Contrasting Extensional Basin Styles and Sedimentary Fill across the Eastern Russian Arctic Shelf as Imaged in Crustal-Scale PSDM Reflection Data*

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Abstract

The Siberian Arctic Shelf is one of the broadest continental shelves on Earth containing the Laptev, East Siberian, and Chukchi Seas across an area of 3×106 km^2. More than 13,000-line km of reflection data in the Laptev, East Siberian, and Chukchi Seas form the basis for the interpretation east of the New Siberian Islands covering the North Chukchi-Vilkitski and New Siberian Sea Rift basins. The basement offshore (acoustic basement) is interpreted as an extension of onshore geology, which is dominated by Phanerozoic fold belts and their associated volcanic and plutonic complexes, and suture assemblages. These surveys and potential field data image a number of Late Mesozoic and Cenozoic basins with at least 7.5 to 10 km of sedimentary fill. In the North Chukchi Basin as much as 20 km of sedimentary fill lie above acoustic basement. The entire shelf is overlain by a post-rift prograding succession. These basins have contrasting structural styles, even though they are connected and collectively relate to the opening of the Arctic Ocean. In the west, the East Siberian Sea Rift is comprised of arrays of tilted fault blocks rooting in a mid-crustal detachment system, underlain by a master fault at or near Moho level. It covers an area equivalent in size to the entire North Sea. In contrast, the North Chukchi Basin is a deep, gently structured basin detached at Moho level and floored by oceanic crust, or possibly by serpentinized mantle. These basins exhibit contrasting styles of stratigraphic fill, related to the tectonics underlying their creation. For example, late-stage (post-rift) architecture in the North Chukchi Basin shows Tertiary shelf-margin progradation traversing over 400 km northward over vertically accreting, Late Cretaceous high-accommodation aggradational sedimentation. In contrast, the East Siberian Sea Rift exhibits more conventional rift basin architecture, with tilted fault blocks bounded by deep troughs and potential large hydrocarbon fetch areas, similar to the North Sea. These basins contain the potential for reservoir development in shelf margin, lowstand systems, sub-unconformity regional stratigraphic traps, and within horst-graben systems typical of Neogene rifts. A mega-regional total sediment (above acoustic basement) isopach map over the large area illustrates that several other large gravity lows are present and suggests substantial potential for additional prospective basins.

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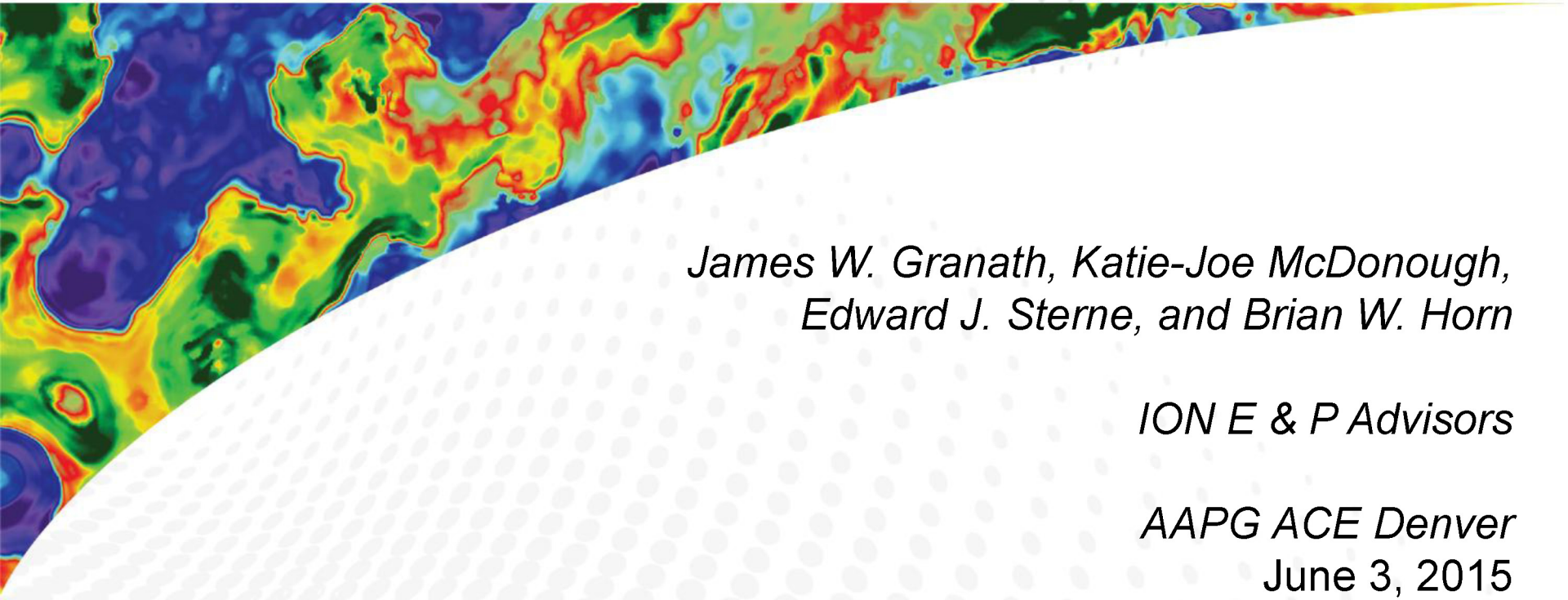
Contrasting Extensional Basin Styles and Sedimentary Fill across the Eastern Russian Arctic Shelf as Imaged in Crustal-Scale PSDM Reflection Data



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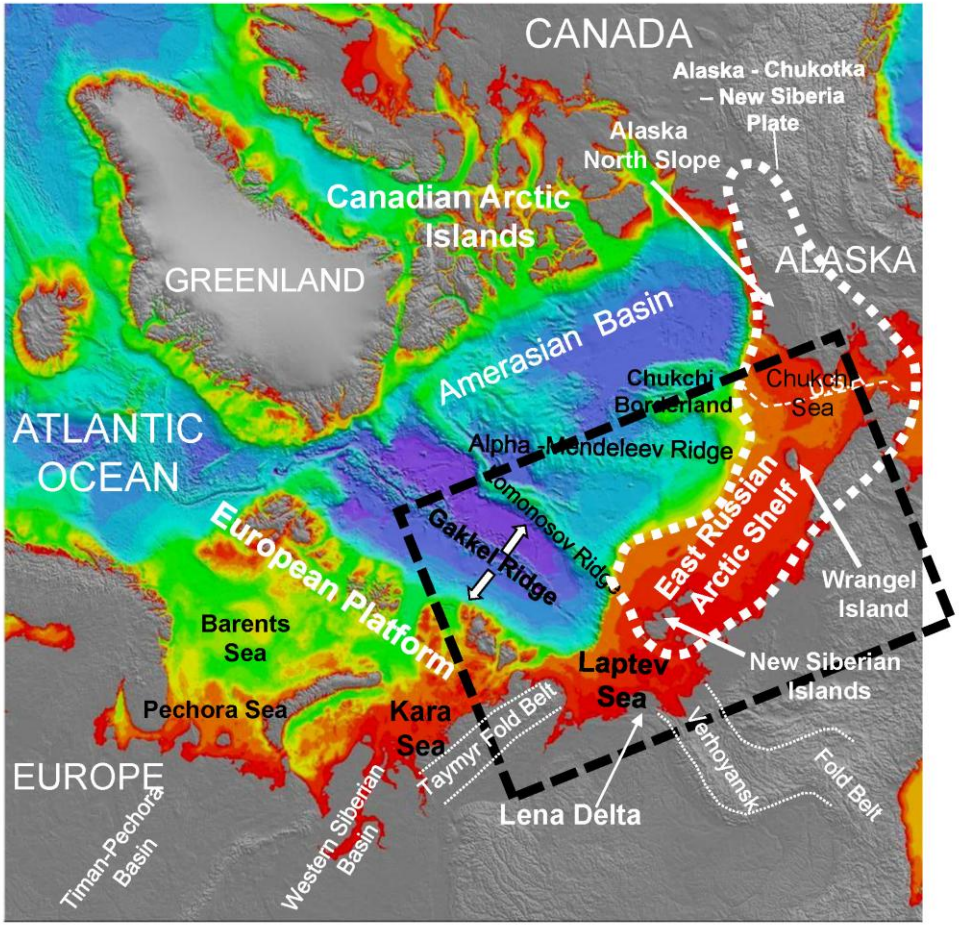
ION E & P Advisors

AAPG ACE Denver
June 3, 2015

Arctic Regional Tectonic Domains



Presenter's notes: In 2011 and 2012 ION acquired some 13000 line-km of 2D data with 18 sec TWT records and has processed them to PSTM and PSDM lines with 16 sec and 40 km depths respectively, as is more or less customary of SPAN datasets. The data represent one if not the most comprehensive data set on the Eurasian Arctic shelf (Presenter's notes continued on next slide)

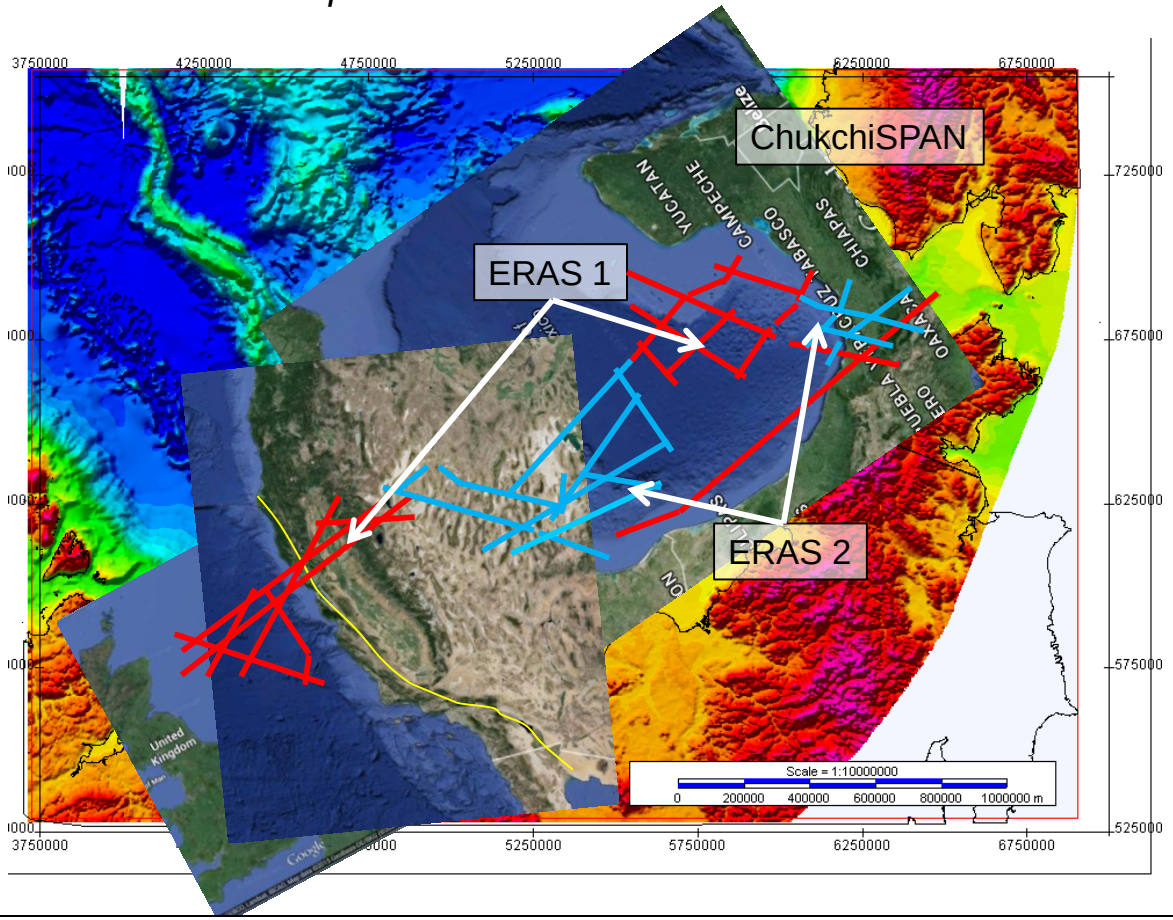
(Presenter's notes continued from previous slide)

spanning the distance from the Laptev Sea to the US boundary, a distance of about 2500 km. In 2013 an additional set of lines was acquired in the Wrangel Island area, in the eastern part of the area blocked out here. Those data are currently in time interpretation and depth processing in ION's London office. Early results have been factored into this report. This is a polar projection of bathymetry/topography of the Arctic showing the major features with the area we discuss outlined in the box. All of Russia's Arctic production is in the European platform here; so the area covered by the SPAN is entirely frontier, and in fact undrilled anywhere in the survey area..

Elsewhere at this meeting we presented a revision of the plate tectonic development of the Arctic since the middle Mesozoic, the gist of which will be shown later in this presentation. The focus here is to characterize the major tectonic elements of the area that contributed to the science behind that other presentation and to provide you with what we think is the petroleum potential of the region.

Eastern Russian Arctic Shelf (ERAS) Program

US Chukchi Sea to Laptev Sea – 4-6x North Sea



Presenter's notes: First a sense of scale: This is a gravity map of the area in the region of the black box with the 2 ERAS surveys highlighted. The basic components of the Russian Arctic are comparable to other more familiar petroleum provinces of comparable tectonic function: (Presenter's notes continued on next slide)

(Presenter’s notes continued from previous slide)

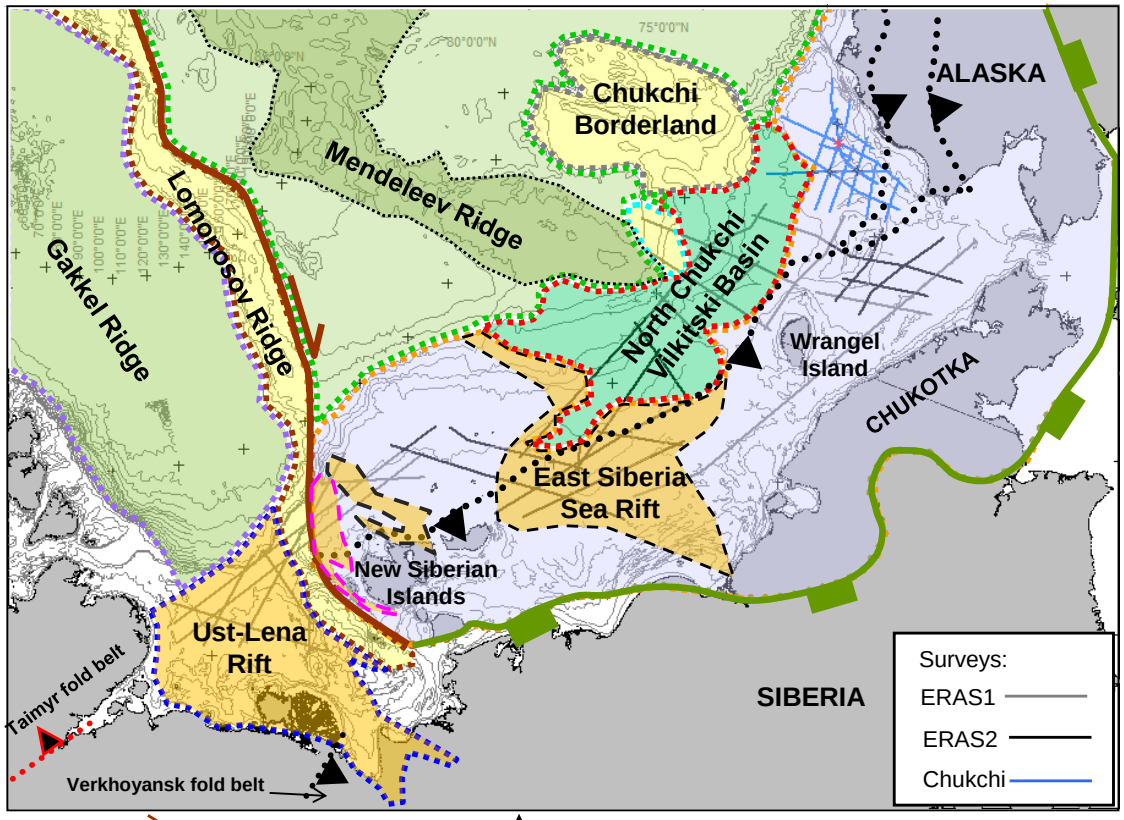
- The Laptev Sea is a rift system comparable in size to the North Sea,
- everything east of the new Siberian Islands compares in size to the entire western GOM rotated to superimpose the Yucatan on the Chukchi borderland (both rotated away from their respective mainlands), and
- the Lomonosov transform separates the earlier opening of the Amerasian Basin from the younger Gakkel Ridge system, compared to the size of the more familiar San Andreas transform.

Outline

- Introduction
- Tectonic Setting (incl “new” basin identification)
  - Put in context of Arctic plate motion history
- Geological control & Workflow
- Compare and contrast the structural style of the major basins
- Petroleum Potential
  - New plays and areas of interest
- Summary

East Russian Arctic Shelf Basins

Crustal domains



Presenter's notes: The gist of the plate tectonic history is that the Eurasian shelf , much of its onshore extent, along with Arctic Alaska and Chukotka (all shown in gray to the right of the Lomonosov transform), has rotated into their current position across the Amerasia Basin from the Canadian side, and has been sutured to central Asia at about the (Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

green line—which incidentally continues into Alaska in the Books Range orogeny. In doing so, it as a collisional fold and thrust belt overrode the Chukotka-Alaska terrane and eventually extended outward to the dotted black line by Late Cretaceous and Paleogene time. That fold belt overrode in part a number of features that developed in the continental crust. The Ch-Ak terrane fragmented during its transit across the Arctic and left oceanic terranes in their wake, shown here in green shades.

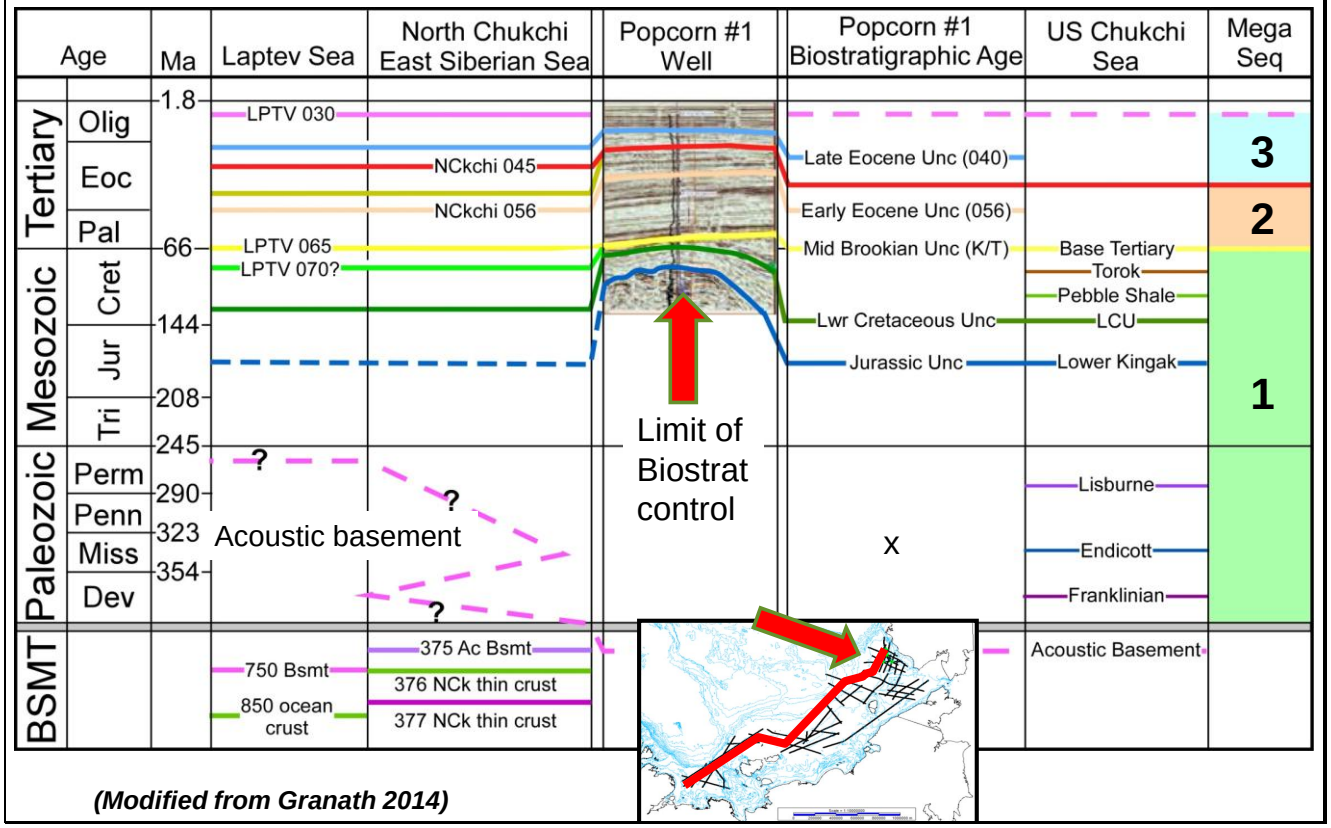
Important elements of that process represented in this map are:

- The Chukchi Borderland in yellow that rotated away from the main terrane leaving the North Chukchi Basin (aka the Vilkitskii Basin) in its wake. ERAS indicates this is floored by oceanic crust or exposed mantle and therefore shown here in a green shade).
- New ESSR, a basin for which we have not found an appropriate Russian name, in orange.
- Some continental elements (ref. Russian literature) of the Mendeleev Ridge that are swamped in basaltic rocks (in dark green),
- Some extensional features in the area of the NSI, e.g., the Anisin Basin. All followed by the oceanic crust of the greater Amerasia Basin (including the Canada Basin off the edge of this map).

In the west, the opening of the Eurasian Basin followed, e. g., the Amerasian, and is represented by spreading at the Gakkel Ridge, which penetrated Asia in the Laptev Sea—the Ust-Lena Rifts, and connects to the current rotational pole just off the map.

Regional Stratigraphic Correlation

Identification of mappable horizons and mega-sequence boundaries



(Modified from Granath 2014)

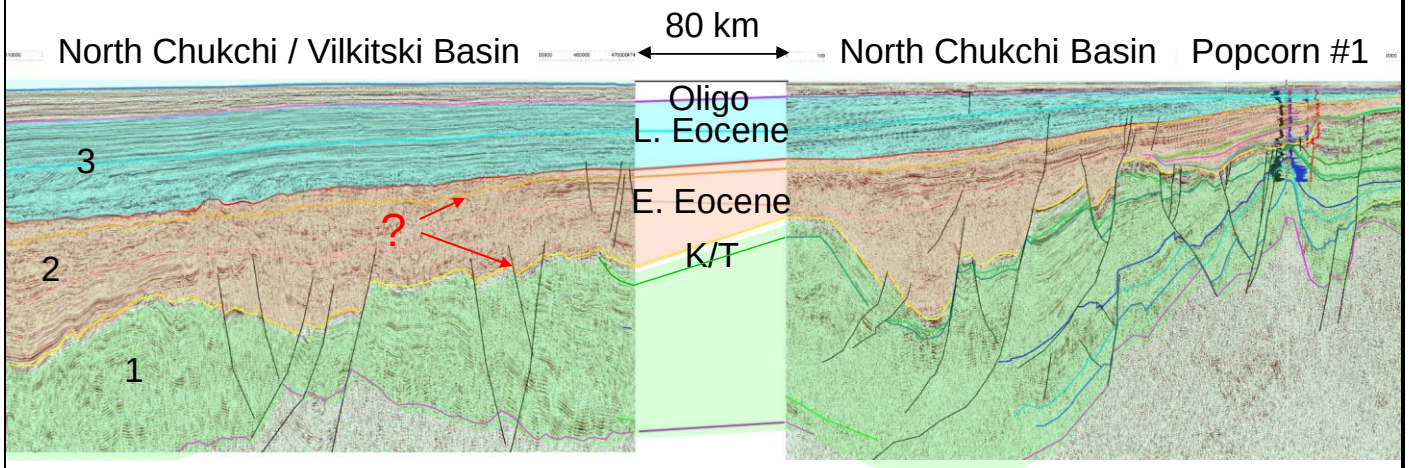
Presenter's notes: WE used 2 ties to "reality," a jump tie to the wells in the US Chukchi Sea that were drilled in the 70's and, particularly, the Popcorn well, where a previous SPAN survey and legacy seismic data are close to the tip of one of the ERAS lines. So the horizons you see here are the ones we used to span across the 2500 km to connect to (Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

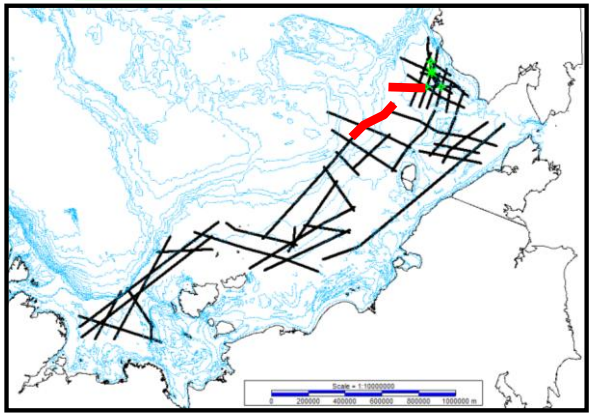
our other control, which was a jump tie from onshore in the New Siberian Islands. We could not "see into" what we called the "acoustic basement," which is the Paleozoic and lowermost Mesozoic of the the Ak_Ch terrane. Consequently, we could not connect some of the classic important units into the ERAS survey, but ERAS III is promising , at least in part, to remedy that situation. Correlation distance of 2500 km; acoustic basement – base of what is mappable across the region (imaging is difficult in many areas – acoustically transparent.

Regional Seismic Correlation

Eastern Russian Arctic Shelf to Chukchi Basin



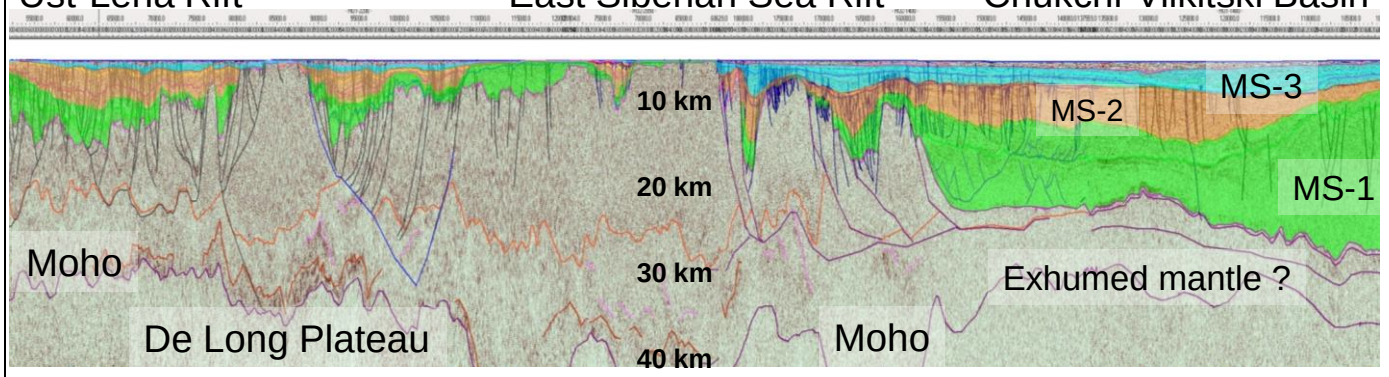
- All stratigraphic well control in Chukchi Basin
- Jump correlation between Chukchi and ERAS lines (being refined with ERAS III)
- Identification of 3 Mega-sequences
- Lower Cretaceous (Mesozoic) section correlation uncertain outside of the Chukchi basin

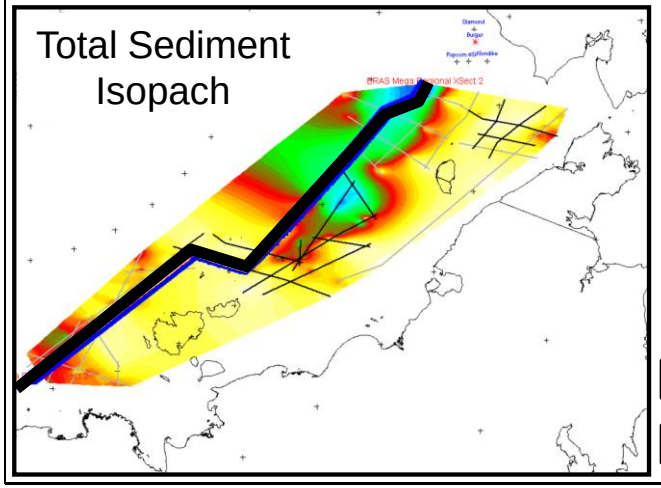


Presenter's notes: Correlation has resulted in recognition of three mega-sequences, or perhaps preferably super-mega-sequences, above the acoustic basement. Basically JK, Pg, and mid-Eocene upwards. Here is the tie across the international boundary.

Regional Correlation Eastern Russian Arctic Shelf

Alternate interpretation / correlation





- MS-1- Rift opening North Chukchi Basin
  - Early Cretaceous syn-rift fill
- MS-2 – Tectonic shift - late rift
  - SW sediment source
- MS-3 – Post rift fill
  - N-NE sediment source

10,000-15,000 m < 5,000 m

> 15,000 m 7,500-10,000 m

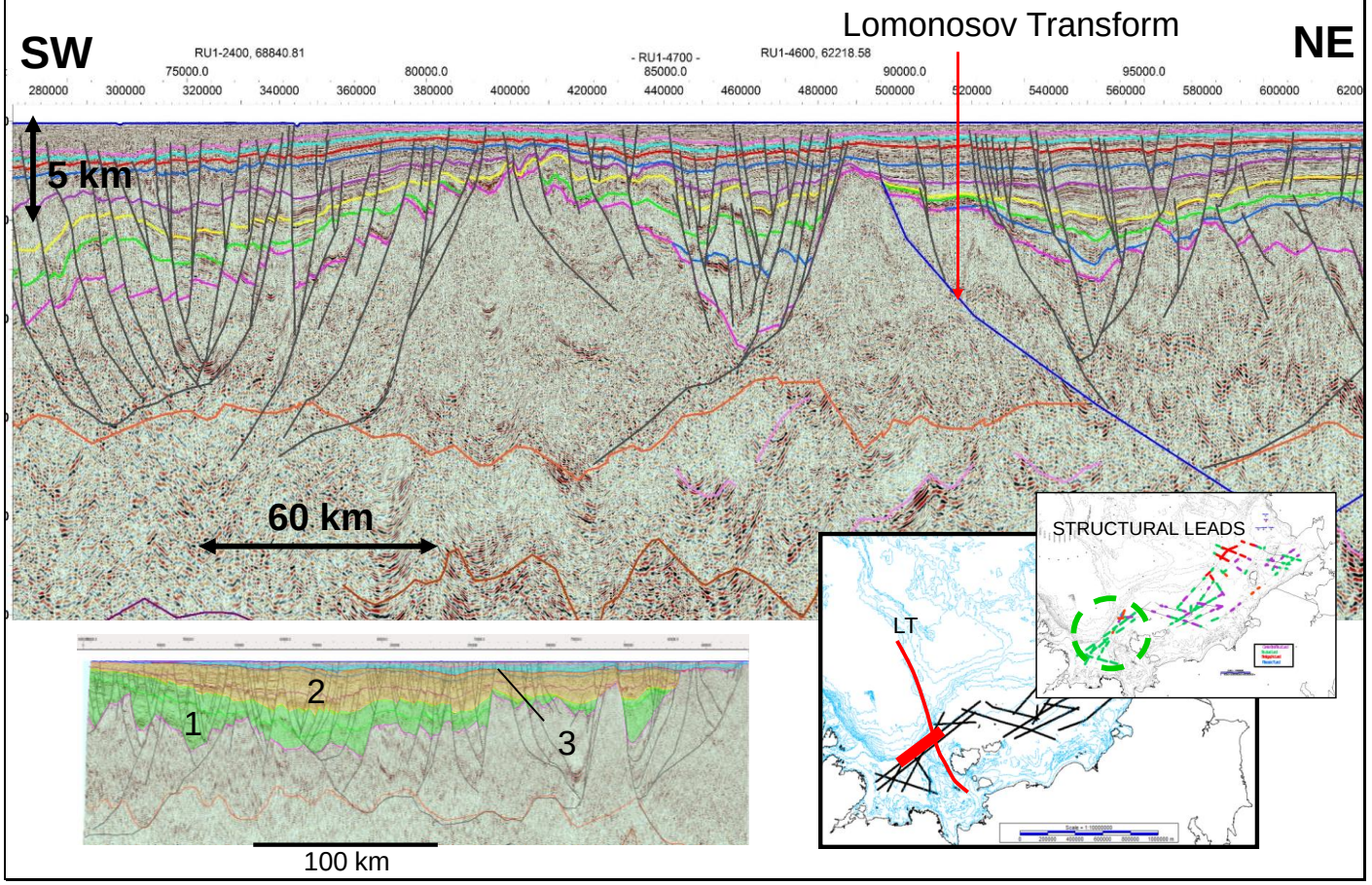
Presenter's notes: IN terms of how these look on the big scale: Here's a full ERAS depth of 40 km on a composite line all the way across the survey, showing 1, 2, and # with some of the crustal boundaries. Comment on Moho, etc. and the depth of the sections, the uniqueness of CV and why we think it is not floored by continental crust. Isopach in the inset map. Of total sediment fill on the three different large-scale features we will contrast in the next few slides. (Presenter's notes continued on next slide)

(Presenter’s notes continued from previous slide)

Mega-Regional Cross section connecting ERAS 1 and ERAS 2 surveys in an outboard position off the continental shelf. Line traverses the Laptev Sea (west) to the North Chukchi Sea (east) and images hydrocarbon prospective basins from the Ust-Lena and East Siberian Sea rifts in the west to the North Chukchi-Vilkitski basin in the east. Location map overlies total sediment isopach. Line is ~ 2100 km long, VE~9:1, SMT scale H ~ 16,500 m, V ~ 1800 m.

Laptev Sea / Ust-Lena Rift

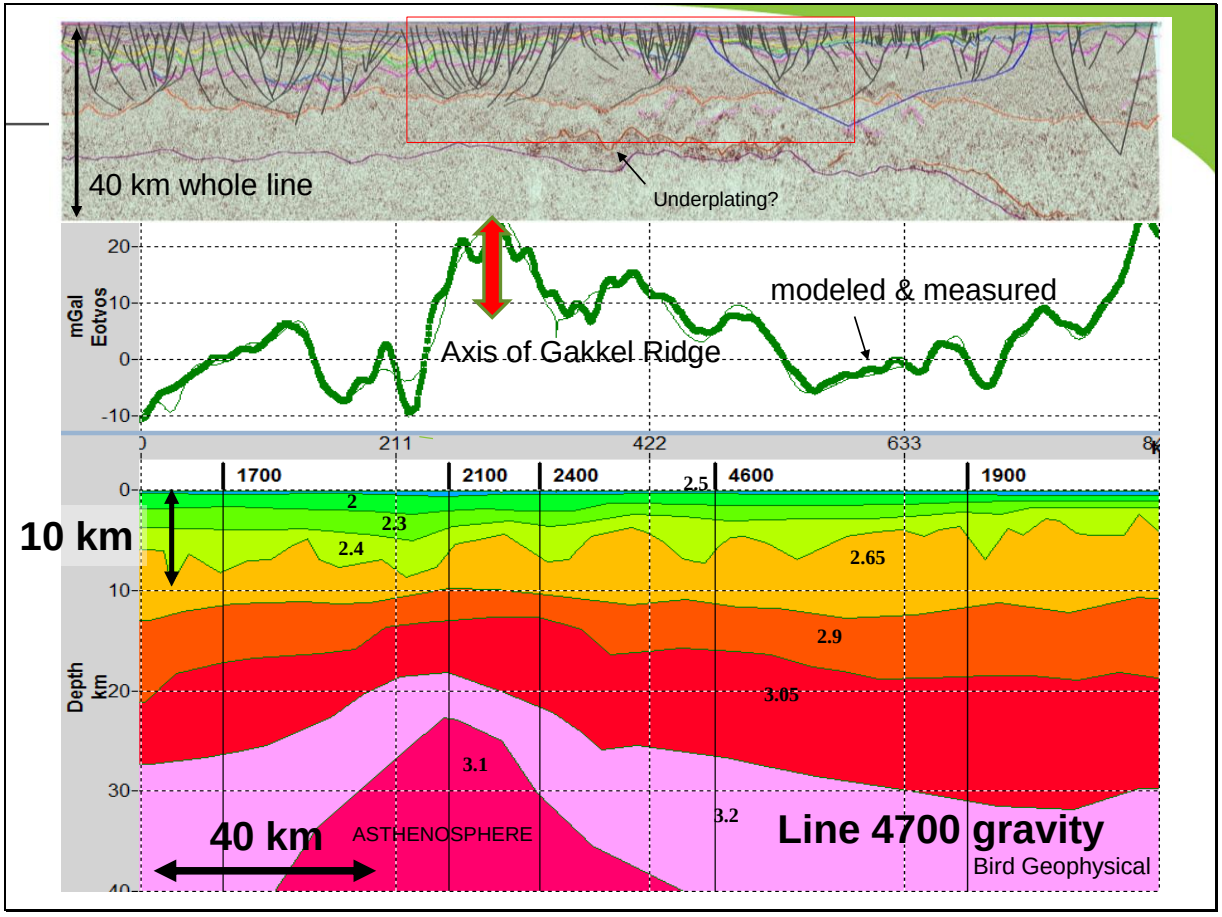
Young, active rift with lots of large fault block, subsidiary linked fault blocks



Presenter's notes: Starting in the west, is RU1-4700 across the mouth of the Laptev Sea, just inboard from the edge of the continental crust, itself a transform separating sea-floor spreading in the Eurasian Basin from the U-L rift. The inset below shows the 3 sequences, and the ms 3 is yet to be fully developed. This is effectively a long-lived (Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

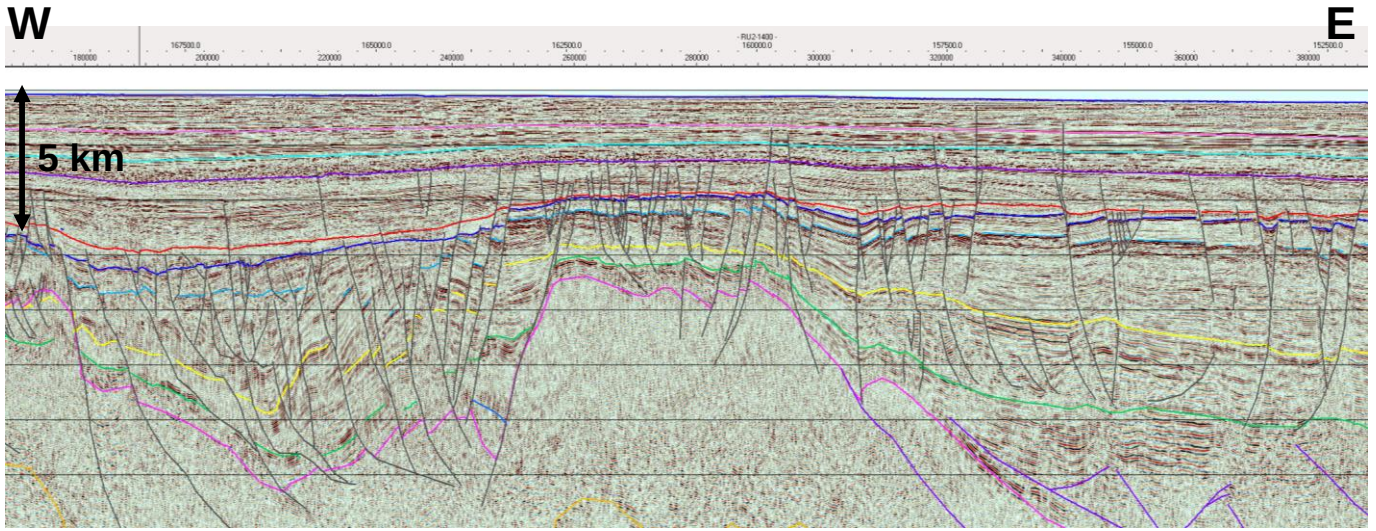
rift stretching back into the K, by not yet finished, with probably several stages of development but currently effectively the onshore equivalent of the Gakkel Ridge. Its architecture is a familiar rift, if not yet "adorned" with the post-rift steers' horns, and thus the prospectivity is dependent on assumptions of a source rock, reservoir rock, and the thermal history one might assume. Yet, the structures are present—numerous high blocks with rotated fault blocks and presumably all the block edges and corners for traps, and plenty of ramp relationships.



Presenter's notes: Just inboard from the previous line is Line 4700, shown in the upper inset as a full 40 km seismic line in a 2:1 exaggeration. Note the high reflectivity along the Moho and the step of Moho to 40 km depth on the east side as the Lomonosov transform –juxtaposing two very different crustal thicknesses, The rest of the slide is a gravity model by Bird Geophysical (gravity modeling is a standard part of processing the data, particularly in the crust and mantl)e. Ssome asthenosphere had to be included in the model to get a good match at precisely the position where the Gakkel Ridge impinges on the continental crust, an indication that may be the spreading center is propagating southward into the Ust-Lena crust.

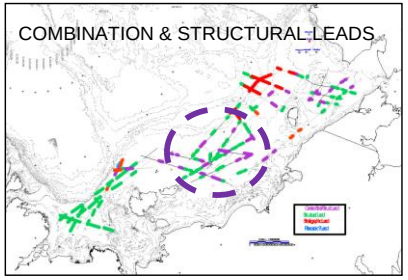
East Siberian Sea Rift

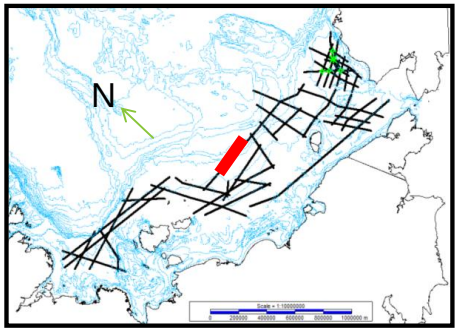
Similar in style to Ust-Lena but older, with post-rift section



- Basement block structures with intervening kitchens
- Field-size fault blocks with ramps to kitchens
- Complex strat harboring source/seal/res

40 km

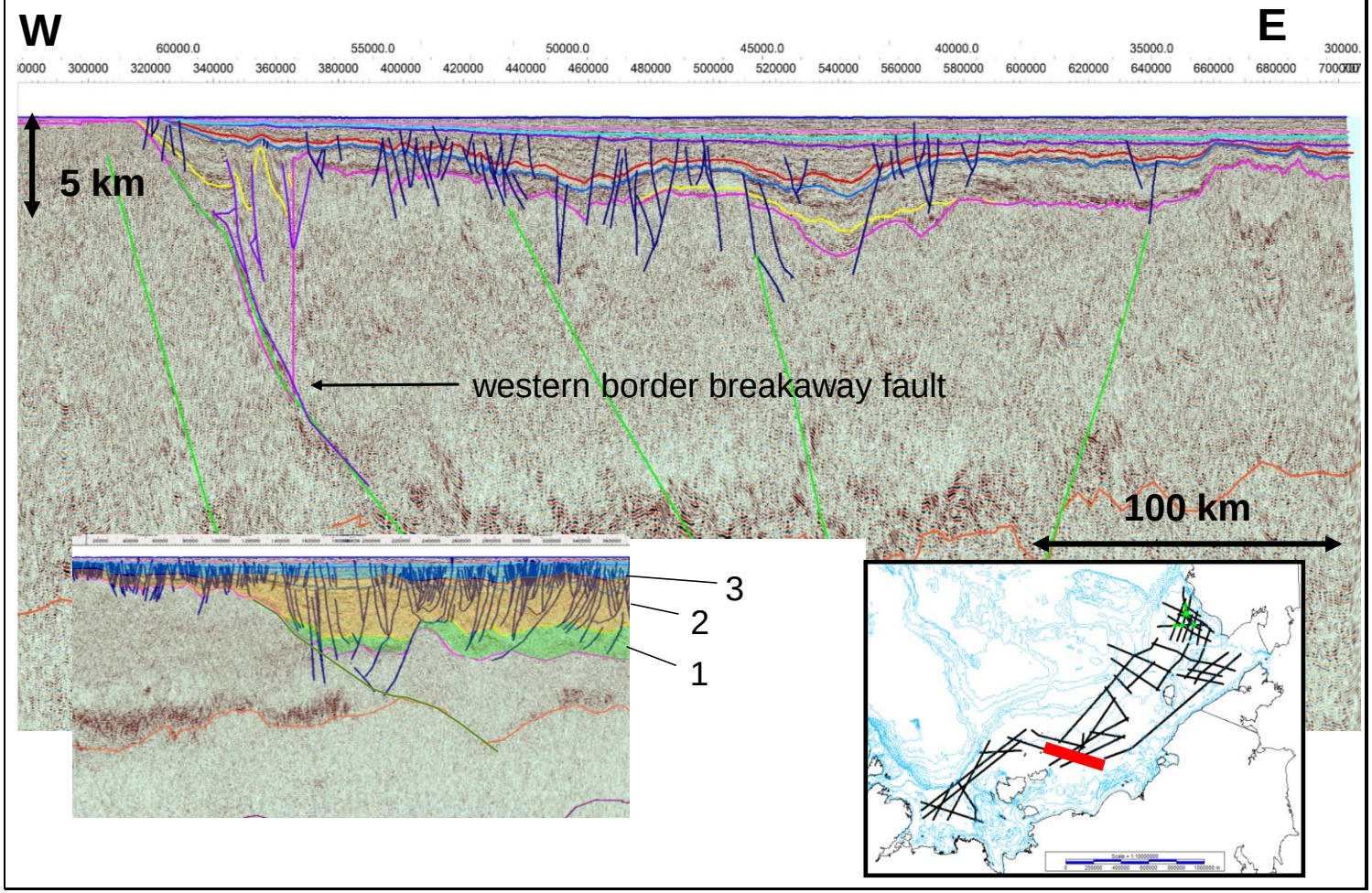




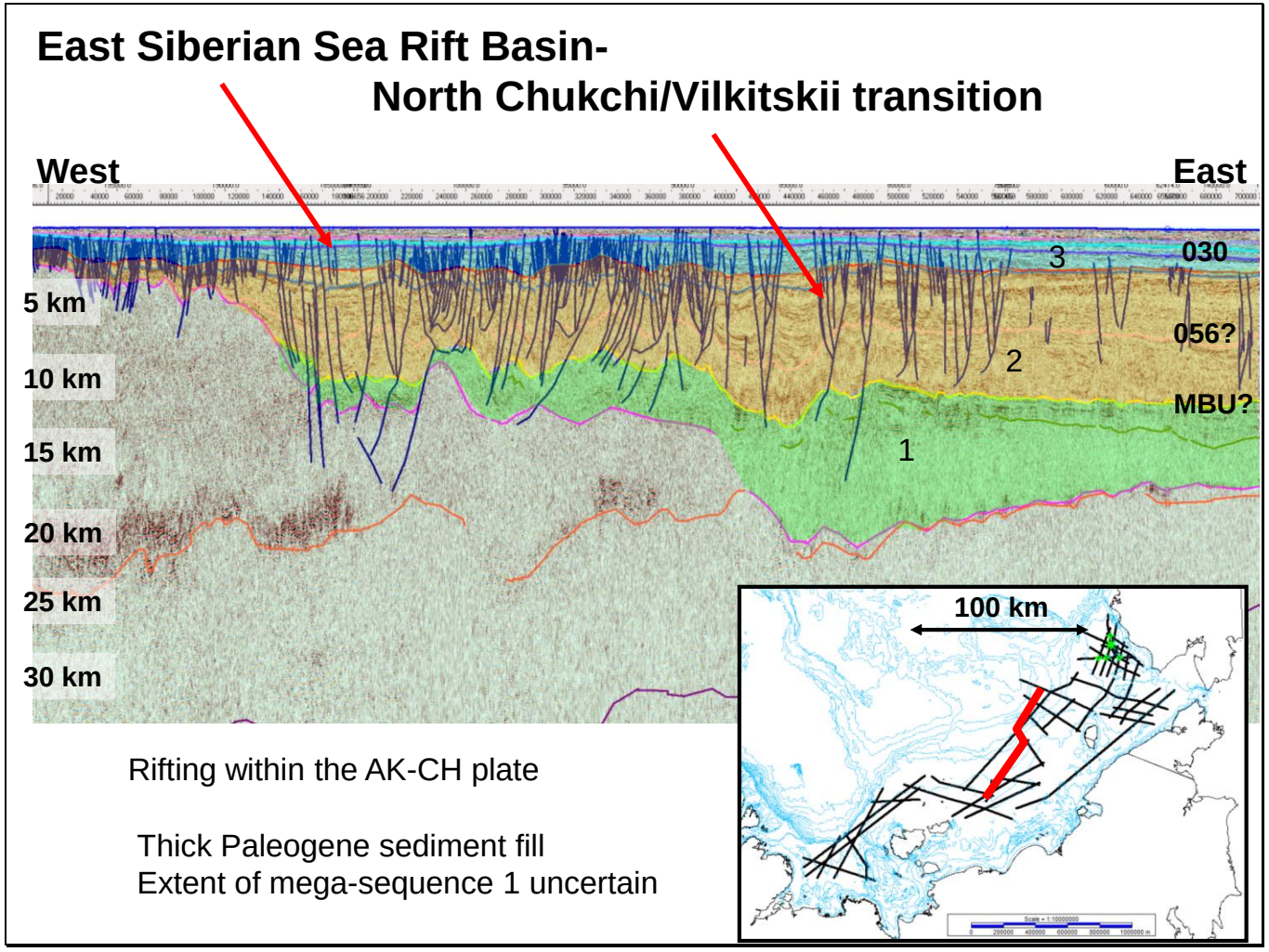
Presenter's notes: Moving east across the New Siberian Islands into the East Siberian Sea Rift, there is much the same structural style, with the block highly broken in rotated blocks with numerous ramps/ Here is the upper 15 km; therefore, rotations indicated that the basins are underlain by curved faults with the whole system lying above deeply penetrating planar faults that preserve the block highs.

East Siberian Sea Rift

On a larger scale



Presenter's notes: Another view of the ESSR, showing the basin-bounding fault (upper) with vertical exaggeration; lower image is a full 40-km section showing Moho and the fault architecture with MS 1-2-3 (RU2-2050).

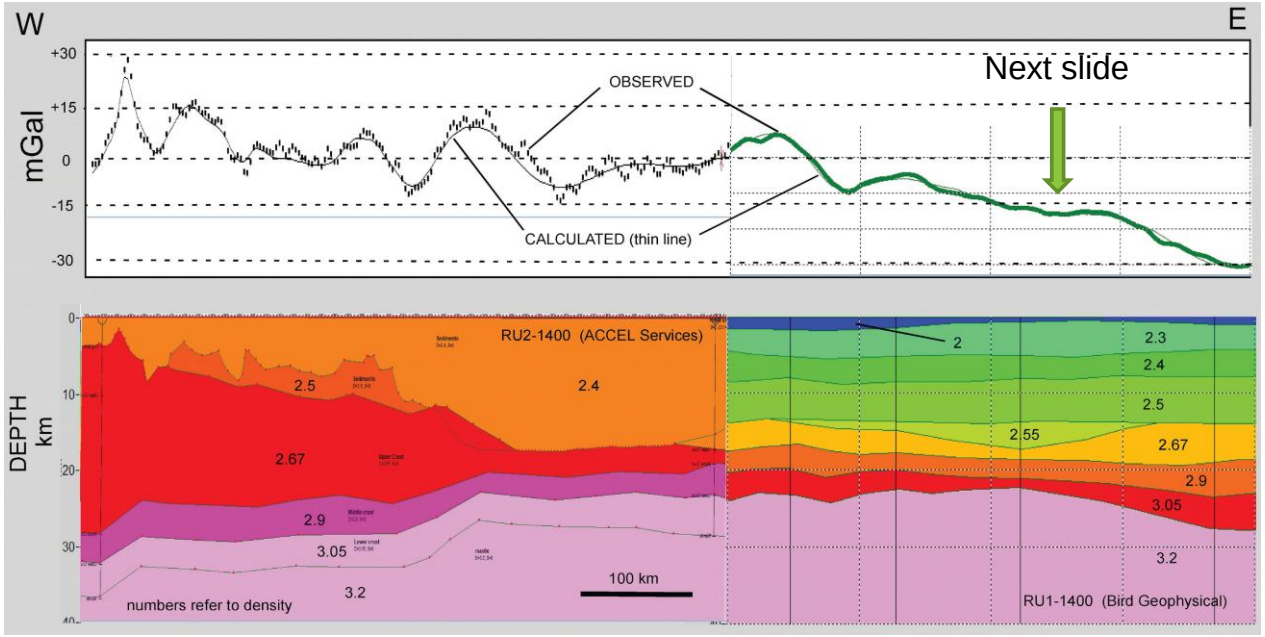


Presenter's notes: In a larger view, we can see ESSR has a good "steers-head" geometry—it is an older rift, effectively K and Pg in age in terms of opening, with an Eocene-Oligocene post-rift subsidence section above. It opens to the east into the North Chukchi-Vilkitskii, where the crust thins and the total section thickens to a mere 20 km of what we think is essentially the same-aged fill.

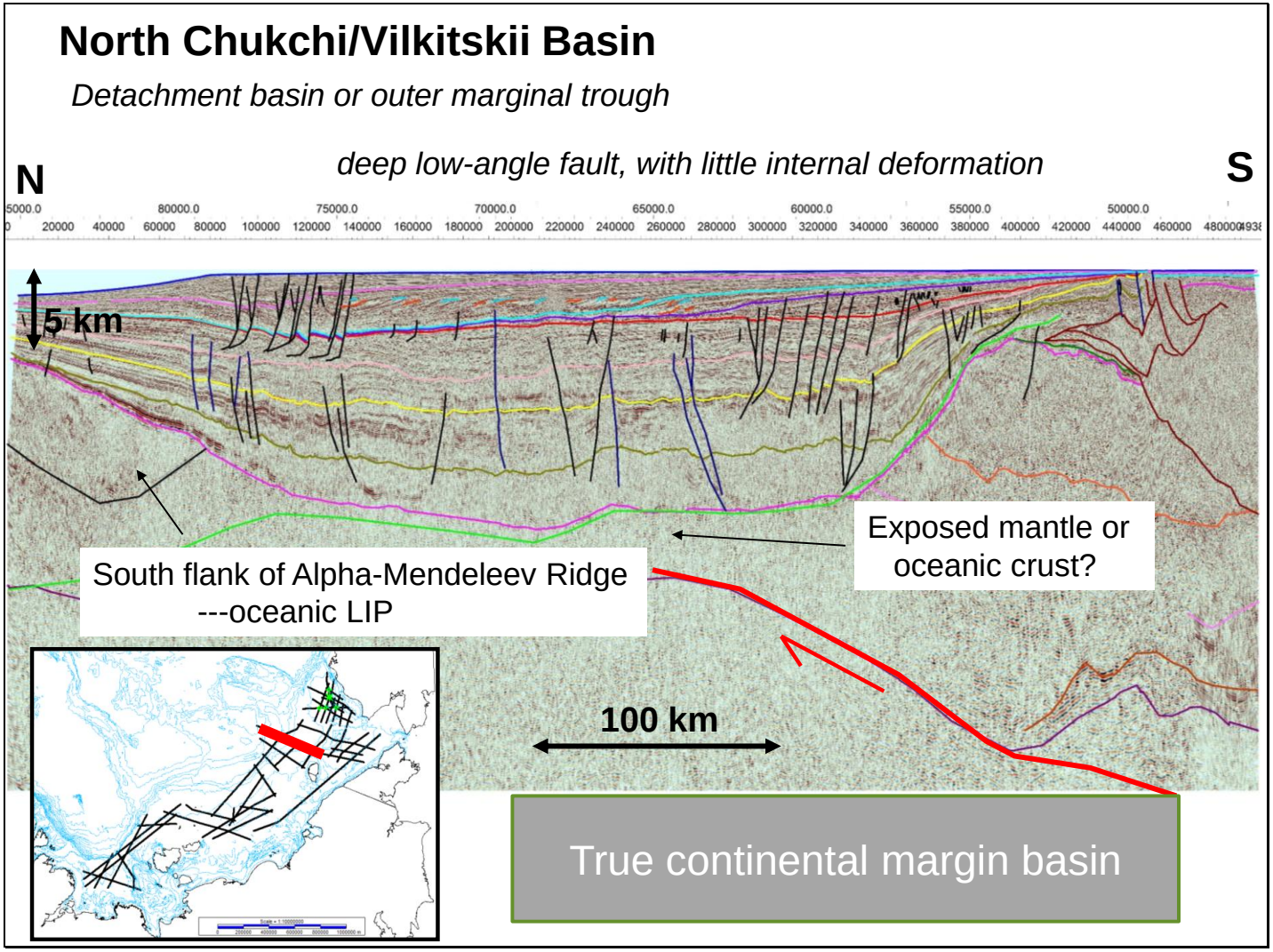
Gravity modeling

East Siberian Sea Rift to North Chukchi/Vilkitskii Basins

Transition from rift within the plate to the AK-CH boundary basin



Presenter's notes: Gravity modeling confirms the interpretation noted on the previous slide. Here are two generations of gravity modeling: one from ERAS I and one from ERAS II by different contractors. It is a strike line along the axis of the two rifts where they feed into each other. Despite the differences in approach are a difference in the number of individual sedimentary units for the section; the modeling shows good agreement with an excellent match between observed and models gravity profiles.



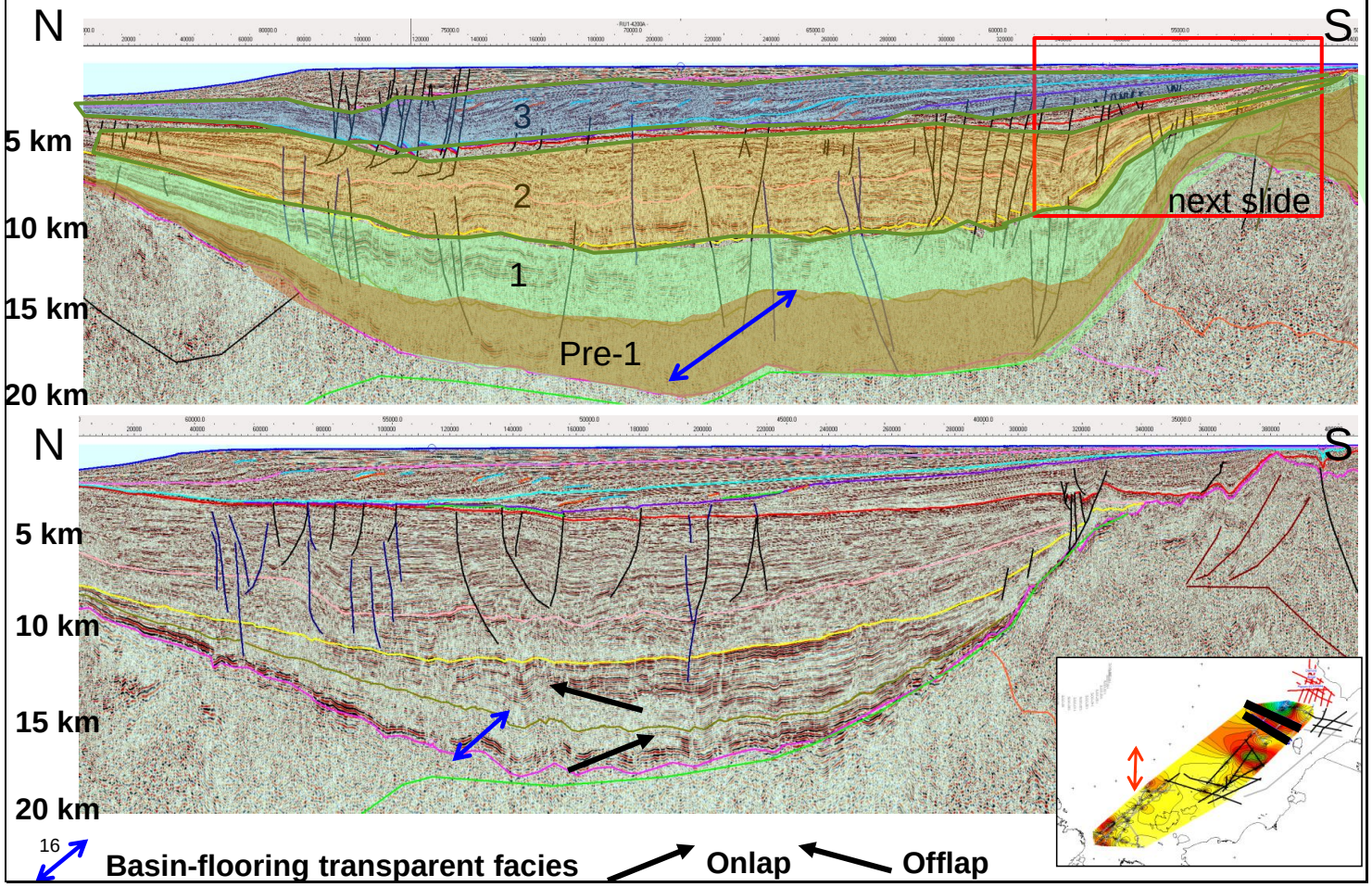
Presenter's notes: This is a full 40-km section dip line across the NC/V from just offshore of Wrangel Island to the southern slopes of the Mendeleev Ridge. We entertained several different interpretations of this line, notably that the crustal block on the left was normal-faulted "off of the Wrangel platform, on the right, but we could never make (Presenter's notes continued on next slide)

(Presenter's notes continued from previous slide)

that "work" kinematically in light of the style of the rift fill. Note Moho constrains the position of any faults; the almost 'aggradational' appearance of the section at this scale. In fact, the section is composed of a number of progradational packages that seem to fill the basin from several directions, the most prominent of which is the one between the cyan and pink horizons which is approximately the Eocene-Oligocene boundary and correlates well into Alaska. The kinematic problem was/is that the section that shows good reflectivity onlaps both sides and does not seem to fill in the space behind this block on the left, if it had, in fact, slid northward away from its footwall. We finally settled on the interpretation that the block is the southern end of the Mendeleev ridge, which is dominantly volcanic in this area and erupted into the basin after it opened. The hanging wall is essentially out of the field of view, and that the syn-kinematic section is hidden in the transparent section—leaving effectively very little crust to build the rift basin. Also there is very little in the way of structure to open the rift basin—some 20 km of J?, Cretaceous, and Paleogene rift fill without the evidence of fault networks obvious in the two western rifts. It had to have opened in a different style; hence the 'detachment' label here –a low-angle fault deep in the continental crust or at the Moho with effectively the early rift fill onlapping the fault plane and the bulk of the basin fill aggrading by progradational packages coming from different directions as the thinned crust subsided.

North Chukchi-Vilkitski Basin

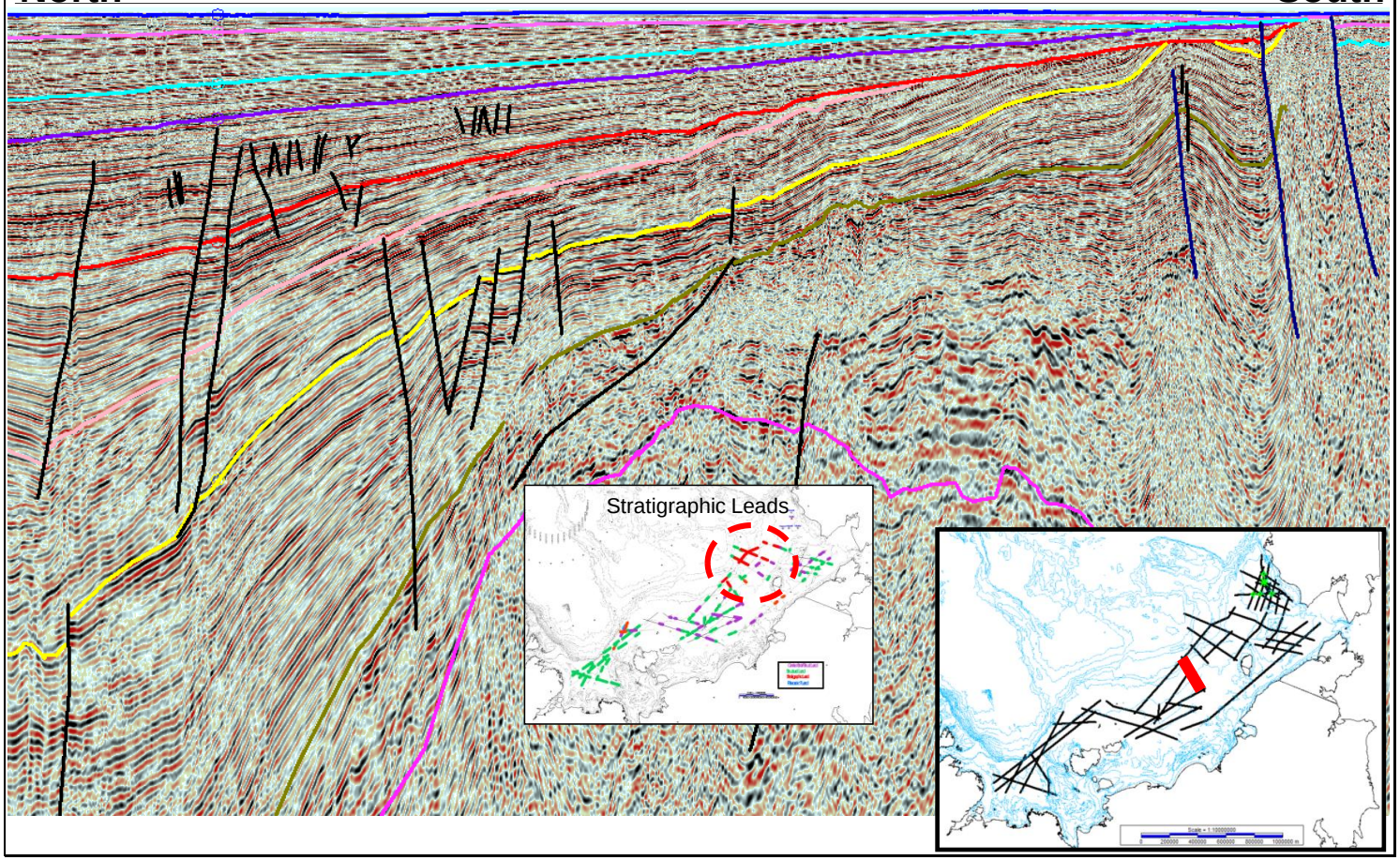
Seismic stratigraphic units and facies definition



Presenter's notes: This is the same line as in the previous slide, with mega-sequences.

North Chukchi Basin

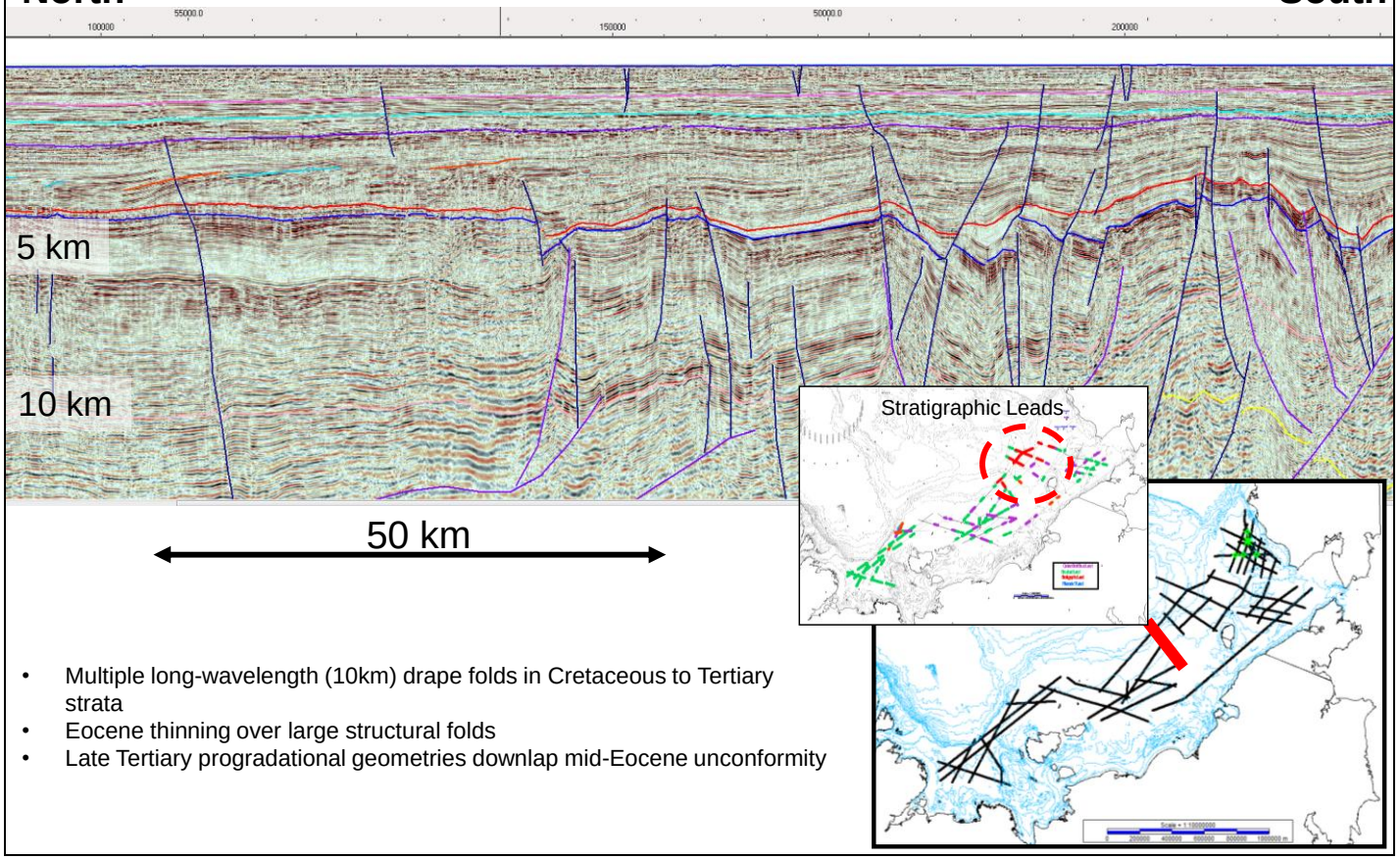
Regional stratigraphic trapping geometries



Presenter's notes: In terms of plays, this section shows some of the dramatic unconformities which leads us to emphasize that this part of the margin may be dominated by stratigraphic leads. Vertically, section=5 km.

North Chukchi Basin

Structural / Stratigraphic leads in Cretaceous and Tertiary strata



- Multiple long-wavelength (10km) drape folds in Cretaceous to Tertiary strata
- Eocene thinning over large structural folds
- Late Tertiary progradational geometries downlap mid-Eocene unconformity

Presenter's notes: This is another section similar to the one previously shown, with some of the localized fault blocks near the upper edge of the basin fill that may afford some localized structural components to the plays.

Summary

- Extremely large geographic area that is unexplored
  - *Petroleum potential likely greater than previously assessed*
- 'Familiar' look of Laptev rifts and East Siberian Sea Rift (new name) provides predominantly structural and combination trapping configurations, of different ages
- Huge detachment style North Chukchi/Vilkitskii Basin provides stratigraphic and combination style trapping potential
- Details of the several basin architectures allow for a new tectonic reconstruction of Amerasia Basin and tighter fit of Chukchi Borderlands

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