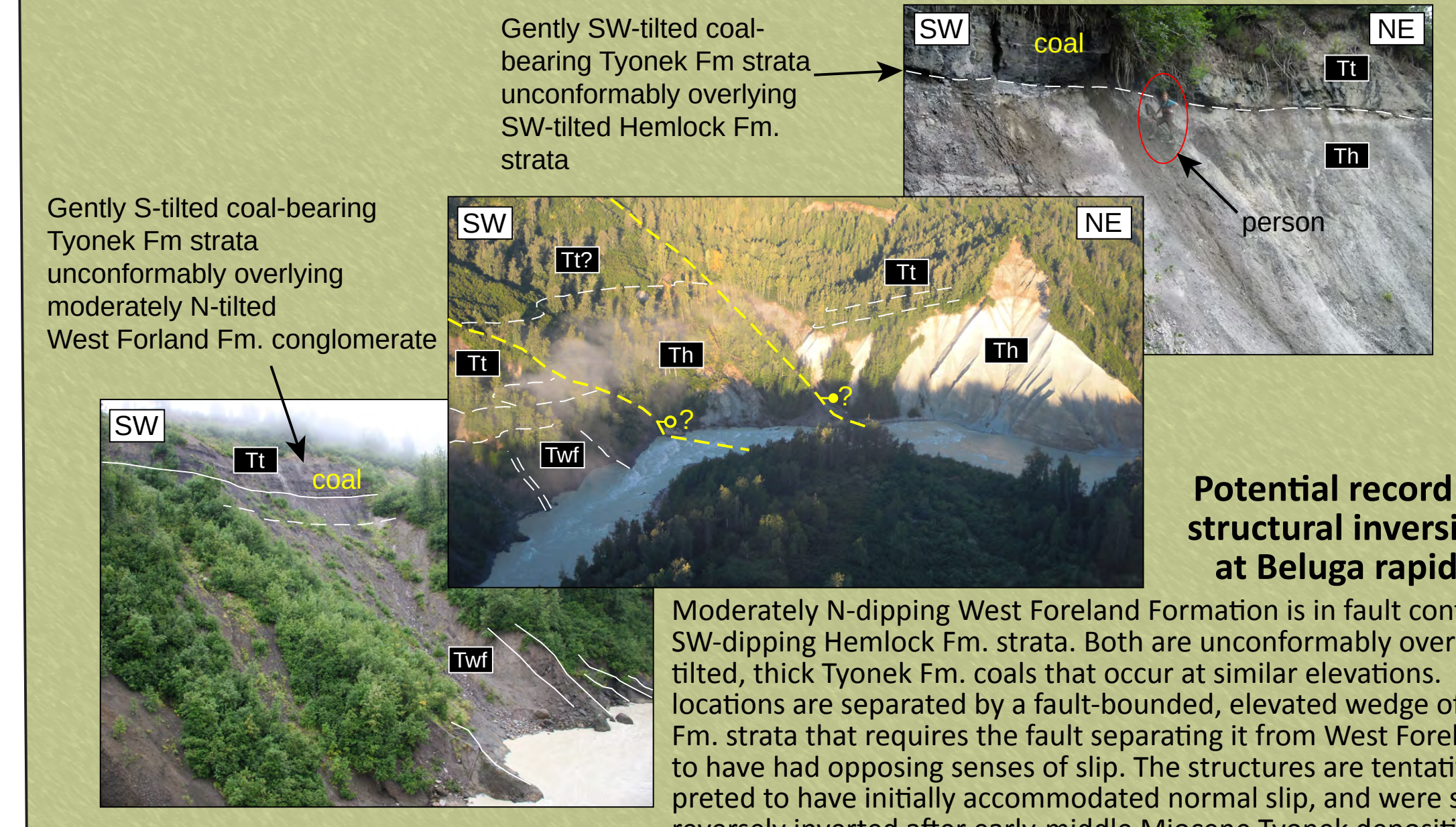
Footwall granite AFT cooling

The Capps granite was emplaced shallowly and commonly produces AFT ages that overlap with the crystallization age. However exhumation ages from both margins of the Capps basin overlap with transtension and basin deposition from ~50-40 Ma.

Schematic diagram of transtensional basin development at the NW periphery of the Cook Inlet forearc basin


W
E
latest Paleocene - middle Eocene transtensional basin formation
58-57 Ma transtensional dikes
58-57 Ma Capps granite (Tg)
Extension direction = 191-215˚
CAPPS GLACIER FAULT
48-39 Ma syn-tectonic basin fill
CASTLE MOUNTAIN FAULT
latest Paleocene - middle Eocene transtensional basin formation
post-Oligocene basin inversion
NE
SW
CGF
CMF
M-BRFS

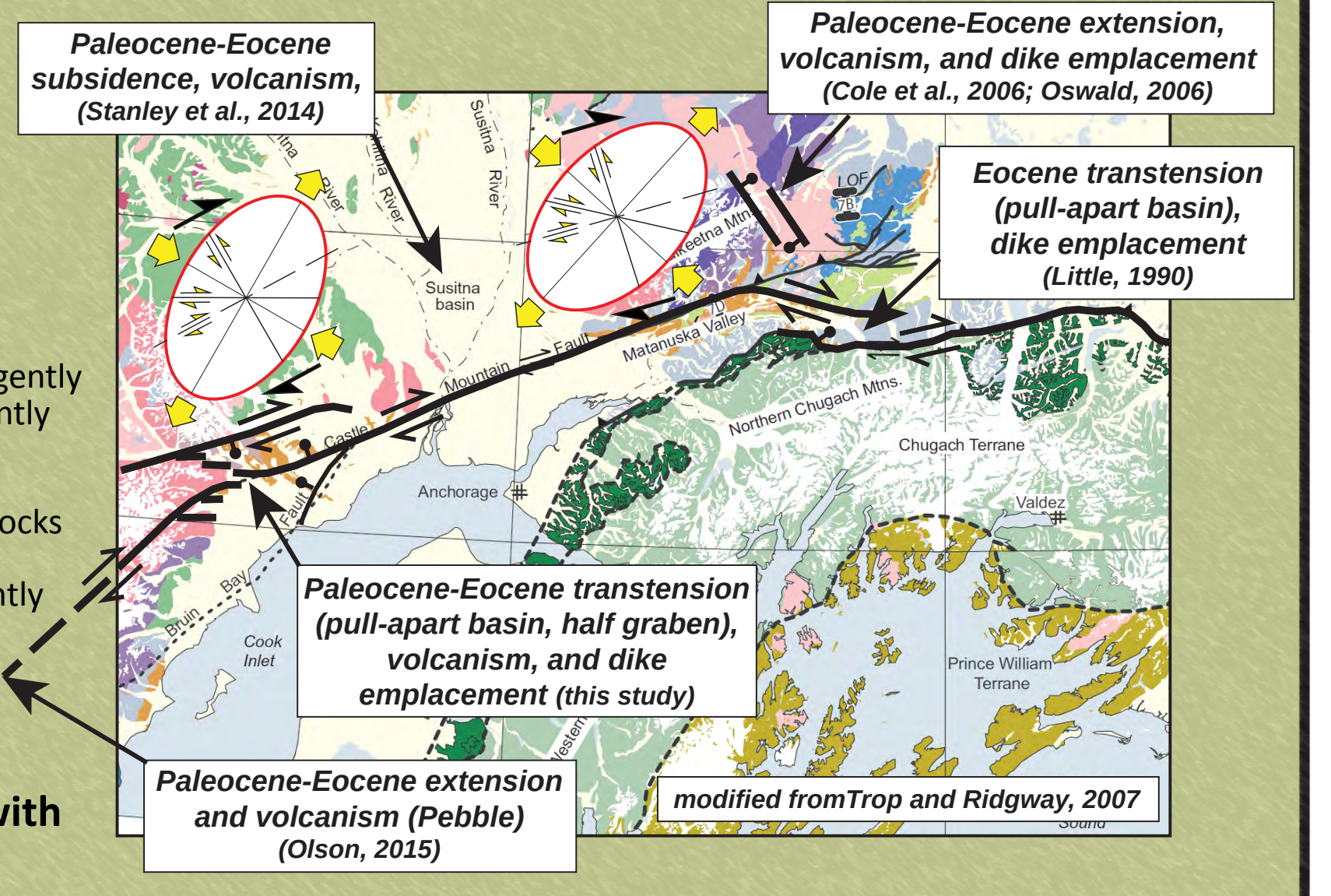

Capps Glacier
CAPPS GLACIER FAULT
Qvu
Tg
Qvc
K?v
Ku
Ku?
Qu
Th
Twfu
Twfm
Twfl
Twf
Tt
Tb
Ts
Kgd
TKgd
A
A'
B
B'
C
C'
Upper Chaka #67-34
TD = Twf @ 1,000 ft. MD
Lower Chaka #62-02
TD = Twf @ 822 ft. MD
Spurr West #26-11
Twf @ 638-3,812 ft. TVD
(>3,173 ft. thk.)
CASTLE MOUNTAIN FAULT
Lone Ridge
BELUGA RAPIDS FAULT
MEANDER FAULT
FAULT SYSTEM
Chuit fault (Flores et al., 1995)
from Flores et al. 1995
CHAKACHATNA TRANSFER ZONE
Chakachatna River
Chuitna River
Beluga River
LAKE CLARK FAULT
McArthur River
Blockade Glacier
MOQUAWKIE
BELUGA RIVER
Chuitna River State #1
Twf + Tc @ 5,800->10,717 ft. MD
(>4,917 ft. thk.)
Chuit State #1
Twf + Tc @ 10,502->12,500 ft. MD
(>1,998 ft. thk.)
Stedatna Creek #1
Twf + Tc @ 4,695-7,130 ft. MD
overlying J granite
(≤2435 ft. thk.)
Cottonwood State #1
Twf @ 3,811-4,192 ft. MD
overlying J granite
(≤381 ft. thk.)
West Tyonek #1
Twf @ 5,943->6,645 ft. MD
(>702 ft. thk.)
West Tyonek #1
Twf @ 8,747->8,841 ft. MD
(>94 ft. thk.)
Range of permissible Tb/Ts contact locations in near subsurface beneath Quaternary erosional unconformity
Nicolai Creek
Moquawkie
Lone Creek
Cook Inlet


Gently SW-tilted coal-bearing Tyonek Fm strata unconformably overlying SW-tilted Hemlock Fm. strata
SW
NE
coal
Tt
Th
person
Gently S-tilted coal-bearing Tyonek Fm strata unconformably overlying moderately N-tilted West Forland Fm. conglomerate
SW
NE
Tt?
Tt
Tt
Th
Th
Twf
SW
Tt
coal
Twf

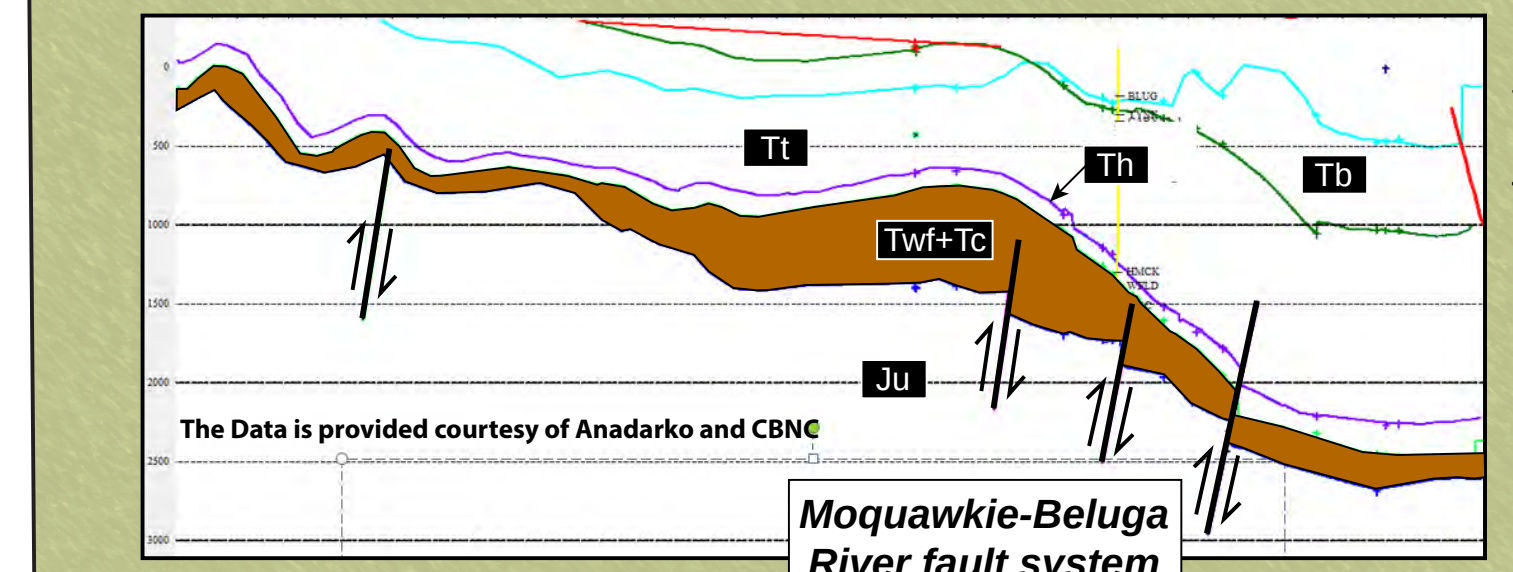
Potential record of structural inversion at Beluga rapids

Moderately N-dipping West Foreland Formation is in fault contact with gently SW-dipping Hemlock Fm. strata. Both are unconformably overlain by gently tilted, thick Tyonek Fm. coals that occur at similar elevations. The coal locations are separated by a fault-bounded, elevated wedge of Hemlock Fm. strata that requires the fault separating it from West Foreland Fm. rocks to have had opposing senses of slip. The structures are tentatively interpreted to have initially accommodated normal slip, and were subsequently reversely inverted after early-middle Miocene Tyonek deposition.

Mechanical-kinematic model for regional Paleocene-Eocene extensional forearc depocenters

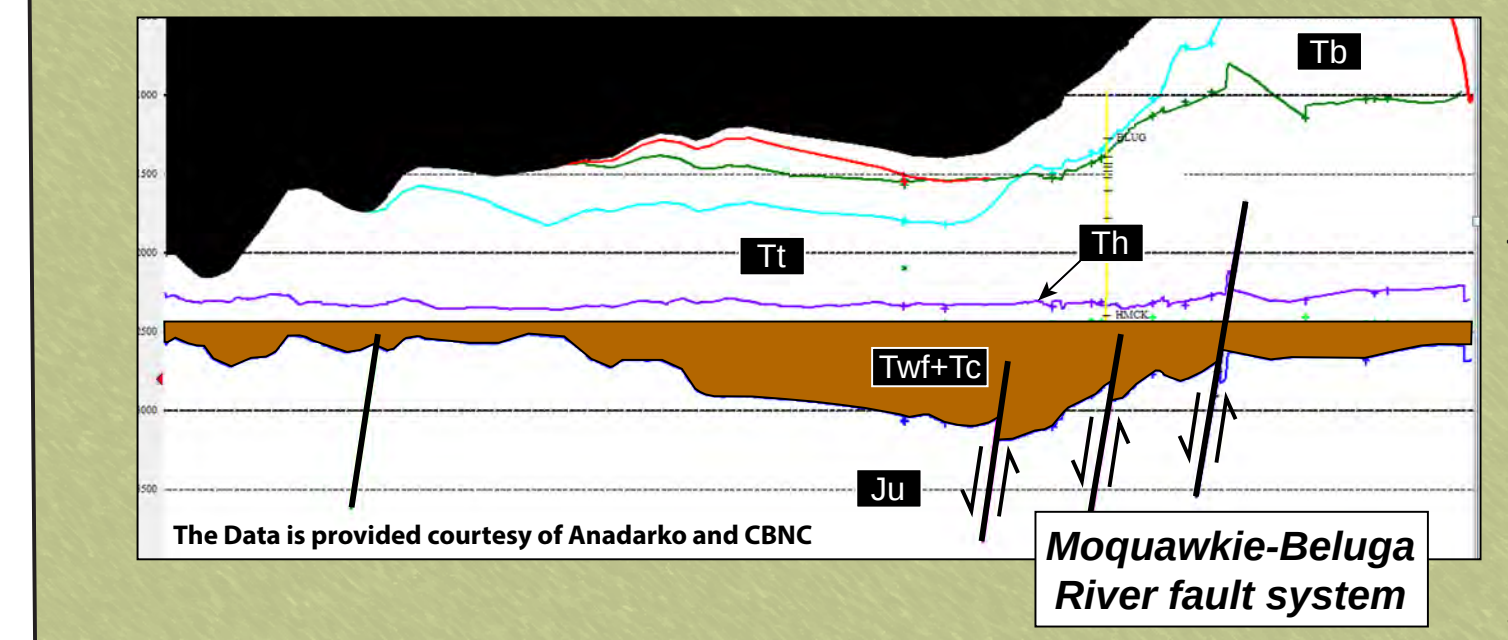

Paleocene-Eocene subsidence, volcanism, (Stanley et al., 2014)
Paleocene-Eocene extension, volcanism, and dike emplacement (Cole et al., 2006; Oswald, 2006)
Eocene transtension (pull-apart basin), dike emplacement (Little, 1990)
Susitna basin
Anchorage
Cook Inlet
Chugach Terrane
Valdez
Prince William Terrane
Northern Chugach Mtns.
Paleocene-Eocene transtension (pull-apart basin, half graben), volcanism, and dike emplacement (this study)
Paleocene-Eocene extension and volcanism (Pebble) (Olson, 2015)
modified fromTrop and Ridgway, 2007

Preliminary seismic interpretation of post-Oligocene inversion of Paleocene-Eocene extensional structures in the SE region of the map


Tt
Th
Tb
Twf+Tc
Ju
The Data is provided courtesy of Anadarko and CBNC
Moquawkie-Beluga River fault system

Data showing present geometry (with vertical exaggeration)

The thick sedimentary wedge positioned in the proximal hangingwall of the Moquawkie-Beluga River fault system suggests structural inversion of a local Paleocene-Eocene depocenter. The relatively uniform thickness of the overlying Hemlock Fm. based on well control suggests that inversion took place after principally Oligocene deposition of the unit.


Tb
Tt
Th
Twf+Tc
Ju
The Data is provided courtesy of Anadarko and CBNC
Moquawkie-Beluga River fault system

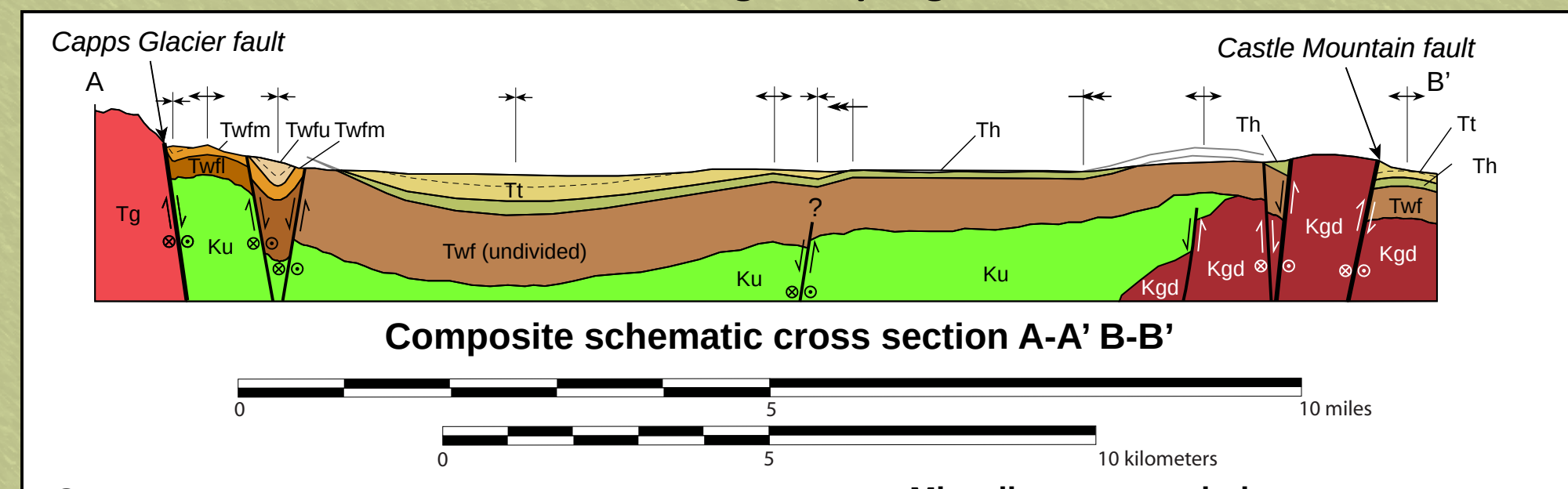
Data flattened on the top of the West Foreland Fm. (middle Eocene configuration)

Thickening of West Foreland Fm. and un-named Paleocene strata (Tc) toward the Moquawkie-Beluga River fault system suggests deposition in a SE-tilting half graben during Paleocene through middle Eocene times. The timing and structural style is consistent Middle Eocene basin development NW of the Castle Mountain fault, and suggests that trantension and extension were not restricted to the Capps pull-apart basin.

SUMMARY

The northwestern periphery of the Cook Inlet forearc basin has experienced a hitherto poorly documented episode of transtension (see Hackett, 1976) that controlled deposition in the area from as early as late Paleocene time to before Oligocene time. Many of the extensional structures were inverted as reverse faults after Oligocene time, and may core hydrocarbon-producing structures in the Cook Inlet basin. If so, then thickened packages of West Foreland Fm. strata in the hanging-walls of basement-involved faults might occur as under-recognized play types, given sufficient reservoir quality is present.

Geologic map legend and schematic cross section through the Capps pull-apart basin


Capps Glacier fault
Castle Mountain fault
A
B'
Twfm
Twfu
Twfm
Twfl
Tt
Th
Tt
Th
Tg
Ku
Twf (undivided)
Ku
Ku
Kgd
Kgd
Kgd
Twf
Kgd
Kgd
0
5
10 miles
0
5
10 kilometers

Composite schematic cross section A-A' B-B'

Lithologic units

	Ice/snow
Q	Quaternary (undivided)

Kenai Group strata (Cenozoic)

Outcrop	Inferred	
Ts	Ts	Sterling Fm.
Tb	Tb	Beluga Fm.
Tt	Tt	Tyonek Fm.
Th	Th	Hemlock Fm.
Twf		West Foreland Fm. (undivided)

Outcrop	Inferred	
Twfu	Twfu	upper sub-unit
Twfm	Twfm	middle sub-unit
Twfl	Twfl	lower sub-unit

Pre-Tertiary economic basement

Outcrop	Inferred	
Ku	Ku	Cretaceous undivided

Igneous rocks

Qvc	Quaternary volcanoclastic
Qvu	Quaternary volcanic (undivided)
Tg	Tertiary granite

Outcrop	Inferred	
TKgd	TKgd	Tertiary-Cretaceous granodiorite
Kgd	Kgd	Tertiary-Cretaceous granodiorite

Folds axes

- Syncline with plunge direction
- Anticline with plunge direction
- Fold w/ double arrows on steeper limb

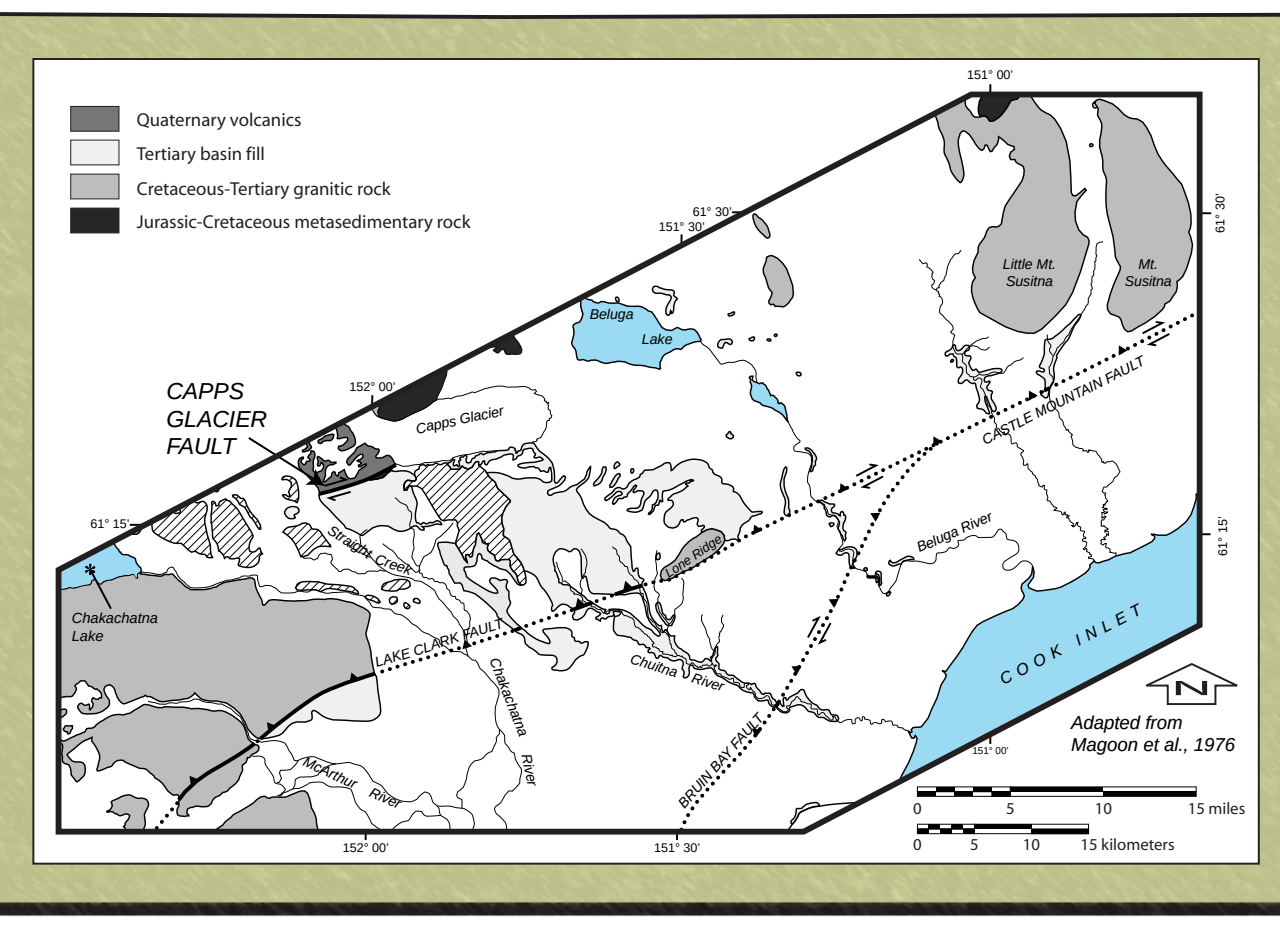
Contacts - symbols shown in red interpreted from seismic and aeromagnetic data (dashed where inferred, dotted where concealed, querried where uncertain)

- Stratigraphic/igneous contact
- Normal or normal-oblique-slip fault (unfilled = subsequent inversion)
- Reverse or reverse oblique-slip fault (unfilled = subsequent inversion)

Miscellaneous symbols

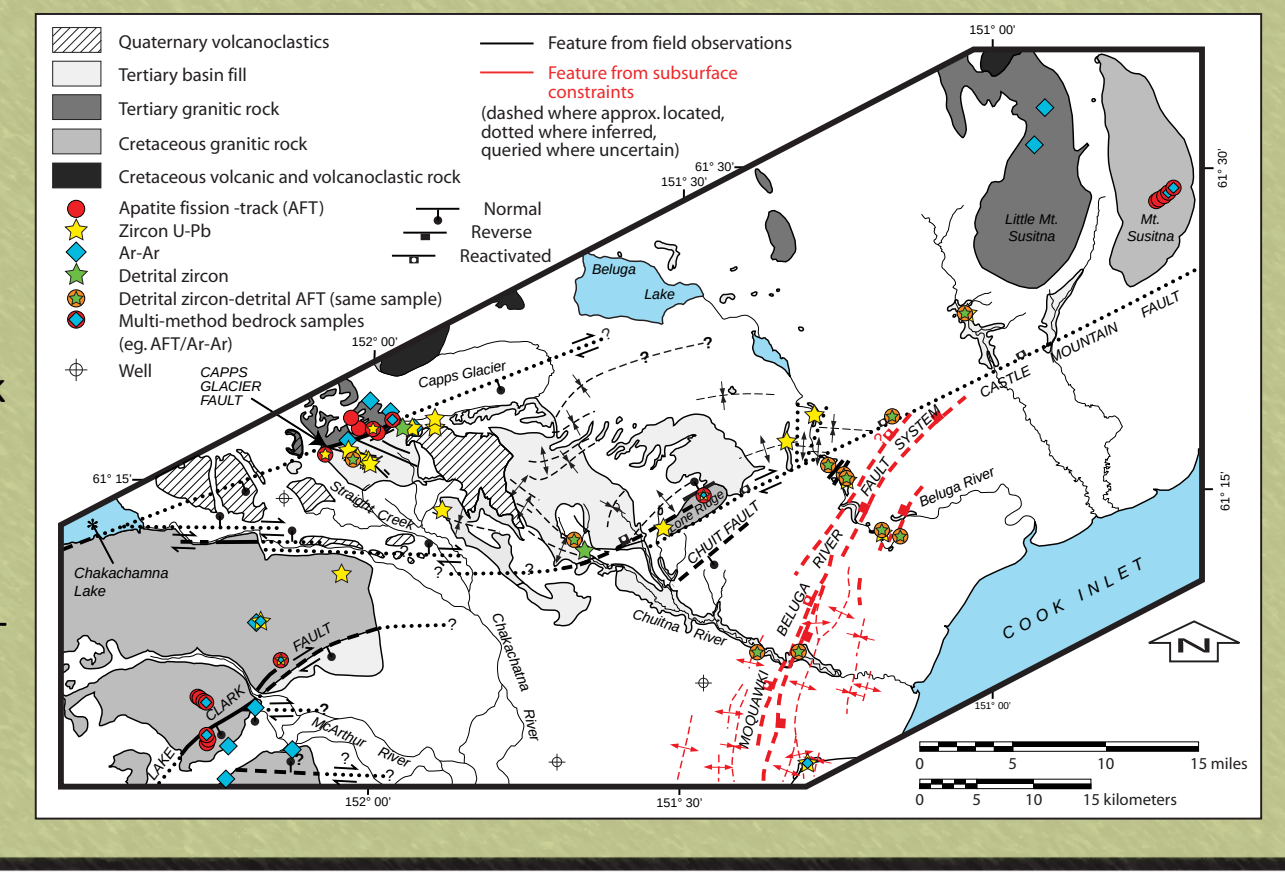
- ▭ Petroleum unit boundary
- ⌖ Well location
- ★ Zircon U-Pb
- ■ 40Ar/39Ar
- ▲ Apatite fission-track
- ● Palynology
- ○ Measured section (base)
- Seismic line (MQ-04 pubically-available data)

Comparison of former and new geologic map interpretations


Quaternary volcanics
Tertiary basin fill
Cretaceous-Tertiary granitic rock
Jurassic-Cretaceous metasedimentary rock
CAPPS GLACIER FAULT
Beluga Lake
Little Mt. Susitna
Mt. Susitna
CASTLE MOUNTAIN FAULT
Chakachamna Lake
LAKE CLARK FAULT
Beluga River
Chuitna River
BRUIN BAY FAULT
COOK INLET
N
Adapted from Magoon et al., 1976
0 5 10 15 miles
0 5 10 15 kilometers

(left) Previous workers have interpreted all of the geologic structures on the west side of upper Cook Inlet as transpressional, with the Lake Clark and Castle Mountain faults as linked.

(right) An alternate interpretation from mapping presented here is that the margin has an important transtensional component, with the Capps Glacier and Castle Mountain faults as the principal linked structures.


Quaternary volcaniclastics
Tertiary basin fill
Tertiary granitic rock
Cretaceous granitic rock
Cretaceous volcanic and volcaniclastic rock
Feature from field observations
Feature from subsurface constraints
(dashed where approx.located, dotted where inferred, queried where uncertain)
Normal
Reverse
Reactivated
Apatite fission -track (AFT)
Zircon U-Pb
Ar-Ar
Detrital zircon
Detrital zircon-detrital AFT (same sample)
Multi-method bedrock samples (eg. AFT/Ar-Ar)
Well
CAPPS GLACIER FAULT
Beluga Lake
Little Mt. Susitna
Mt. Susitna
CASTLE MOUNTAIN FAULT
Chakachamna Lake
LAKE CLARK FAULT
CHUIT FAULT
BELUGA RIVER
Chuitna River
Beluga River
COOK INLET
0 5 10 15 miles
0 5 10 15 kilometers

Acknowlegements

Funding for this project was provided by The U.S. Geological Survey's STATEMAP Program (2009 & 2010), and by the State of Alaska. Cook Inlet Regional Corporation, Inc., Tyonek Native Corporation, Pathfinder Aviation, Anadarko and CBNC are thanked for land access, logistical support, and valuable data.