Atlas of 3D seismic surfaces and thickness maps, central and southwestern Scotian Slope

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CNSOPB - SCOPE Project

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December 2020

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Executive Summary:

Renewed exploration interest in 2011 and 2012 lead to the issuance of a number of exploration licences by the Canada-Nova Scotia Offshore Petroleum Board, covering large swaths of the central and western Scotian Slope. In the seven years that followed, two large wide-azimuth 3D reflection seismic volumes were acquired on the slope (Shelburne 3D and Tangier 3D) and three wildcat exploration wells were drilled (Cheshire L-97/L-97A, Monterey Jack E-43/E-43A, and Aspy D-11/D-11A). These wells enable, for the first time, high-confidence correlation of post-Bajocian strata across wide areas of the continental slope, and also improve the correlation confidence to equivalent, generally better age-constrained strata on the continental shelf. In light of these newly acquired data-sets, and now that the data confidentiality periods have expired, it is timely to re-appraise the geology of the central to western Scotian Slope.

This Atlas presents mapping results from the CNSOPB *SCOtian sloPE (SCOPE)* project, which aims to unravel the broad-scale evolution of the slope, better understand early margin development, and evaluate spatial and temporal variations in potential reservoirs and the factors controlling reservoir mode/style. The SCOPE Atlas represents the initial phase of this effort, providing foundational mapping results needed for more detailed assessments. It includes more than 20 markers and thickness maps correlated across nine semi-contiguous 3D seismic volumes that cover more than 29 000 km² on the central to western Scotian Slope. The study area spans a number of notable along-margin geological changes, including:

- A west to east transition from magma-rich to magma-poor rifting
- A change in salt tectonic style from mainly isolated salt diapirs in the west to amalgamated salt canopies in the east (middle image)
- Abrupt lateral variations in Middle to Late Jurassic sedimentation, when an aggradational rimmed carbonate platform with a steep bypass foreslope developed in the west, and an aggradational to progradational mixed clastic-carbonate ramp-style system with higher sedimentation rates developed in the east
- Abrupt lateral variations in Cretaceous sedimentation (lower image in the next panel), with long periods of sediment starvation and slope bypass in the west, and clastic influx associated with the Sable Delta in the east where there is increased potential for trapping of turbidite sands on the slope

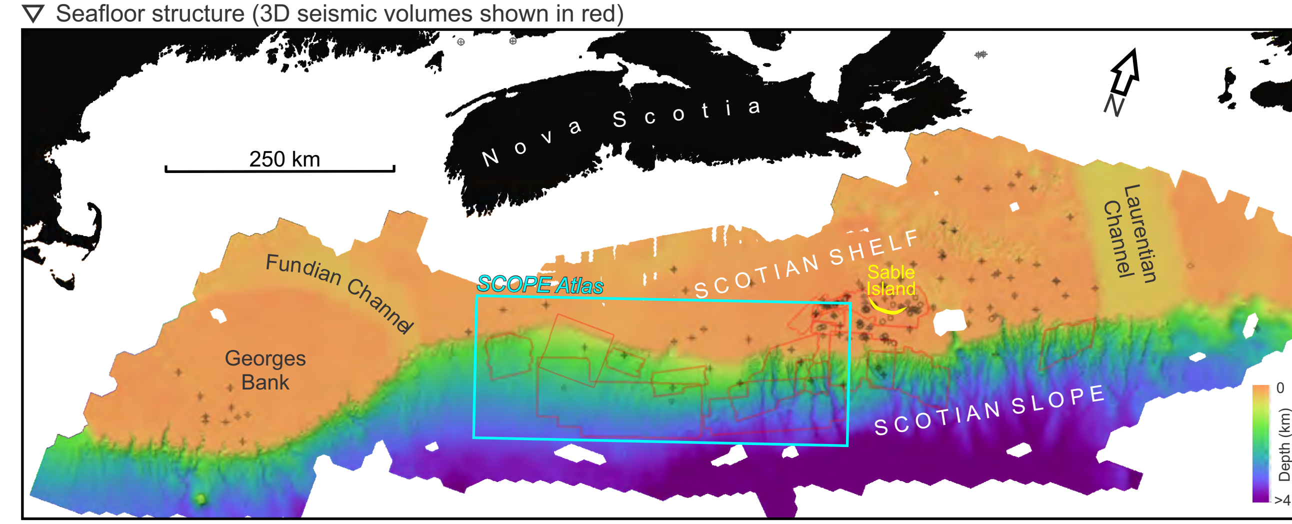
The Atlas provides a higher-fidelity view of these changes, containing 52 detailed panels, generally alternating between structure maps and intervening thickness maps. Each is accompanied by text and is illustrated with example seismic profiles or attribute extractions. Following an introductory chapter, the Atlas is organized stratigraphically, starting with a chapter on Basement and Salt, followed by chapters on the Jurassic, Cretaceous, and Cenozoic successions.

Crustal thickness, salt accumulation, and early sediment loading:

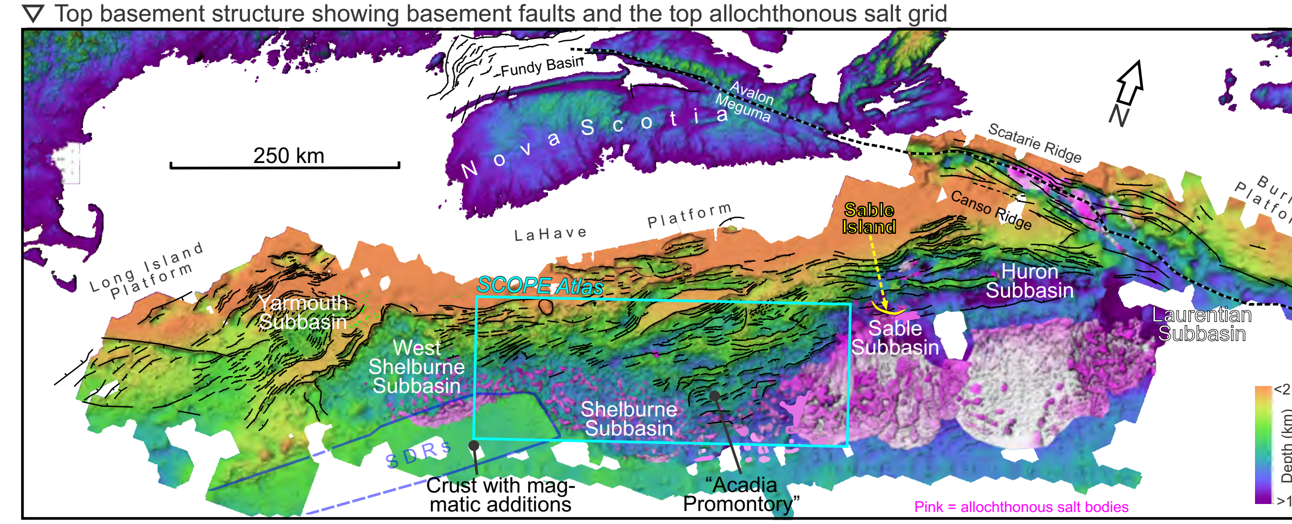
Correlation of a base crust marker (interpreted reflection Moho) and the top crust surface provides a direct measure of crustal thickness along the central and southwestern Scotian margin. Similarly, correlation of the top and base of autochthonous salt provides a direct measure of the present day distribution of primary salt, while welded-out Early to Middle Jurassic minibasins (accommodated through salt expulsion) provide some constraints on the original salt thickness and early salt tectonics. A number of key results are highlighted below:

- Crustal thickness decreases abruptly seaward, across a narrow necking domain; transition from decoupled necking domain crust to coupled hyperextended crust coincides with negative magnetic anomaly inboard ECMA (similar to the Brunswick anomaly?)
- Stepped lateral changes in crustal thickness along this crustal boundary probably reflect segmentation by NW trending synrift transfer faults or accommodation zones; similar offsets are recognized in magnetic anomaly data (bottom image)
- Seaward most protrusion of decoupled crust coincides with the 'Acadia Promontory' (middle image); marked increase in basement depth to its east
- Positive magnetic anomaly along the inner part of the ECMA coincides with coupled hyperextended or transitional crust
- Crustal thickness increases southwest of Yarmouth transfer fault zone, seaward of salt basin, due to magmatic additions (SDRs), with potential for more subtle magmatic additions to the east
- Necking domain crust coincides closely with the landward thinning margin of the overlying primary salt basin (later coinciding with the foreslope of the Late Jurassic carbonate bank, in turn coincident with a region of Cretaceous slope bypass)
- Hyperextended crust (<10 km thick) underpins the thickest parts of the primary salt basin that formed along the axial part of the rift system (thinnest crust = thickest primary salt)
- Rugose, faulted base salt surface implies salt is syntectonic (deposited during late-stage crustal thinning)

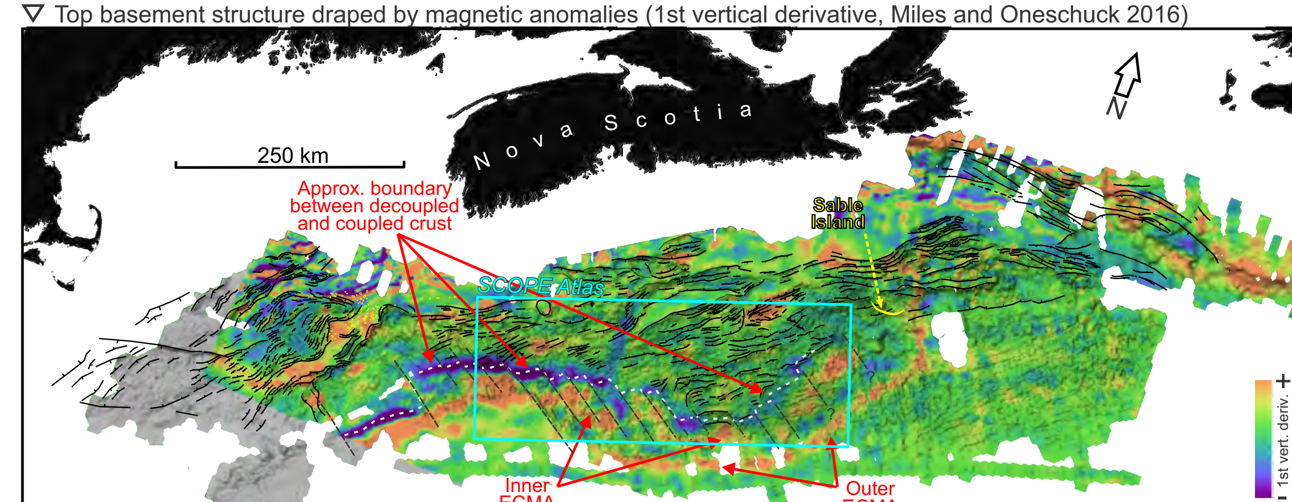
▽ Seafloor structure (3D seismic volumes shown in red)



▽ Top basement structure showing basement faults and the top allochthonous salt grid



▽ Top basement structure draped by magnetic anomalies (1st vertical derivative, Miles and Oneschuck 2016)



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Executive Summary, continued...

- Locally thick (up to 4 km) pre-Bathonian successions accumulated where focused sedimentation took place (i) along the remnant axes of platform rift basins, and (ii) where primary salt thickness appears to have abruptly increased seaward of necking domain crust; the latter form complex salt withdrawal minibasins above hyperextended crust, with thinner pre-Bathonian successions draping the top salt surface in more basinal settings
- Some pre-Bathonian salt-withdrawal minibasins welded-out in the Middle Jurassic; pre-weld stratigraphic thicknesses imply the primary salt basin was locally more than 3.5 km thick above hyperextended crust
- The laterally stepped trend of "taller" salt bodies is a useful proxy for the laterally stepped transition from necked to hyperextended crust, where the increased salt budget above the latter allowed for sustained downbuilding and salt expulsion; the landward edge of these more prominent salt bodies mimics laterally stepped changes in underlying crustal thickness

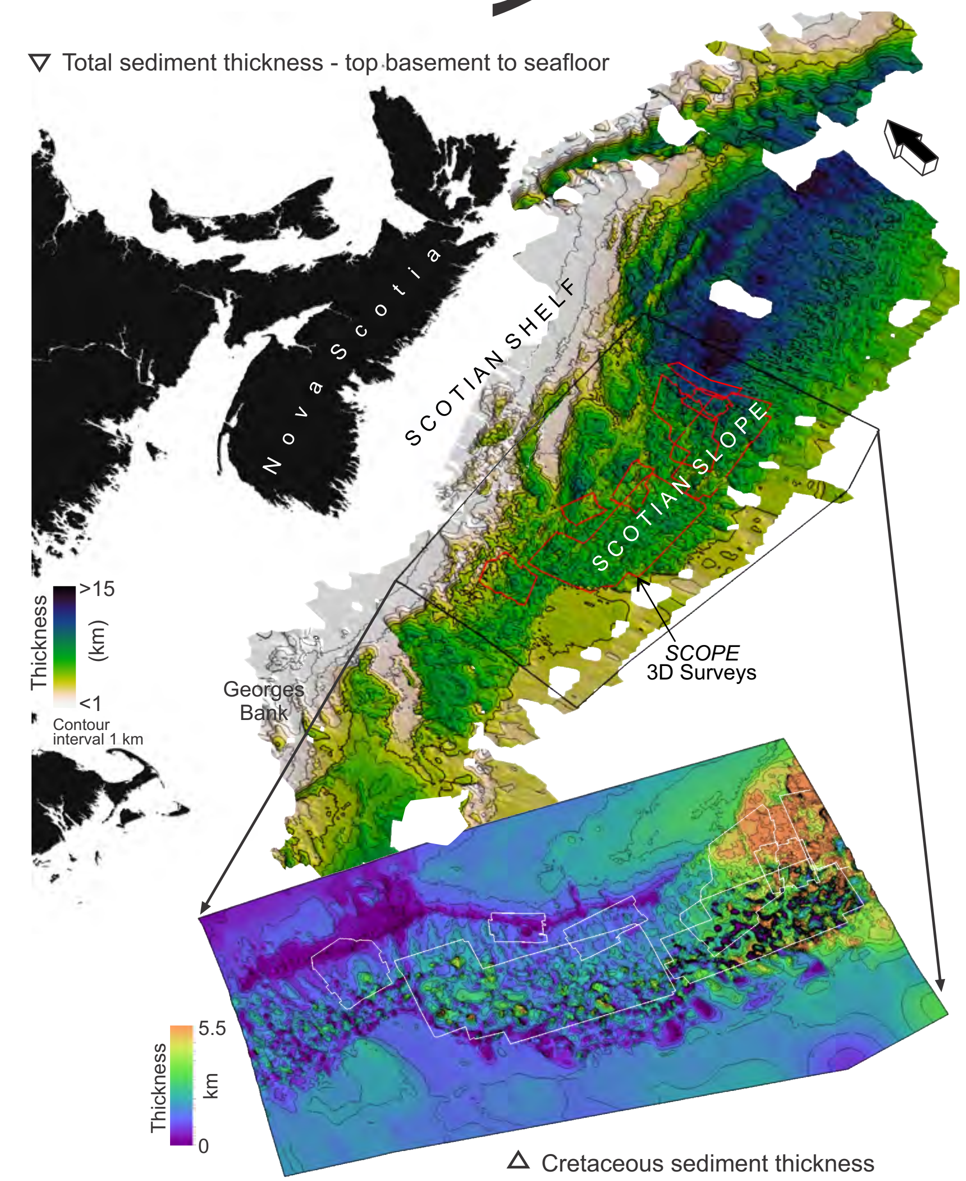
Temporal variations in sedimentation

The initial results from the SCOPE Project provide a clearer picture of both temporal and cross-margin variations in sedimentation. A number of important breaks in the post-salt stratigraphic record, with clear changes in the style of sedimentation, are noted below:

- A wholesale change in margin sedimentation took place in the Middle Jurassic, across the composite J165/170 surface
- The pre-J170 shelf-edge locations and depositional settings are uncertain, making it challenging to interpret reservoir and source rock type/distribution during early salt loading
- The onset of widespread erosion at the poorly-dated J170 surface, with deeply eroded dendritic network of canyons, marks a change in margin subsidence along the necking domain and initial establishment of a bypass slope
- Aggradation of a carbonate bank in the Middle to Upper Jurassic, with a sharply defined bank edge and steep foreslope, probably marks a period of enhanced seaward thermal subsidence; the bank edge roughly separates thicker landward crust (> 20 km thick) from thinner necking domain crust (<20 km thick), forming an important long-lived physiographic element across the western study area
- Numerous periods of widespread slope erosion and prevalent canyon incision are recognized (e.g. J152, J145, K125, K101, T65, T50, T40 surfaces)
- <u>Low accommodation upper slope</u> - J152 to K101 surfaces merge above the carbonate foreslope, producing an erosive, amalgamated or condensed slope bypass assemblage along the western Scotian Slope
- <u>Higher accommodation upper slope</u> - increased K101 to K78 aggradation above the carbonate foreslope, probably reflecting westward migration/progradation of clastic shelf depositional system to or beyond the carbonate bank edge, with enhanced sediment delivery to the slope
- K125 - onset of southwest-flowing bottom currents sweeping both the upper slope and the abyssal plain seaward of salt basin
- K101 to K78 - Enhanced evidence for southwest flowing bottom currents where increased aggradation records clear eastward migration of successive slope canyons and "sediment wave like" intercanyon highs (hybrid contourite-turbidite systems); giant hybrid turbidite/contourite channels seaward of salt basin
- K94 to T40 - period of chalks, marls, and calcareous mudstones, separated by widespread erosive surfaces
- T50 - widespread erosion and mass failure related to Montagnais impact event
- T40 to T25 - Eocene-Oligocene Transition (EOT); major change in slope configuration and sedimentation
- Post-T25 - aggradation and migration of giant elongated contourite drifts, enhanced mass failures, and more sinuous channel systems or canyons floored by erosive sinuous channels

Implications for reservoir distribution across SCOPE study area

The scarcity of reservoirs and lack of hydrocarbons in the Cheshire and Monterey Jack wells in the Shelburne Subbasin (western Scotian Slope), sharply contrast the Newburn, Aspy, and Annapolis wells in the distal Sable Subbasin (central Scotian Slope) that encountered both turbidite reservoirs and hydrocarbons (gas and condensate). The controls on the distribution and style of mid-Jurassic and older reservoirs and source rocks throughout the study area remain cryptic and require further study. In contrast, there are clear patterns in the distribution and style of mid-Jurassic to Cretaceous slope sedimentation, reservoir expectations, as well as linkage to shelf depositional systems across the study area. Some of these spatial patterns are highlighted below, and described in more detail on related Atlas panels:



<u>***West** - Barrington, WG, Mamou, Shelburne, Torbrook 3D volumes:*</u>

- Sediment starved Mid-Jurassic to Lower Cretaceous slope succession (condensed Missisauga-equivalent strata)
- Post-J160 sediment transport perpendicular to carbonate bank; early strong basement control
- Steep, heavily canyoned 'bypass' upper slope - 8 to 10 periods of widespread canyon formation identified in J152 to T40 interval (thickness variations strongly influenced by erosion)
- Most likely post-J145 reservoirs correspond to axial deposits above canyon floors or wide erosive corridors; reservoir potential may be poor, but has not been tested
- Strong evidence for post-K125 SW-flowing bottom currents sweeping upper slope and abyssal plain; scope for Cretaceous or Cenozoic contourite reservoirs?
- Salt tectonics - mainly salt diapirs/walls, with episodic salt movement triggered by canyon incisions that unroof stalled/buried salt bodies ("diapir liberation" - some canyon reaches occupied by salt)

<u>***East** - Thrumcap, Weymouth, Tangier, and Veritas 3D volumes:*</u>

- Voluminous mid-Jurassic to Lower Cretaceous sediment accumulation (reflecting MicMac/Sable fluvial-deltaic input)
- North-south sediment transport (parallel to Sable Delta progradation direction)
- Westward expansion of fluvial-deltaic input across the central LaHave Platform, improving mid-Cretaceous reservoir potential in central SCOPE area; e.g. increased potential for perched aprons east of the Cheshire Minibasin
- Less obvious influence from upper slope bottom currents
- Strong evidence for Cretaceous bottom currents on lower slope, seaward of salt basin; reservoir potential associated with lateral migration/aggradation of giant post-K101 hybrid turbidite-contourite channel-levee systems
- Salt tectonics driven by N-S sedimentation from Sable Delta (diapirs with common salt overhangs, salt tongues, amalgamated canopies, and roho systems)

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Chapter 1 – Introduction

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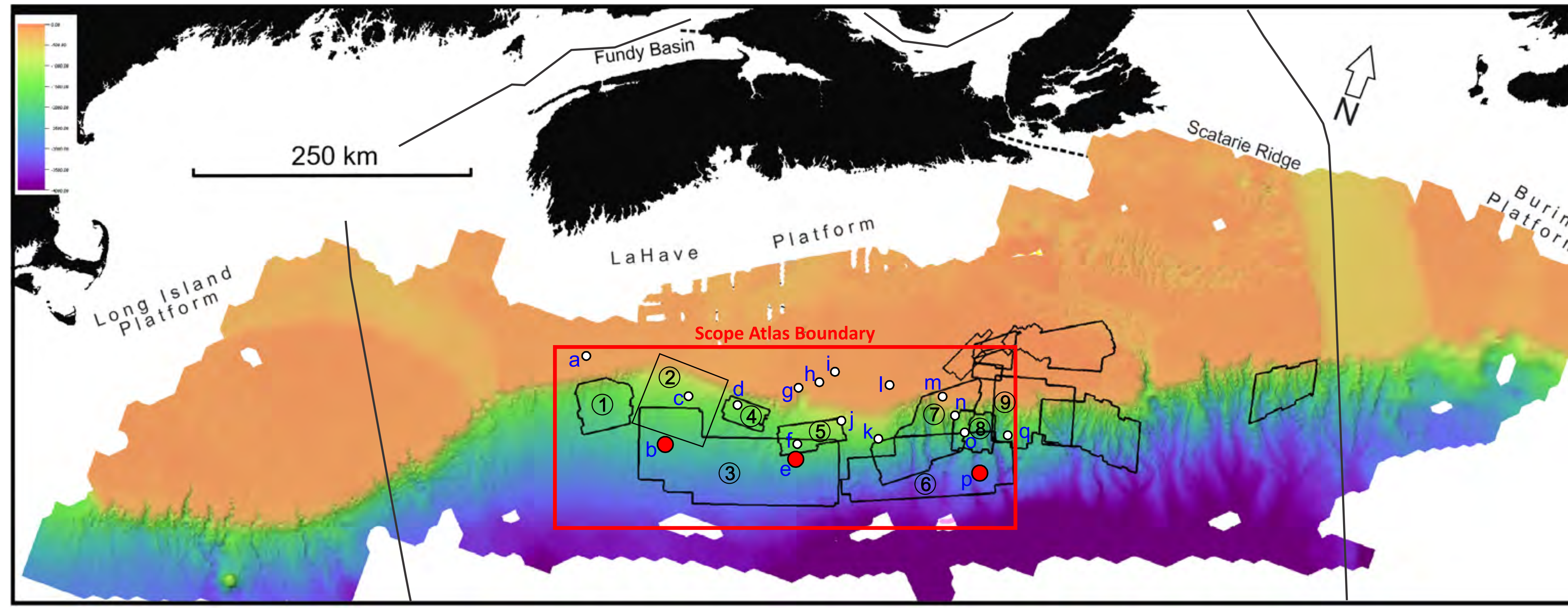
Kristopher L. Kendell and Mark E. Deptuck

One mandate of the Canada-Nova Scotia Offshore Petroleum Board is overseeing the submission, storage and archiving of various geological and geophysical data acquired during oil and gas exploration activities in the Canada-Nova Scotia Offshore Area. These datasets are released to the public following defined confidentiality periods and are also used internally to improve the CNSOPB's understanding of the subsurface geology of the Scotian Basin.

The improved quality of new data-sets collected across the western and central Scotian Slope during recent industry exploration efforts have substantially improved our geological understanding of the area. Two regional-scale 3D wide azimuth reflection seismic surveys, covering 18 200 km², significantly improve seismic imaging and coverage across a complex region of salt tectonics. These large surveys also bridge gaps between seven older 3D seismic volumes, providing near-contiguous 3D seismic coverage across an area of more than 29 000 km², or a little over half the total area covered by the Province of Nova Scotia. The resulting seismic stratigraphic framework and regional interpretations provided in this atlas offer important geological context for these formerly isolated "postage stamp" sized surveys otherwise not possible.

This study also benefits from new well control provided by Cheshire L-97/L-97A, Monterey Jack E-43/E-43A and Aspy D-11/D-11A (red circles on map to the right). In particular, the Cheshire well provides calibration for previously undrilled Middle Jurassic strata on the slope. The SCOPE Atlas combines and updates earlier geological and geophysical interpretations presented in CNSOPB resource assessments, Call for Bids geoscience packages, and a number of Geoscience Open File Reports (GOFRs). It also builds on the framework presented in OETR (2011).

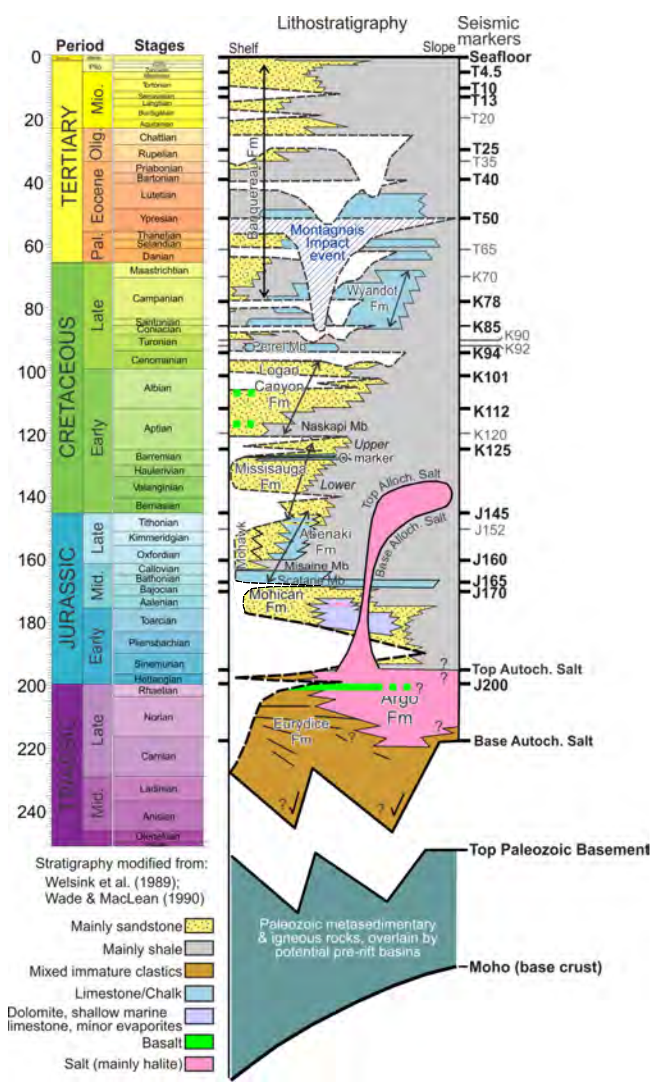


3D Seismic Programs

① NS24-P003-004E ("Barrington 3D")
② NS24-W013-002P, 003P ("WG 3D")
③ NS24-S006-003E ("Shelburne 3D")
④ NS24-G005-008P ("Mamou 3D")
⑤ NS24-P003-002E ("Torbrook 3D")
⑥ NS24-S006-001E, 002E ("Tangier 3D")
⑦ NS24-B071-001E ("Thrumcap 3D")
⑧ NS24-P003-004E ("Weymouth 3D")
⑨ NS24-V003-002P, 003P, 004P ("Veritas 3D")

Key Wells (listed from west to east)

a. Mohawk B-93
b. Monterey Jack E-43/E-43A
c. Shelburne G-29
d. Albatross B-13
e. Cheshire L-97/L-97A
f. Torbrook C-15
g. Mohican I-100
h. Moheida P-15
i. Glooscap C-63
j. Acadia K-62
k. Shubenacadie H-100
l. Oneida O-25
m. Evangeline H-98
n. Newburn H-23
o. Weymouth A-45
p. Aspy D-11/D-11A
q. Balvenie B-79



Seismic volumes used

Nine near-contiguous 3D seismic volumes form the core reflection seismic data-sets used in this study. Their program numbers are listed above, with the informal names of the surveys in brackets (these are the survey names referenced in the atlas). Geophysical reports for each of these surveys are available from the CNSOPB Data Management Centre. https://cnsopbdigitaldata.ca/dmc-summary/

Atlas content

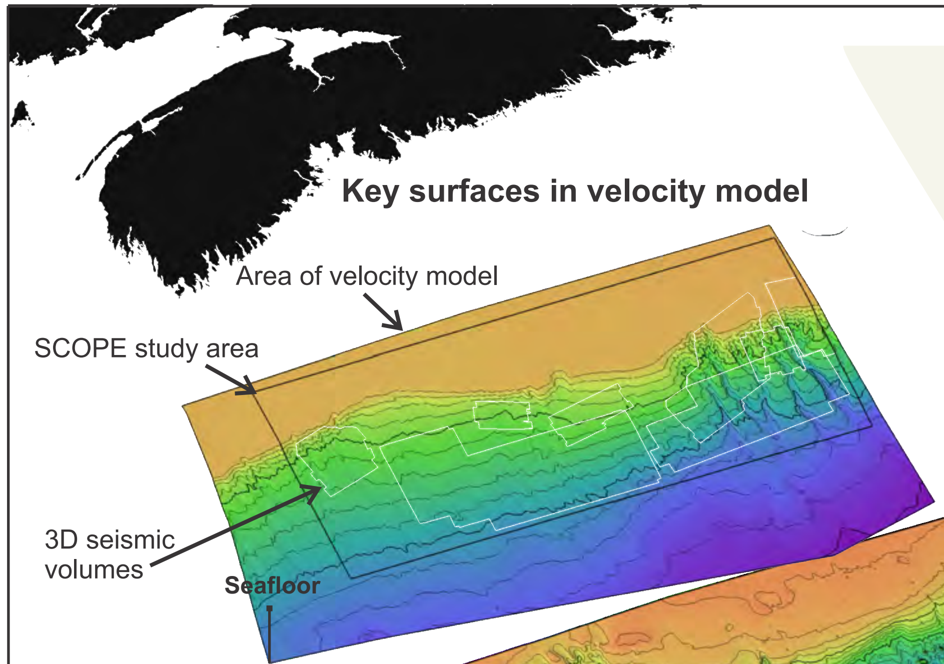
The atlas includes roughly 20 structure maps, 22 thickness maps, 34 interpreted seismic profiles, and 19 amplitude attribute extractions, along with explanatory text. Each structure map combines horizons correlated on seven peripheral time-migrated 3D seismic volumes with equivalent horizons correlated on the two more recent depth-migrated volumes, using a velocity model described on the following page. Structure maps were gridded at 100 m x 100 m using a low degree of smoothing, with some inset maps gridded more finely. The age of seismic horizons are constrained by wells where possible and most coincide with regional biostratigraphic events identified in publicly available exploration well reports and published papers. The age constraints provided by Fensome et al. (2008), Weston et al. (2012), and RPS (2018) were particularly helpful.

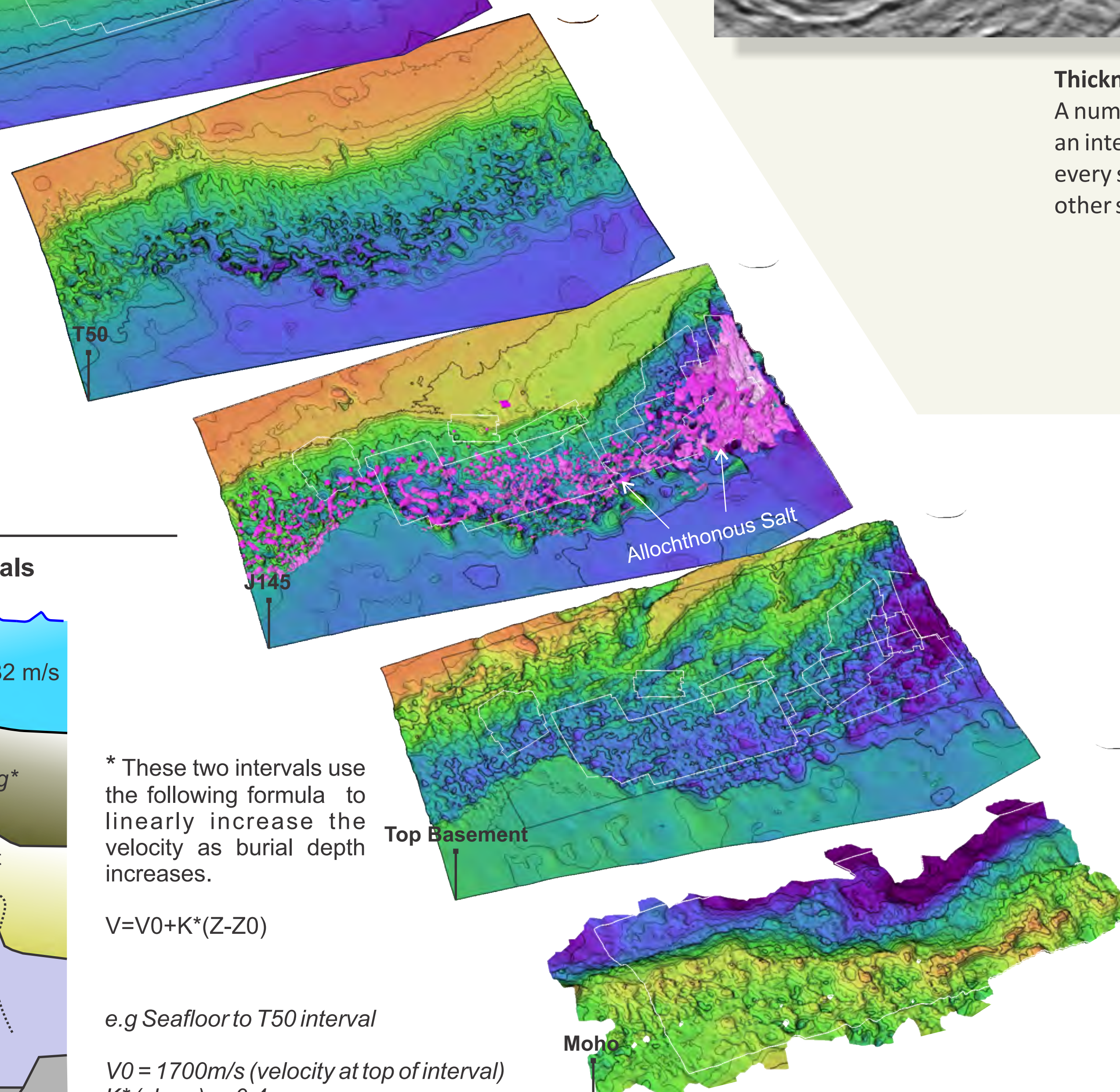
Thickness maps were generated by subtracting one depth structure map from another. This process limits the regional extent of the thickness map to the surface with the smallest area. The gridding parameters for each thickness map are equivalent to the surfaces, generally 100 m x 100 m. In some cases anomalous thicknesses were produced where one marker overlies salt while the other does not, producing an erroneous thickness that includes an interval of overhanging salt. We attempted to identify these situations on atlas panels where they occur.

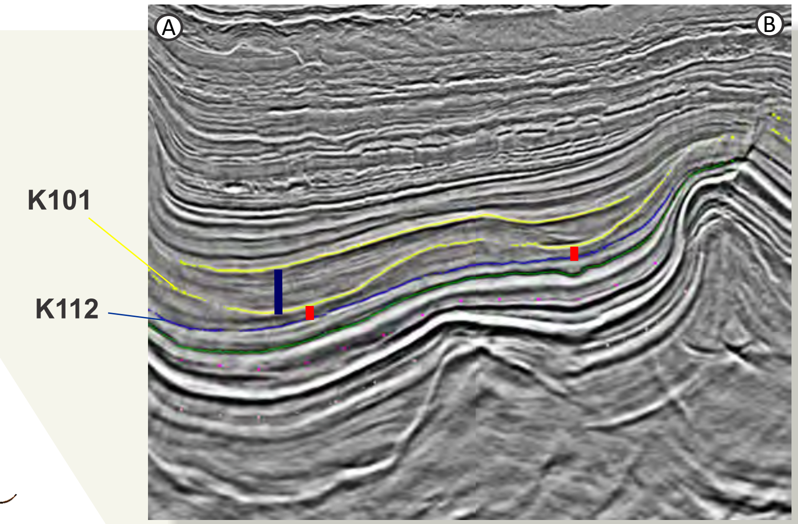
A number of atlas panels also incorporate mapping results from regional 2D seismic profiles - particularly on the LaHave Platform, providing a fuller picture of thickness variations between shelf fluvial-deltaic deposits and deep water depositional systems. Note that in some cases the stratigraphic intervals are not exactly equivalent, as noted on relevant panels.

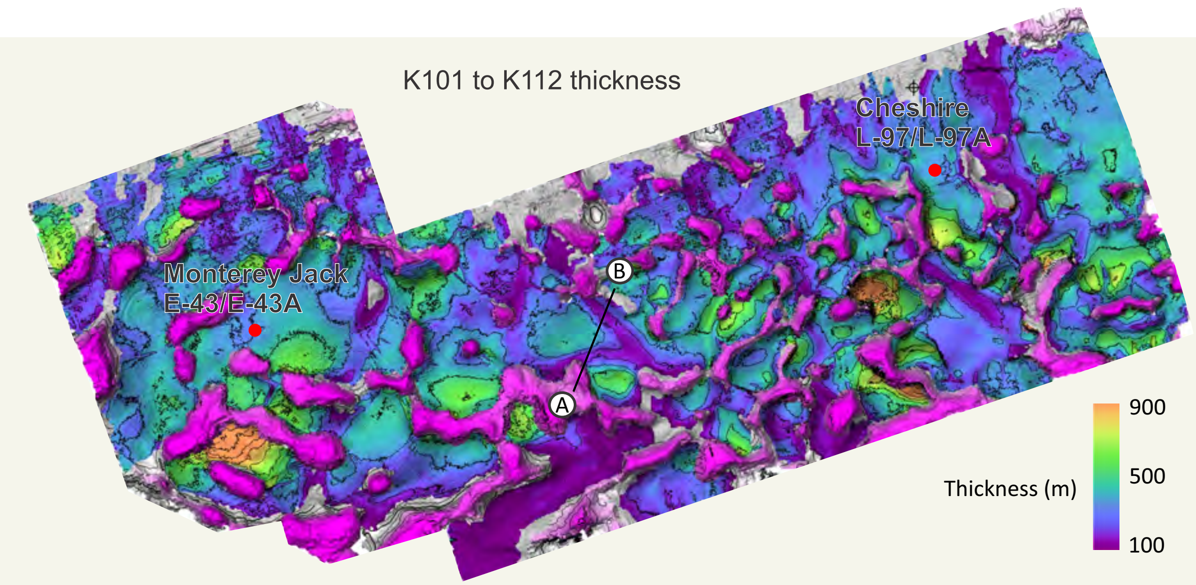
Acknowledgments - We wish to thank CNSOPB management, the Nova Scotia Department of Energy and Mines, and the Offshore Energy Research Association for their support. Carl Makrides, Brian Altheim, and Shaun Rhyno provided important input throughout the project, and without technical support provided by Jason Butts, Debbie O'Brien, and Troy MacDonald (who brilliantly enabled us to work from home during a Covid-19 lockdown), the Atlas would not have been possible. We also wish to thank Fraser Keppie, Russell Dmytriw, Natasha Morrison, Janice Weston, Bridget Ady, Richard Whittaker, Calvin Campbell, Andrea Christians, Andrew MacRae, Carol Decalf, John Martin, Anita Nicoll, and Debra Wheeler who have all contributed to this atlas in different ways.

Recommended citation:
Kendell, K.L. and Deptuck, M.E. 2020. SCOPE Project, Chapter 1 - Introduction, In: Atlas of 3D Seismic Surfaces and Thickness Maps, Central and Southwestern Scotian Slope, Canada-Nova Scotia Offshore Petroleum Board Geoscience Open File Report: 2020-002MF, 5 panels.



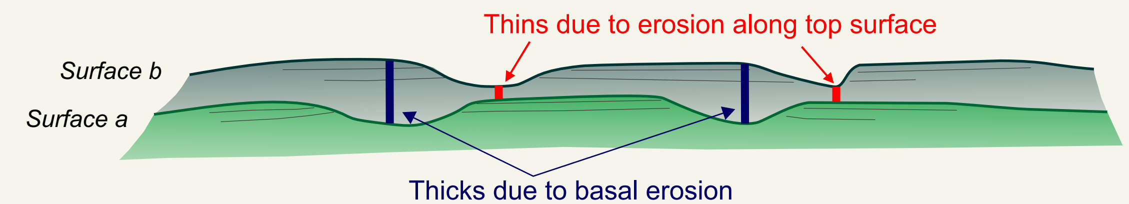


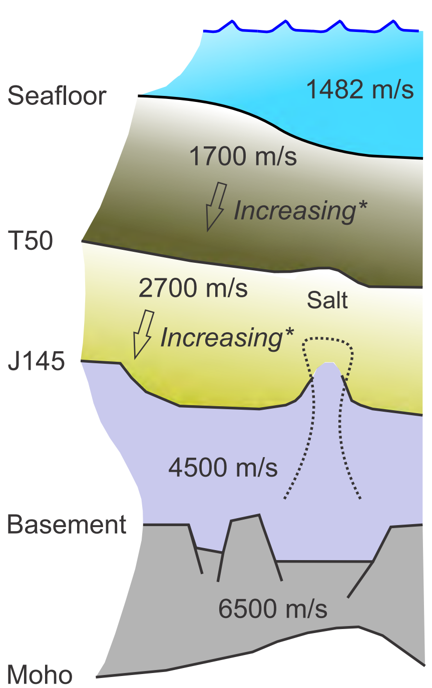




Thickness Maps.

A number of factors control thickness variations between two surfaces on the Scotian Slope. Canyon erosion from above or at the base of an interval, in particular, can produce cryptic "thins" and "thicks" that can lead to erroneous interpretaions. There is erosion along almost every surface we have mapped in the study area, so careful scrutiny is required to distinguish thickness variations caused by erosion from other sources associated with ponding in salt withdrawal minibasins, growth of levees, or aggradation/migration of contourite drifts.





* These two intervals use the following formula to linearly increase the velocity as burial depth increases.

V=V0+K*(Z-Z0)

e.g Seafloor to T50 interval

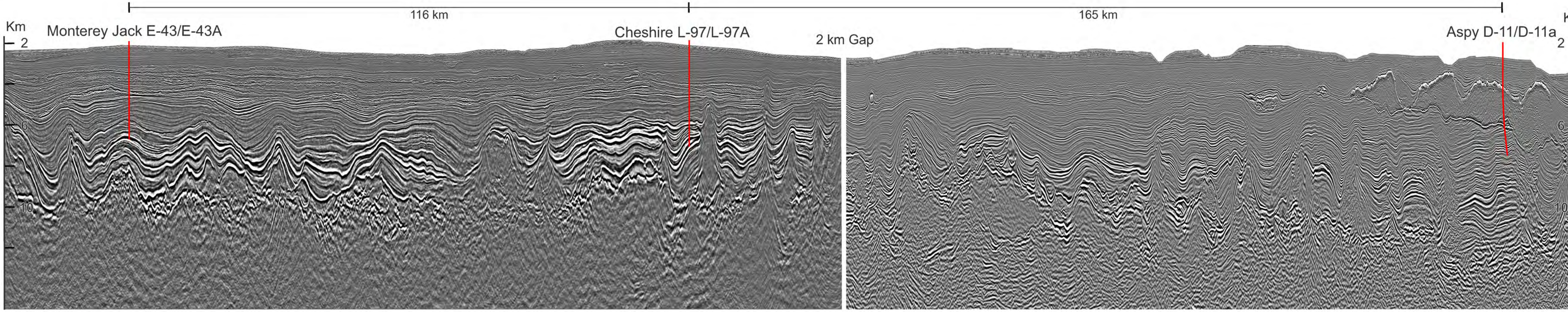
V0 = 1700m/s (velocity at top of interval)
K (slope) = -0.4*
Z = Depth at base of interval
Z0 = Depth at top of interval

Velocity Model

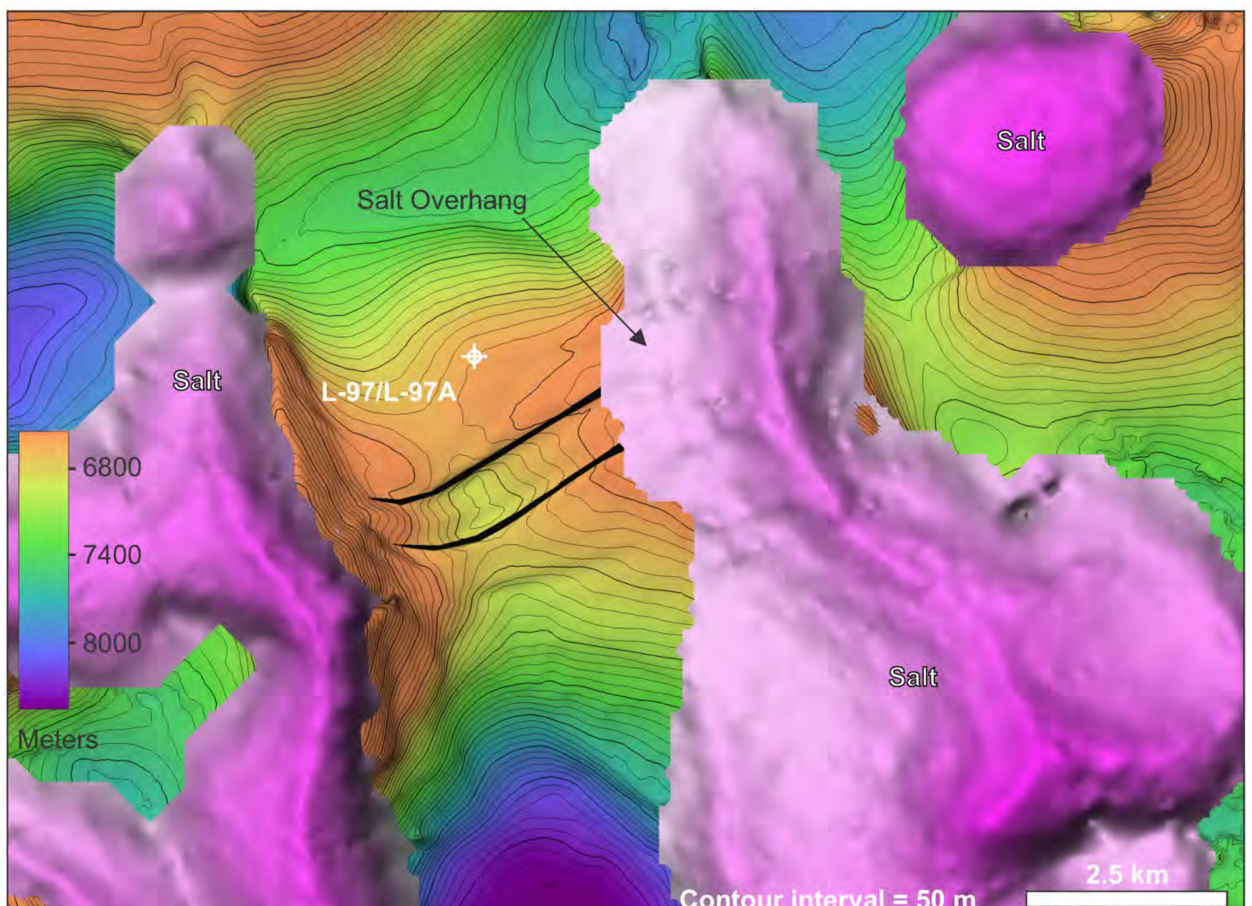
The NS24-B71-1E (Tangier 3D) and NS24-S6-3E (Shelburne 3D) seismic programs are PSDM volumes that were depth migrated by the operators. All other seismic data used in this study are time-migrated programs that require depth conversion. Because a large portion of the mapping was carried out on the Shelburne and Tangier surveys, whose velocity models (and in particular treatment of salt) are more precise than what we are able to achieve, surfaces mapped from these surveys were used as reference datums for evaluating the consistency of our velocity model. Some trial and error was carried out to achieve the least amount of error between the two sets of surfaces, to ensure that depth-converted maps from the model merged as seamlessly as possible with equivalent surfaces mapped in the Shelburne and Tangier surveys.

For time-migrated volumes, a layered interval velocity model covering the study area was developed to convert two-way time products to depth (figure to the left). The model consists of five velocity intervals separated by four surfaces. The internal bounding surfaces are the seafloor, T50 (Early Eocene), J145 (Berriasian-Tithonian), and Top Basement. Checkshot surveys from all available wells in the study area were compiled and used to generate average interval velocities between the bounding surfaces and to assess changes in velocity with depth. No stacking velocity information was available for this study. Constant velocities were applied to the water column (1482 m/s), the J145 to Top Basement interval (4500 m/s; interval includes salt) and to the crust (6500 m/s). The Cenozoic and Cretaceous interval velocities start at 1700 and 2700 m/s, respectively, supported by average interval velocities just below the seabed and the T50 marker, respectively, in a number of slope wells. Linear velocity gradients were applied to the Cenozoic and Cretaceous intervals, guided by checkshot data, but adjusted to minimize the error between depth-converted surfaces and depth-migrated wide-azimuth 3D volumes.

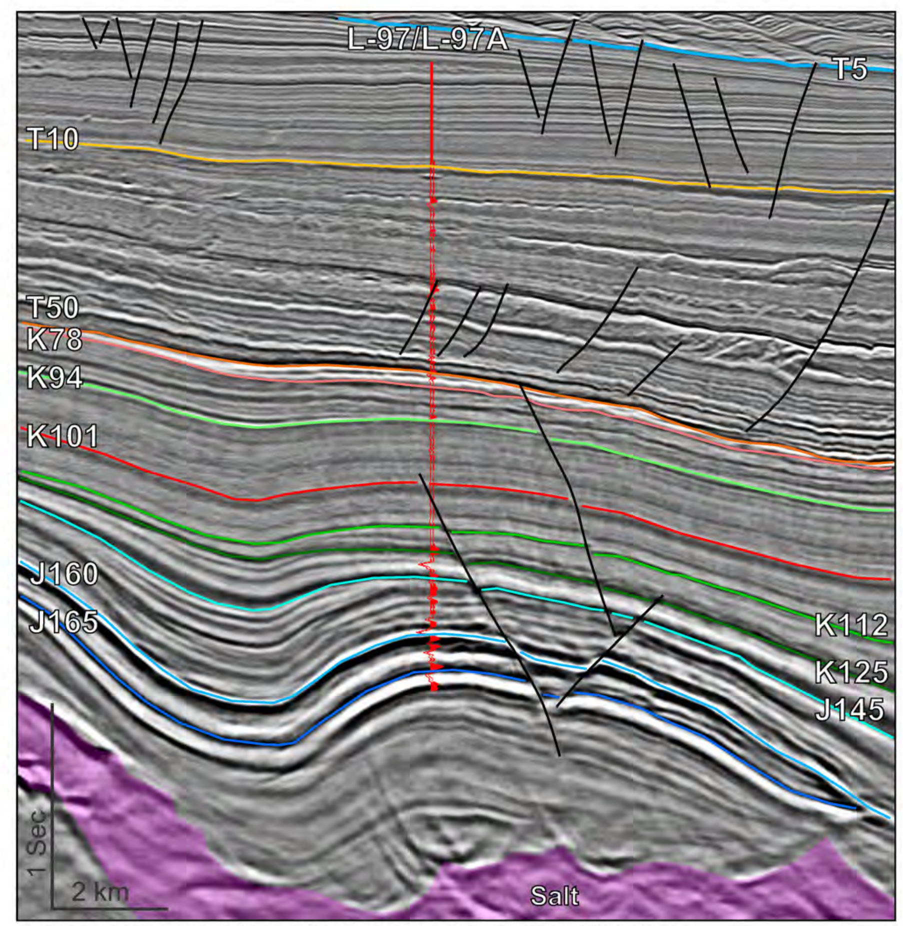
With so few wells penetrating Jurassic strata on the slope, average interval velocities here are constrained only by Cheshire and Monterey Jack; similar average interval velocities are also found in a number of other wells that penetrate salt (Shimeld 2004) as well as underlying Triassic strata, making 4.5 km/s a reasonable approximation for the pre-J145 interval. Note that a number of wells on the shelf show up to 1 km/s faster average interval velocities within the carbonate bank (J145 to J163); as such, thicknesses here are probably underestimated (though this shelf region is not the focus of this study). Also note that the single crustal velocity layer used here is clearly an over-simplification, and the resulting crustal thickness and Moho structure should be treated as approximate. In general, most of our depth-converted surfaces are consistent with the depth surfaces mapped in the Tangier and Shelburne surveys to within 100 m.



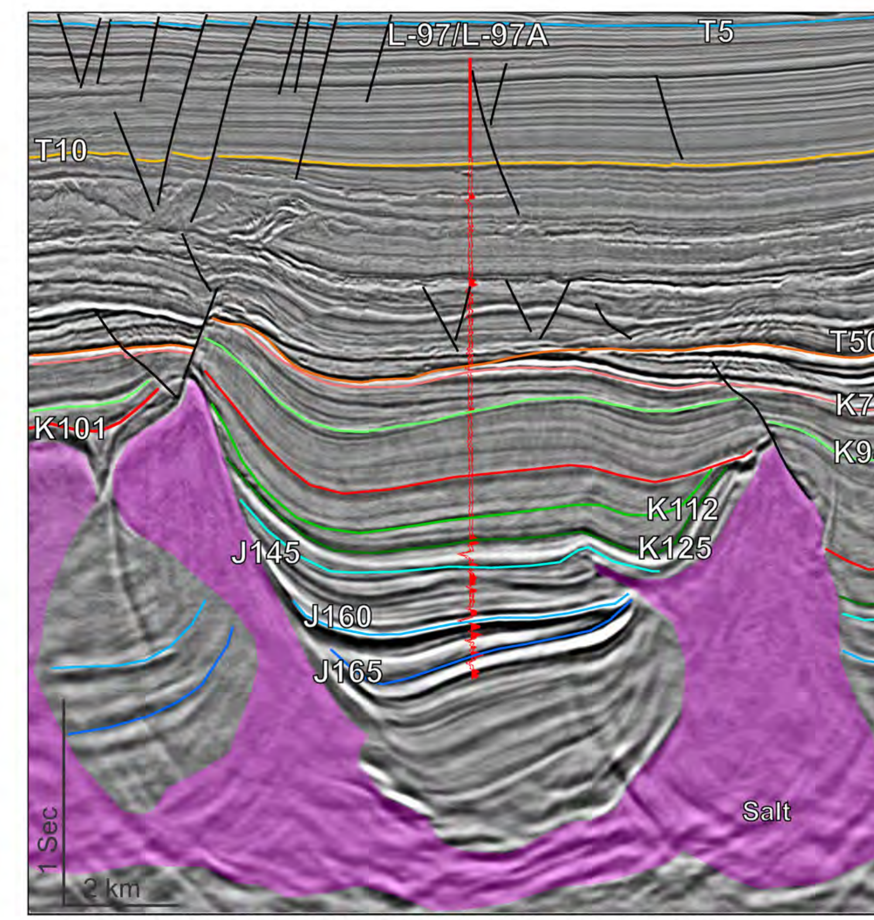
This ~300 km long strike line crosses the Shelburne (NS24-S006-003E) and Tangier (NS24-B071-001E) wide azimuth seismic surveys, intersecting three key wells, and avoids most vertical piercing salt bodies.



J160 structure map and the location of Cheshire L-97/L-97A



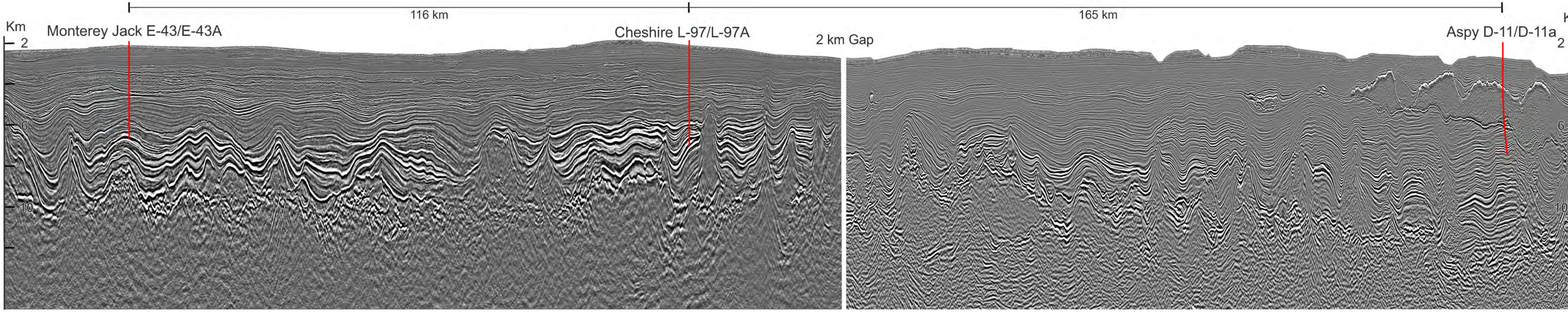
Dip oriented seismic profile through Cheshire L-97/L-97A



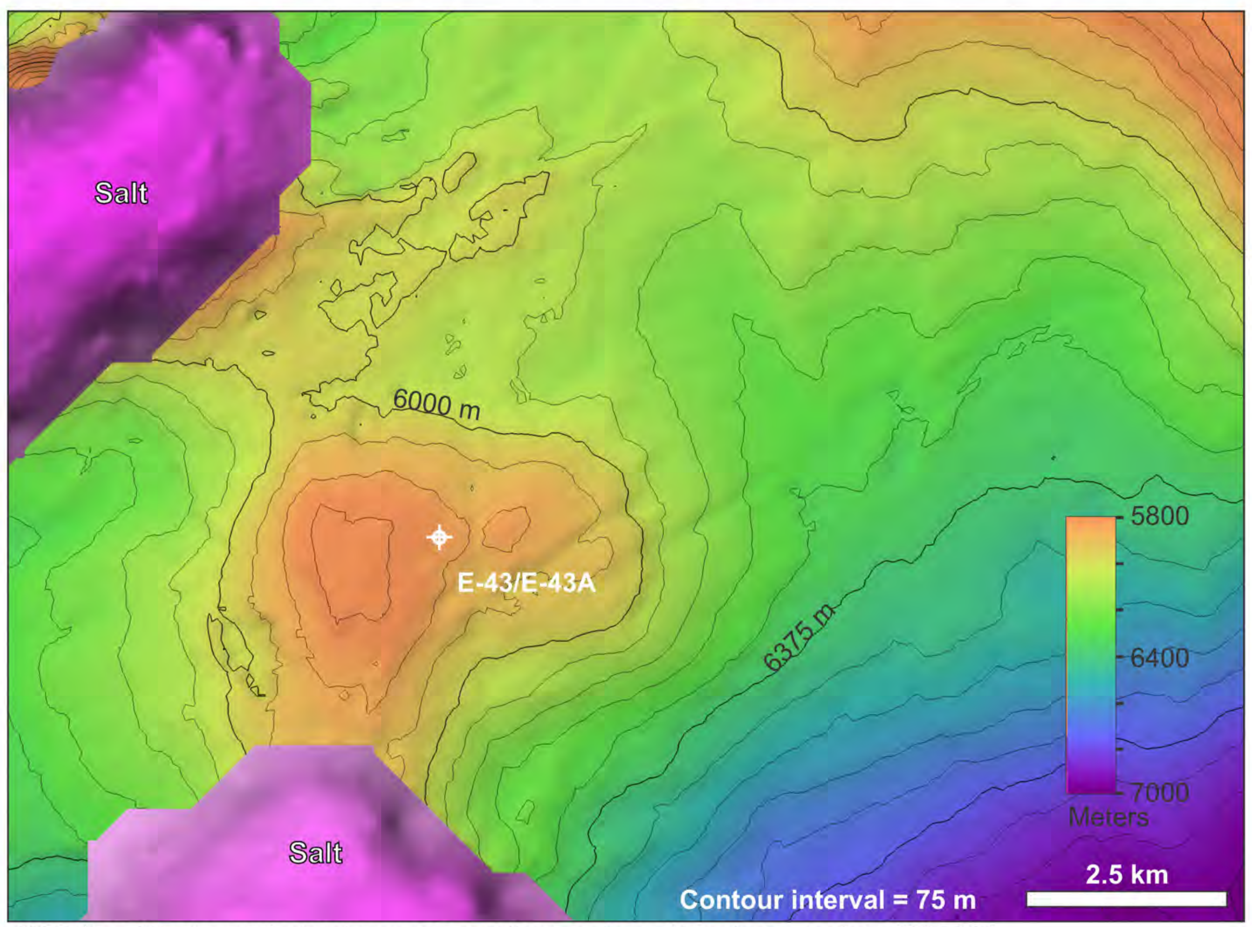
Strike oriented seismic profile through Cheshire L-97/L-97A

Cheshire L-97/L-97A
Shell Canada Ltd.
Water Depth: 2141m
Total Depth (md): 7068 m
Completed: Sept. 22, 2016
Well type: Exploratory
Well Classification: Dry hole

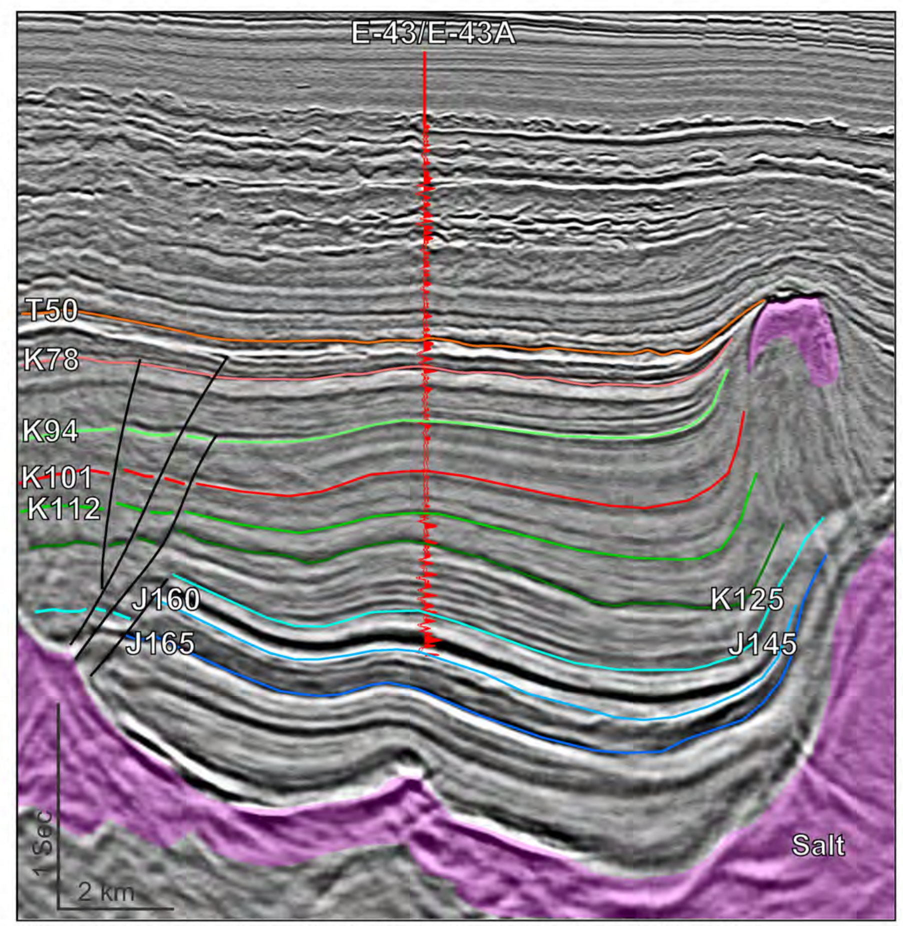
The Cheshire well targeted a structural high between two north-south oriented diapiric salt bodies. It is a three-way closure against salt, with a salt overhang providing seal for deeper Jurassic reservoirs (as shown on the above structure map at the J160 level). Minor-offset faults are present at the crest of the structure. **Pre-drill -** The structure was interpreted to consist of an inverted minibasin of Cretaceous age, downdip turbidite equivalents of the Missisauga Formation. Secondary reservoir objectives of Jurassic aged Mohawk and Mic Mac formations were also noted to be possible (Shell, 2018). **Post Drill -** The top of the Jurassic was encountered 160 m shallower than expected, this 'thinned' the targeted Missisauga reservoir interval. The thinner than anticipated Missisauga Fm. was predominantly claystone, shale and marls. The well continued drilling to the Bajocian and no significant reservoir intervals or hydrocarbon-bearing zones were encountered. The wells may have targeted a mounded geometry that was in-part formed via external erosional processes rather than a depositional stacking of fans.



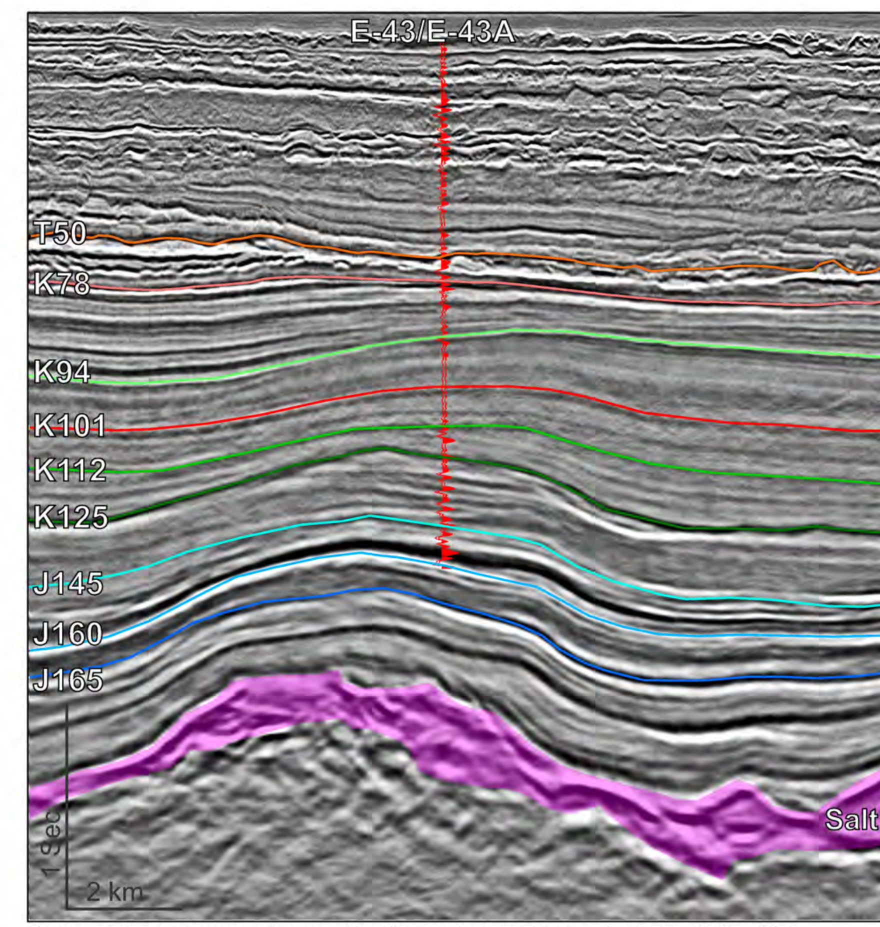
This ~300 km long strike line crosses the Shelburne (NS24-S006-003E) and Tangier (NS24-B071-001E) wide azimuth seismic surveys, intersecting three key wells, and avoids most vertical piercing salt bodies.



K125 (Top Missisauga) structure map and the location of Monterey Jack E-43/E-43A



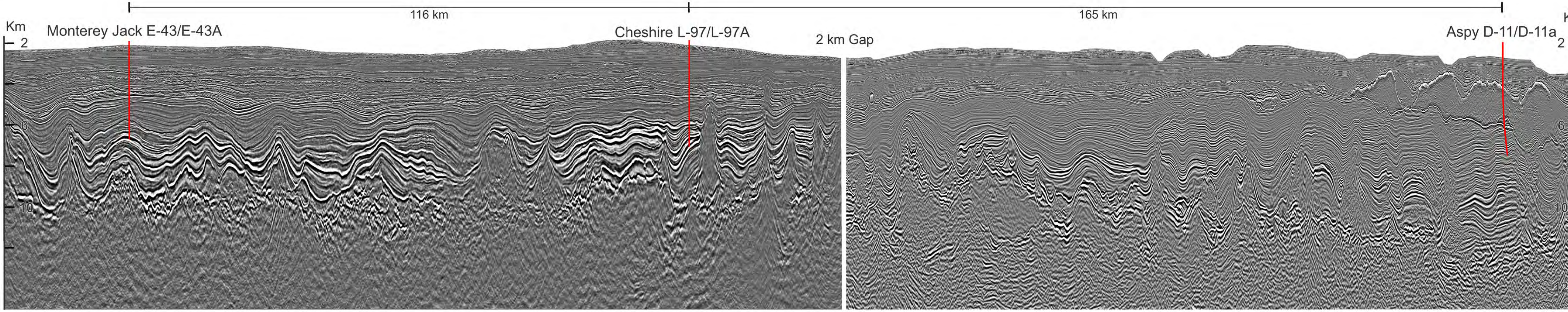
Dip oriented seismic profile through Monterey Jack E-43/E-43A



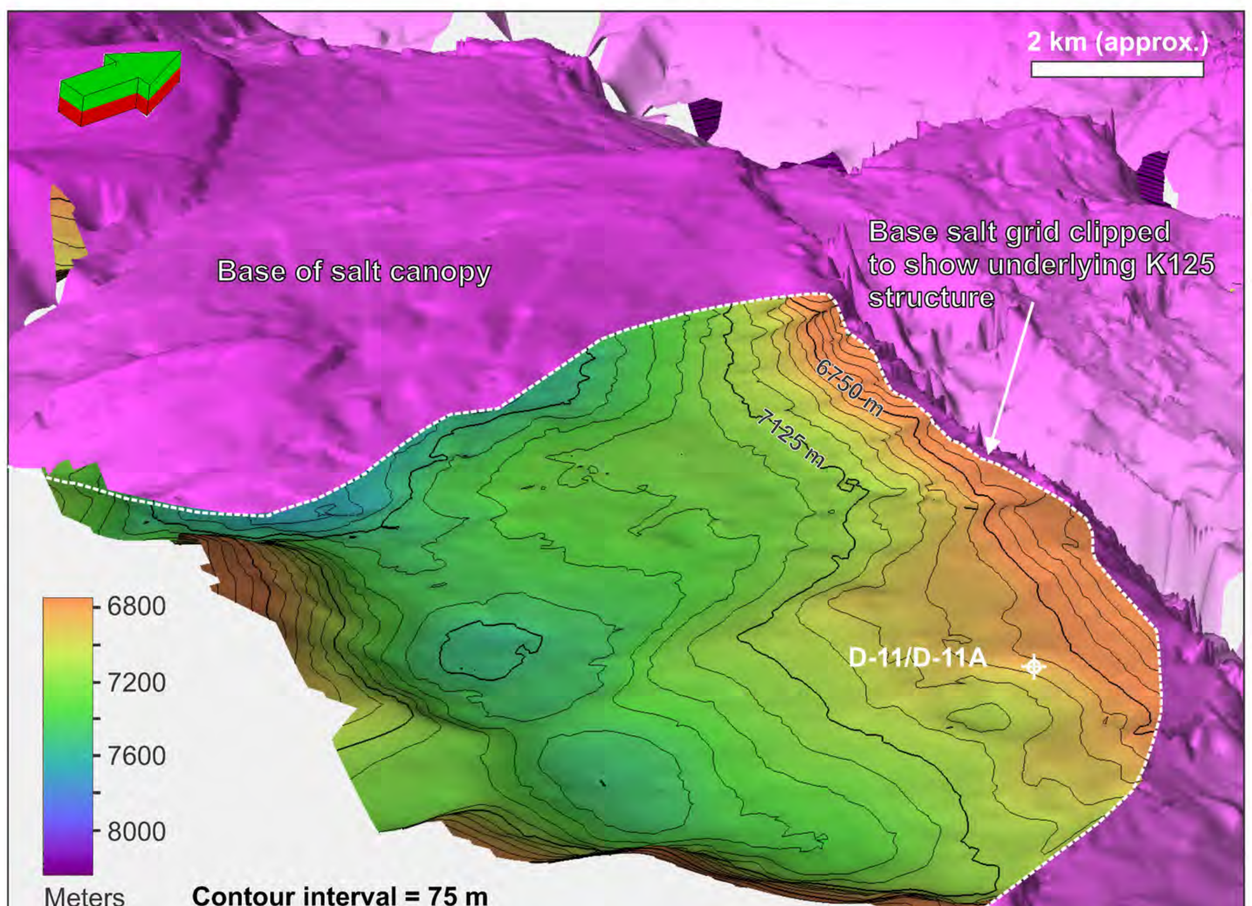
Strike oriented seismic profile through Monterey Jack E-43/E-43A

Monterey Jack E-43/E-43A
Shell Canada Ltd.
Water Depth: 2117 m
Total Depth (md): 6692 m
Completed: Jan. 21, 2017
Well type: Exploratory
Well Classification: Dry hole

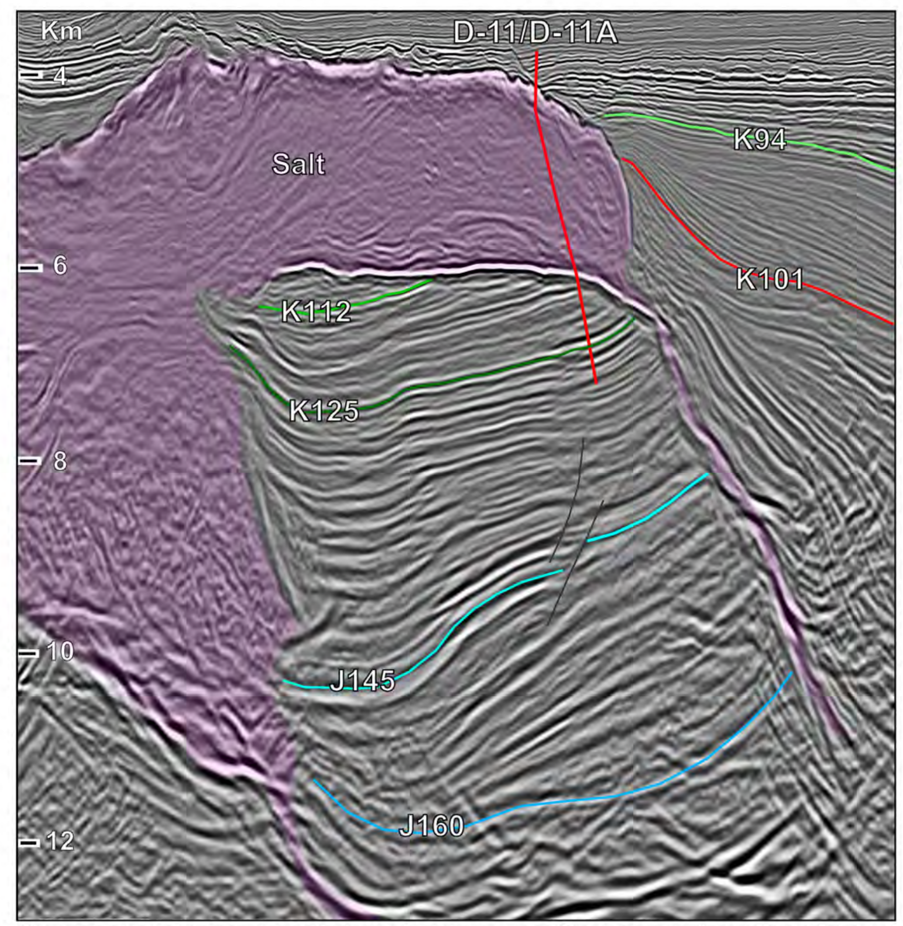
The Monterey Jack structure is a simple four-way closure with large upside if filled across a saddle to the north (Shell, 2017). **Pre-Drill -** The structure was interpreted to contain folded Cretaceous and Jurassic strata and the targeted reservoirs were downdip turbidite equivalents of the Missisauga Formation. **Post Drill -** Intervals were intersected at the prognosed depths and were the expected thickness however, no hydrocarbon-bearing zones were encountered. The targeted Missisauga reservoir interval was predominantly composed of claystone, shales and marls. The age of strata at the base of the well is Callovian (Shell, 2017). Similar to Cheshire L-97/L-97A , Monterey Jack penetrated an erosional remnant of fine-grained Cretaceous and Jurassic strata. Multiple erosional surfaces between the K101 and the J160 are visible on the above strike seismic line intersecting the well.



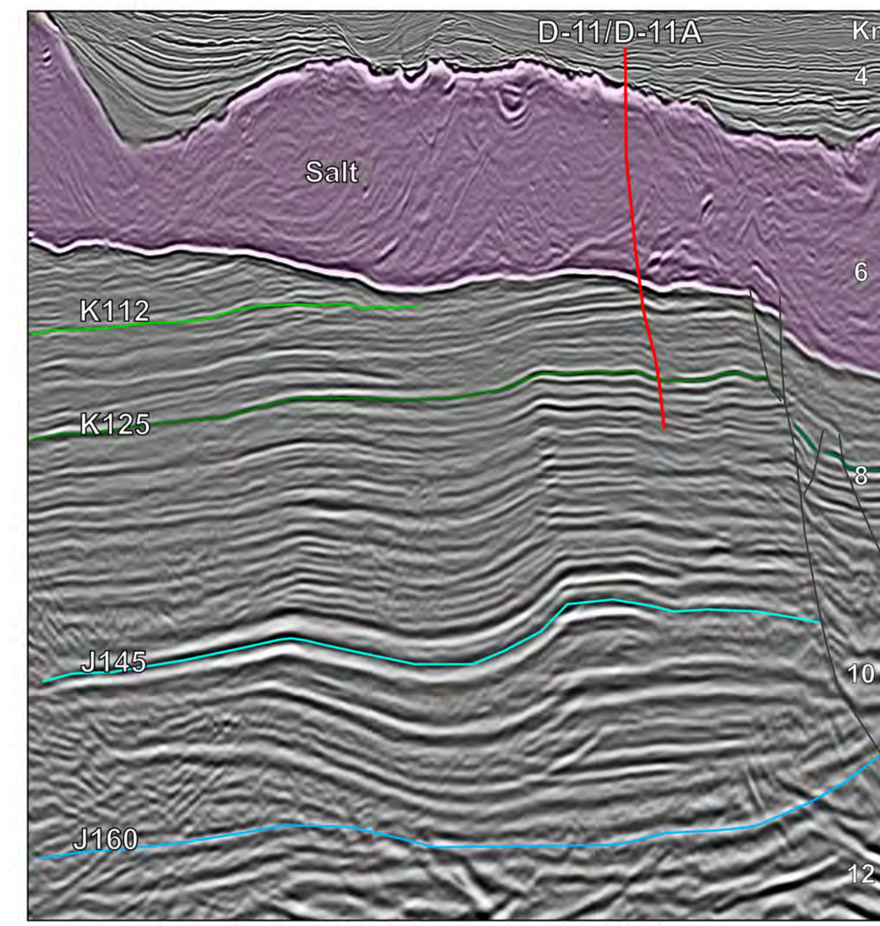
This ~300 km long strike line crosses the Shelburne (NS24-S006-003E) and Tangier (NS24-B071-001E) wide azimuth seismic surveys, intersecting three key wells, and avoids most vertical piercing salt bodies.



K125 (Top Missisauga) structure map and the location of Aspy D-11/D-11A



Dip oriented (along deviated well) seismic profile through Aspy D-11/D-11A



Strike oriented seismic profile through Aspy D-11/D-11A

Aspy D-11/D-11A
BP Canada Energy Group
Water Depth: 2771 m
Total Depth (md): 7400 m
Completed: Dec. 11, 2018
Well type: Exploratory
Well Classification: Dry hole*

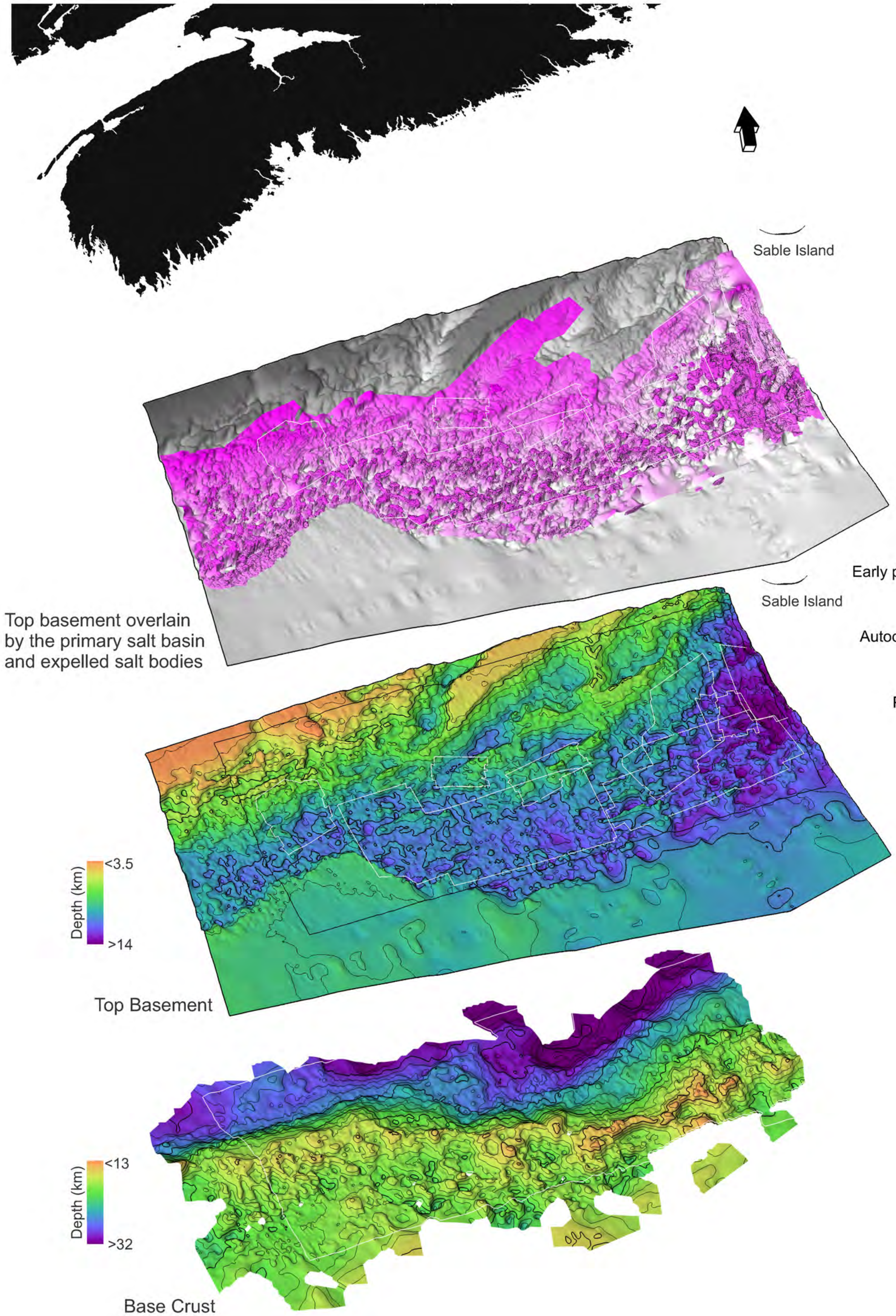
The Aspy structure is a narrow, east-west trending, sub-canopy trap, requiring three-way closure against a combination of overlying salt and a fault/salt-weld to the east. The structure is within a complicated area surrounded by younger mini-basins, salt-welds and salt feeder systems. **Pre-Drill** - Aspy D-11/D-11A targeted interpreted Early Cretaceous turbidite lobes and channel complexes within the Missisauga and Logan Canyon formations. The reservoir zones were expected to be present below a 2 km thick allochthonous salt canopy. **Post Drill** - A 130 m thick interval containing multiple Aptian aged siltstones was encountered 45 meters below the salt canopy. Throughout this interval the well had significantly elevated mud-gas readings and the cuttings fluoresced. While reservoir quality sandstones were not encountered in this interval there were clear indications of gas charge. Deeper in the well, two Barremian-Hauterivian aged sandstone intervals were encountered. The shallower interval, from 7115-7134 m, is a 19 m sequence of three upward-coarsening reservoir quality sands interbedded with shales and silts. The second is a 2 m thick sandstone interval at the base of the well. The two lower intervals have no indications of hydrocarbon charge and may have lacked an effective seal across a salt weld.
*In the Aspy D-11/D-11A Well History Report, BP describes the well as a dry hole with gas shows (BP, 2019).

Atlas of 3D seismic surfaces and thickness maps, central and southwestern Scotian Slope

Chapter 2 – Basement and Salt

Chapter 2 – Basement and Salt

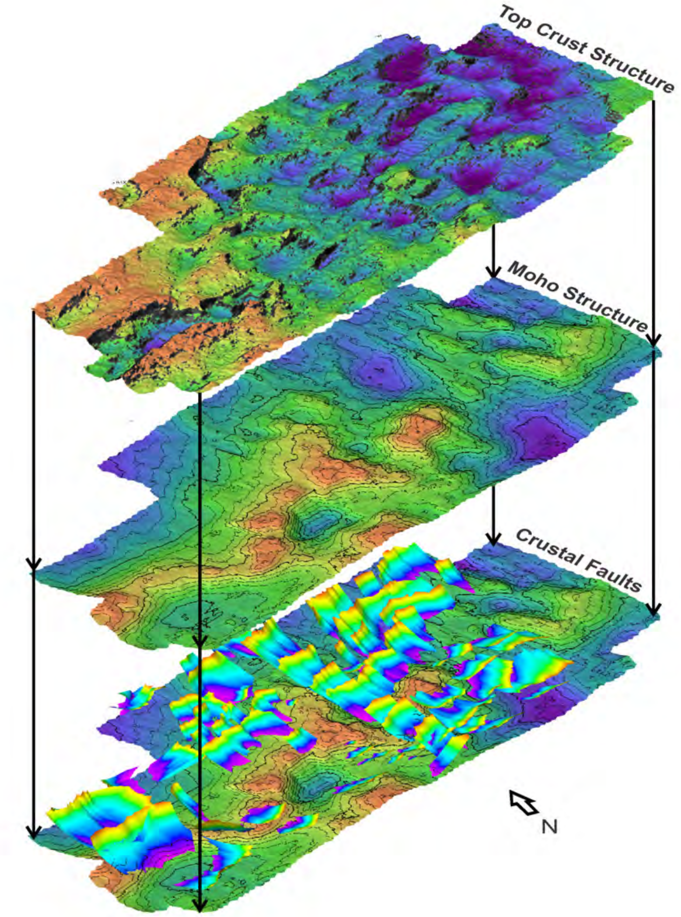
Mark E. Deptuck and Kristopher L. Kendell

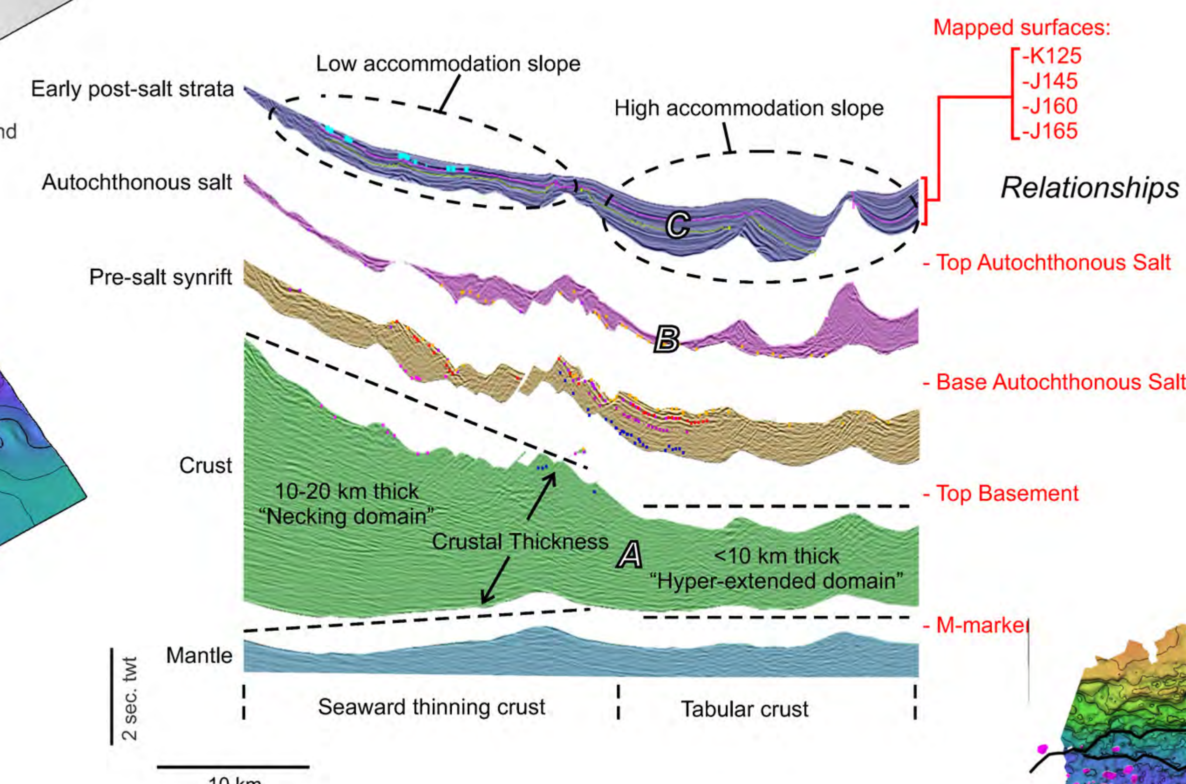


Looking deeper...

Assembly and interpretation of an extensive reflection seismic dataset collected mainly for hydrocarbon exploration over the past five decades, enables us to study proximal to distal changes in crustal structure across the SCOPE study area. Widespread correlation of top basement (middle left) and a bright marker near the base of the crust - interpreted as a reflection Moho (lower left) - provides insight into crustal thickness (lower right), while excellent imaging in some surveys provides a clearer picture of how the reflection seismic character of the crust varies as well as its deformation style. Likewise, the ability to overlay multiple layers like crustal thickness, magnetic anomaly maps, salt distribution, and early sediment distribution, provides insight into the interdependency between layers - for example, the relationship between crustal thickness, thickness of the primary salt layer, and distribution of early minibasins, or the linkage between certain crustal domains and patterns in overlying depositional systems (e.g. bypass slope localized above necking domain crust; carbonate bank aggradation above proximal domain crust, etc.).

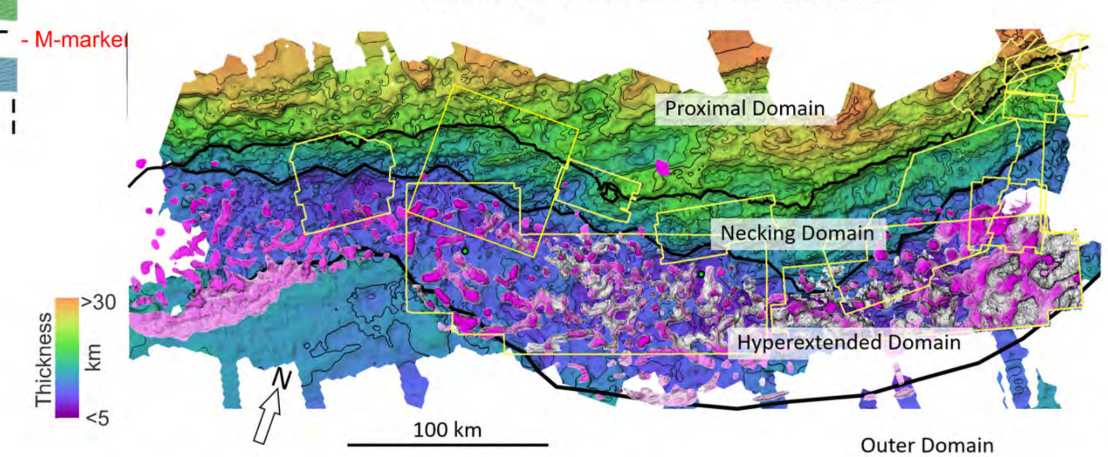
This chapter includes nine panels that summarize mapping results from both 2D and 3D reflection seismic data-sets in the SCOPE study area. We start with the M-marker, interpreted as a reflection from the crust-mantle interface, then the top crust marker, followed by a first-order approximation of crustal thickness based on a necessarily simplified crustal velocity model (and a more robust velocity model for the over-burden). We then present a series of panels showing the structure, distribution, and thickness of both the primary salt layer and salt bodies expelled from the primary salt layer (allochthonous salt that is located within younger strata).



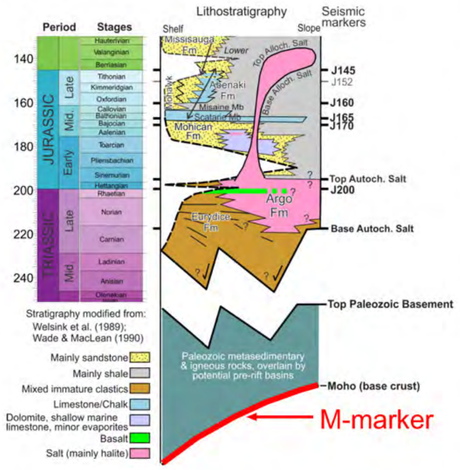


*Relationships between **A**, **B**, and **C***

Crustal Thickness and Crustal Domains



Recommended citation:
Deptuck, M.E. and Kendell, K.L. 2020. SCOPE Project, Chapter 2 - Basement and Salt, In: Atlas of 3D Seismic Surfaces and Thickness Maps, Central and Southwestern Scotian Slope, Canada-Nova Scotia Offshore Petroleum Board Geoscience Open File Report: 2020-003MF, 10 panels.



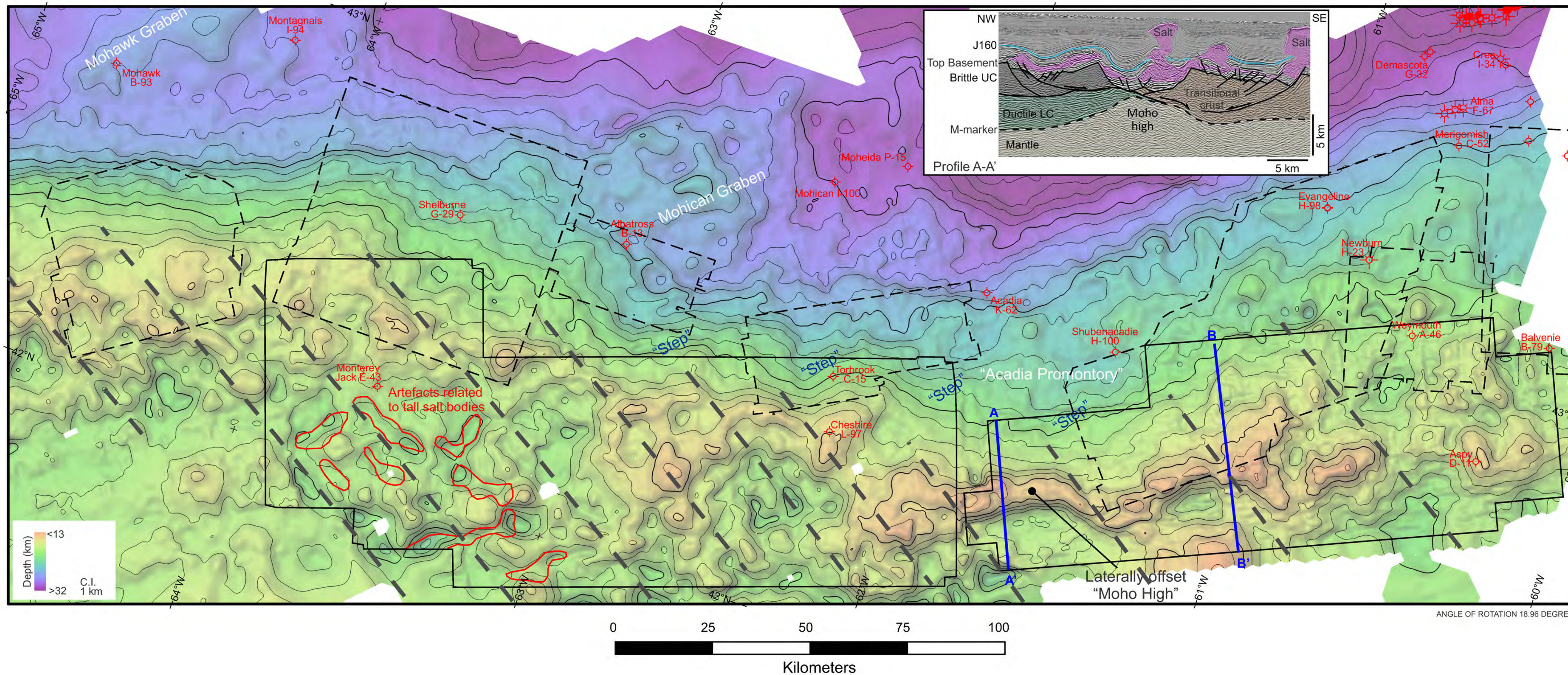
M-marker - Base of the crust (Moho)

The M-marker is the deepest widespread coherent marker correlated in the study area. It forms a strong to weak marker between 9 and 12 s two-way travel time in a number of deeper penetrating 2D multichannel seismic profiles, and three of the 3D seismic volumes used in this study (Barrington, Shelburne, and Tangier). The marker is equivalent to the M-marker defined by Keen et al. (1991), who interpreted it as a reflection Moho. The M-marker locally forms a strong reflection in landward areas, with diminished coherence further seaward, beneath the primary salt basin. In the Barrington survey for example, it forms a discrete, crisp trough-peak reflection, with most of the energy and continuity located in the underlying peak. It is also well-imaged seaward of the primary salt basin in the southwestern corner of the study area, where it forms a high amplitude and generally high continuity undulating peak-trough-peak reflection beneath crust veneered by seaward dipping reflections (Deptuck 2020).

An average crustal velocity of 6.5 km/s was used in our velocity model to depth convert the M-marker (a necessary simplification given the dearth of crustal velocity constraints). Its precise depth-structure will undoubtedly change with a more sophisticated velocity model. For example, its maximum depth in landward areas, where the crust is thickest, could be 2.1 km shallower with 6.0 km/s crust or 2.1 km deeper with 7 km/s crust, with a substantially smaller error bar further seaward where the crust is commonly < 5 km thick (for example, the M-marker would be roughly 500 m deeper even if p-wave velocities were 7.5 km/s in seaward 'transitional' crust). The structure of the M-marker, and resulting crustal thickness, should be regarded as notional until a more sophisticated velocity model is possible.

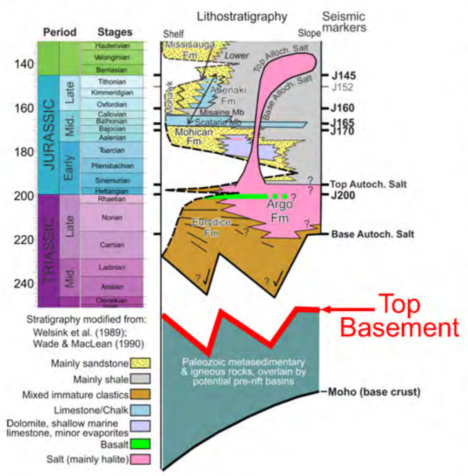
Overall, the M-marker is shallowest in the seaward parts of the study area, directly below the primary salt basin, where it is 14 to 17 km deep. The surface plunges deeply below the LaHave Platform in the landward direction, where it is 26 to 28 km deep in the western study area and below the Mohican Graben, deepening to 35 km in the eastern study area. The steeper gradient along which the M-marker deepens towards the LaHave Platform, is offset along-strike by a number of right-lateral steps towards the "Acadia Promontory" located near the western parts of the Thrumcap and Tangier surveys. In the Barrington survey, a number of shorter wavelength undulations characterize the shallower parts of the Moho surface, coincident with abrupt thickness variations in the generally thin overlying crust. A number of shorter wavelength undulations are also recognized in the Shelburne survey, but some of these, like the localized lows in the western parts of the survey, are likely artefacts related to poor handling of salt velocities in the psdm volume we used to interpret top basement (where velocity pull-ups beneath salt produced erroneous "basement highs"). In contrast, the M-marker was interpreted from pstm data, and did not strictly honour the abrupt velocity pull-ups immediately beneath the same salt bodies (i.e. the M-marker was "smoothed over" crossing some of these abrupt localized velocity pull-ups). As such, crustal thickness beneath the salt bodies identified in red is erroneously thick, pushing the M-marker too low in these areas after depth conversion.

In the Tangier psdm survey, which does not appear to suffer from the same salt-related velocity artefacts, the M-marker forms a narrow high with distinct lateral offsets that mimic the lateral "steps" in the higher gradient parts of the marker (e.g. see profile A-A'). Its topographic expression diminishes in the eastern parts of the survey, where the M-marker is increasingly challenging to identify.



Chapter 2 – Basement and Salt

Mark E. Deptuck and Kristopher L. Kendell

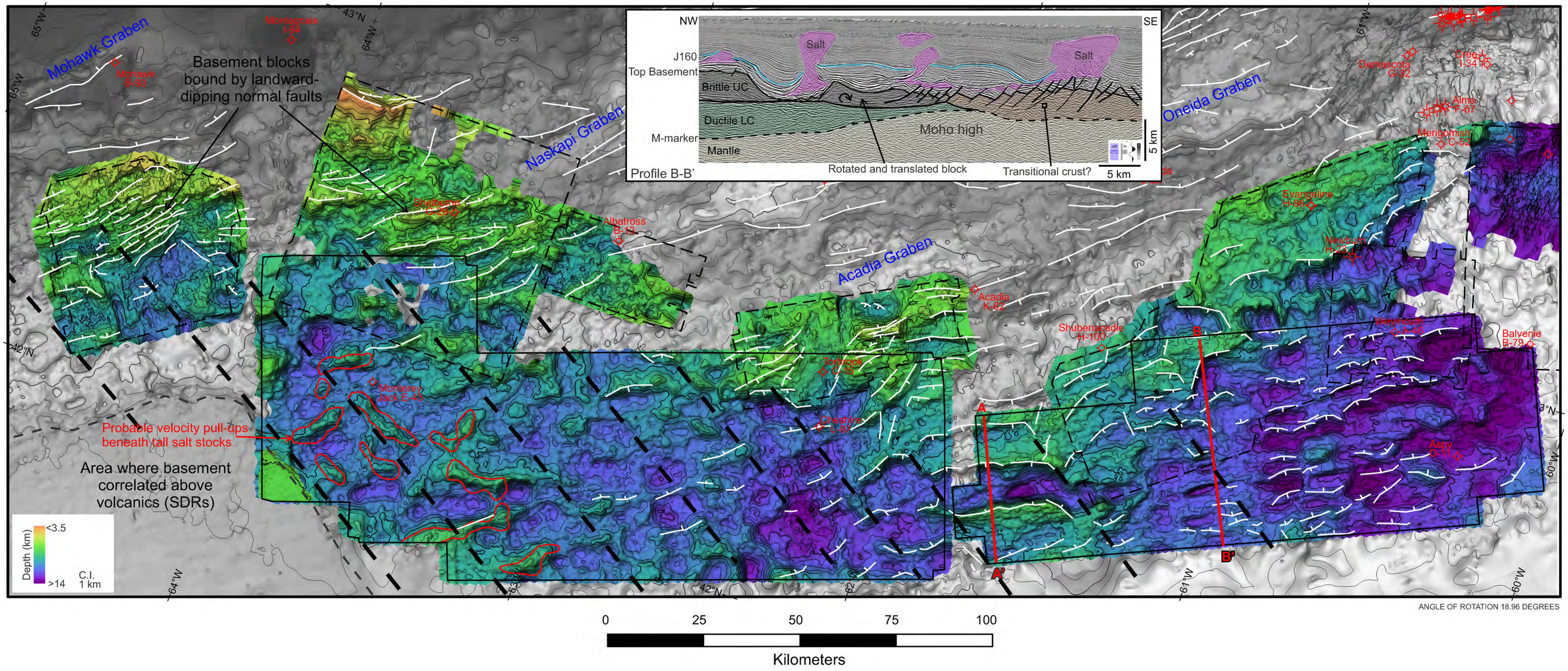


Top Basement

The absence of a strong, consistent impedance contrast between crystalline basement and overlying syn-rift strata makes correlation of the 'top basement' surface challenging. As such, the top basement marker carries a higher degree of uncertainty than most other markers in this study. With one exception, top basement was carried below the deepest seismically layered stratigraphic successions, guided by some of the better quality surveys and calibrated in a number of wells on the platform that terminated within Lower Paleozoic Meguma meta-sedimentary rocks or the mid- to Late Paleozoic plutonic rocks that intrude them. Seaward of the primary salt basin (along and seaward of the outer band of the East Coast Magnetic Anomaly), however, the marker was instead correlated with a much higher degree of confidence *above* highly reflective rocks likely corresponding to volcanics or igneous crust (for example, the marker was carried above the area of seaward dipping reflections in the southwestern study area). This surface, however, almost certainly defines the top of younger "new" crust than the top basement surface carried above Paleozoic basement further landward. Together the top Paleozoic basement and top SDR markers define a regional composite 'top basement' surface, but with significant age diachroneity and compositional variability.

The top basement surface reveals the intricate arrangement of basement fabrics along the central to southwestern Scotian margin. It deepens from roughly 2 km above heavily eroded flat-topped basement highs on the platform (e.g. Mohawk B-93, encountered Devonian granites at a depth of 2.11 km in the landward parts of Figure 3; see Pe-Piper and Jansa 1999) to more than 6 km deep beneath intervening rift basins where the top basement surface is offset along a series of mainly landward dipping border faults that sole into mid-crustal shear zones. The landward parts of the Barrington, WG, Mamou, and Torbrook surveys cover some of these landward dipping faults. Here, the top basement surface is rugose with extensional faults producing linear basement highs (e.g. at Shelburne G-29) that strongly controlled the accumulation of younger strata, including salt.

Further seaward beneath the present-day slope, towards the axis of the primary salt basin, the top basement surface is offset by both landward- and seaward-dipping faults. Distinct rift basins are absent, replaced instead by broken reflective intervals of unknown composition above basement, in turn overlain by salt. Basement depth increases steadily from ~8 km deep in the southwest to > 14 km deep in the northeast. There are a number of basement highs here also, but in the Shelburne 3D survey in particular, some coincide closely with overlying vertical salt bodies (red polygons), which probably reflects poor handling of salt velocities in the psdm volume available to us (i.e. velocity pull-ups beneath the salt remain in the depth-migrated volume). The more detailed salt model used in the Tangier psdm survey produces a more reliable top basement surface, confirming the presence of a number of complex basement elements. Some very abrupt changes in top crust elevation (> 4 km vertical changes over distances less than 2 km) correspond to offsets or detachment of brittle upper crust fragments above ductile middle to lower crust (see Profile B-B'). There also appears to be a change in the reflection character of the crust in the Tangier survey, from decoupled crust with clear brittle and ductile components landward of the Moho high, to coupled crust with a more heavily faulted appearance seaward of the Moho high. The latter may correspond to transitional crust.



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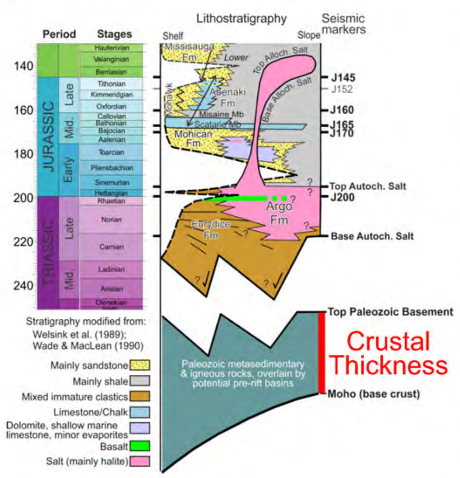
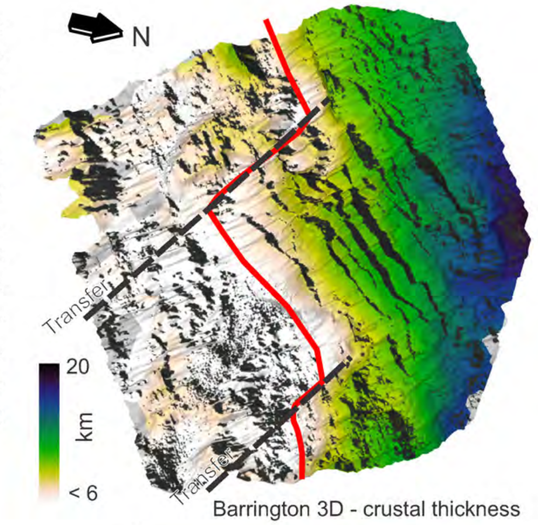


Crustal Thickness - Moho to Top Basement

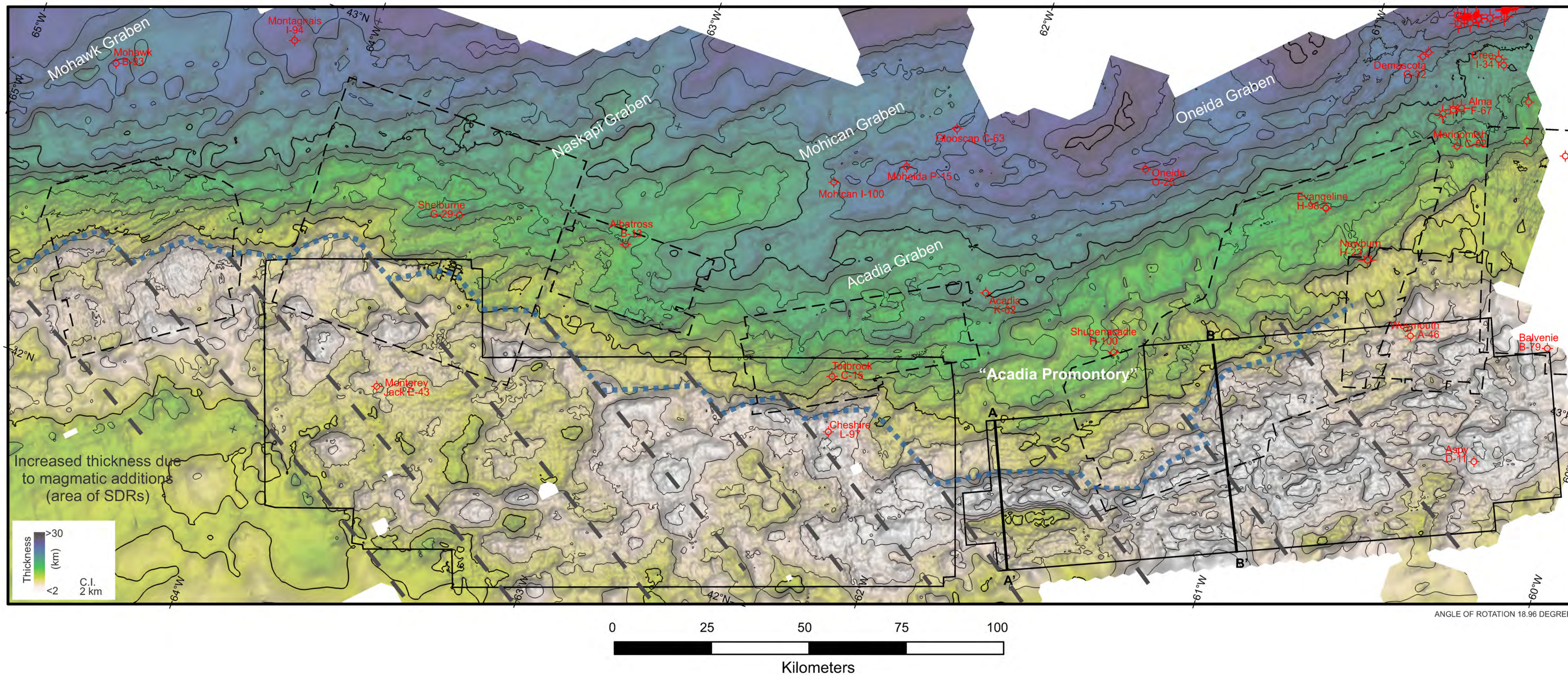
Widespread correlation of the Top Basement and M-markers provides a direct measure of crustal thickness across much of the study area. The crust is thickest beneath the outer parts of the LaHave Platform where, using a 6.5 km/s p-wave velocity, it is up to 31 km thick. Crustal thickness diminishes abruptly seaward, from 20 to just 10 km thick over distances less than 45 km. Whereas proximal to distal thinning was accommodated at least in part by the landward dipping NE-SW oriented normal faults that sole into shear zones in the middle crust, abrupt lateral crustal thickness variations are also evident. Crustal thinning is strongly segmented along-strike, with the distal limit of the necking domain (roughly the 10 km crustal thickness contour) thinning abruptly across a series of 12 to 30 km spaced right-lateral steps (e.g. see inset to the right) that change to left-lateral steps approaching Sable Subbasin. The change from right-stepping to left-stepping offsets coincides with the seaward most promontory of thicker continental crust, which we refer to as the "Acadia Promontory". These sharp lateral changes in crustal thickness are interpreted as products of NW-SE synrift transfer faults or accommodation zones oriented orthogonal to the trend of most other basement faults. Extensional fault arrays commonly terminate abruptly approaching them (e.g. see image to the right).

The Tangier, Thrumcap, Weymouth and Veritas surveys are located above or east of the Acadia Promontory; the Shelburne, Torbrook, Mamou, WG, and Barrington surveys are located west of it. Further seaward in all of these surveys, crust beneath the primary salt basin is fragmented, generally ranging from 8 to 6 km thick, thinning to <5 km thick along the Moho high that underpins it. In contrast to thicker crust further landward, both landward- and seaward-dipping faults offset the crust in the Shelburne and Tangier surveys. The synrift transfer faults invoked to explain the stepped offsets in thicker crust, are also interpreted to continue seaward where they segment the thinnest and weakest crust, paralleling the sharp offset in the primary salt basin referred to as the Yarmouth transfer/ transform fault zone (Deptuck 2011; 2020).

Crust in the western part of the Shelburne survey is generally thicker than crust in the eastern part of the Tangier survey. Likewise, the crust is up to 11 km thick in the southwestern corner of the study area, seaward of the primary salt basin. The increased thickness here (and perhaps also immediately to the east) reflects magmatic additions to the crust, including SDRs (Dehler et al. 2004; Deptuck 2020).



Barrington 3D - crustal thickness



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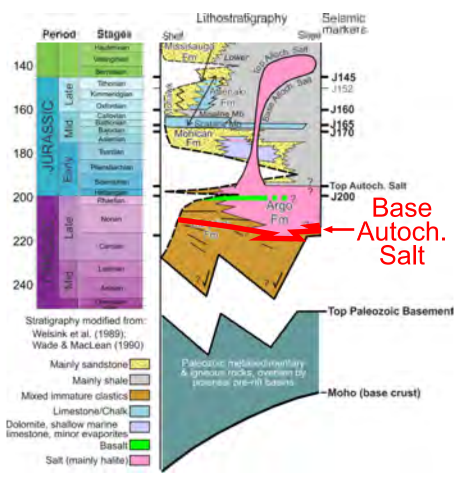
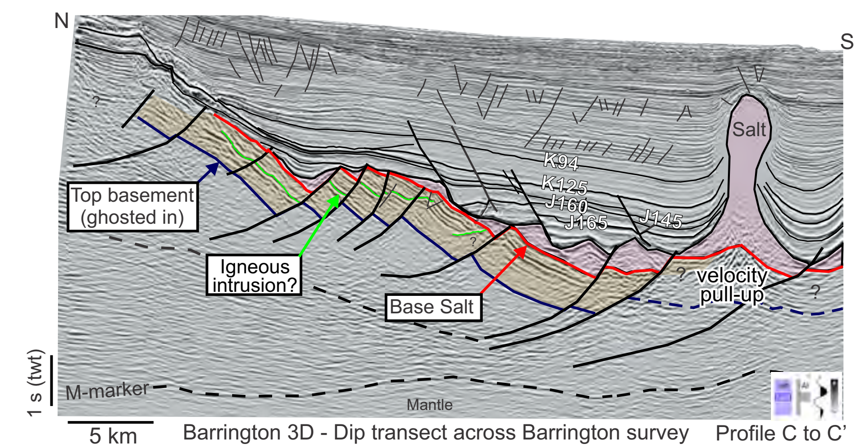


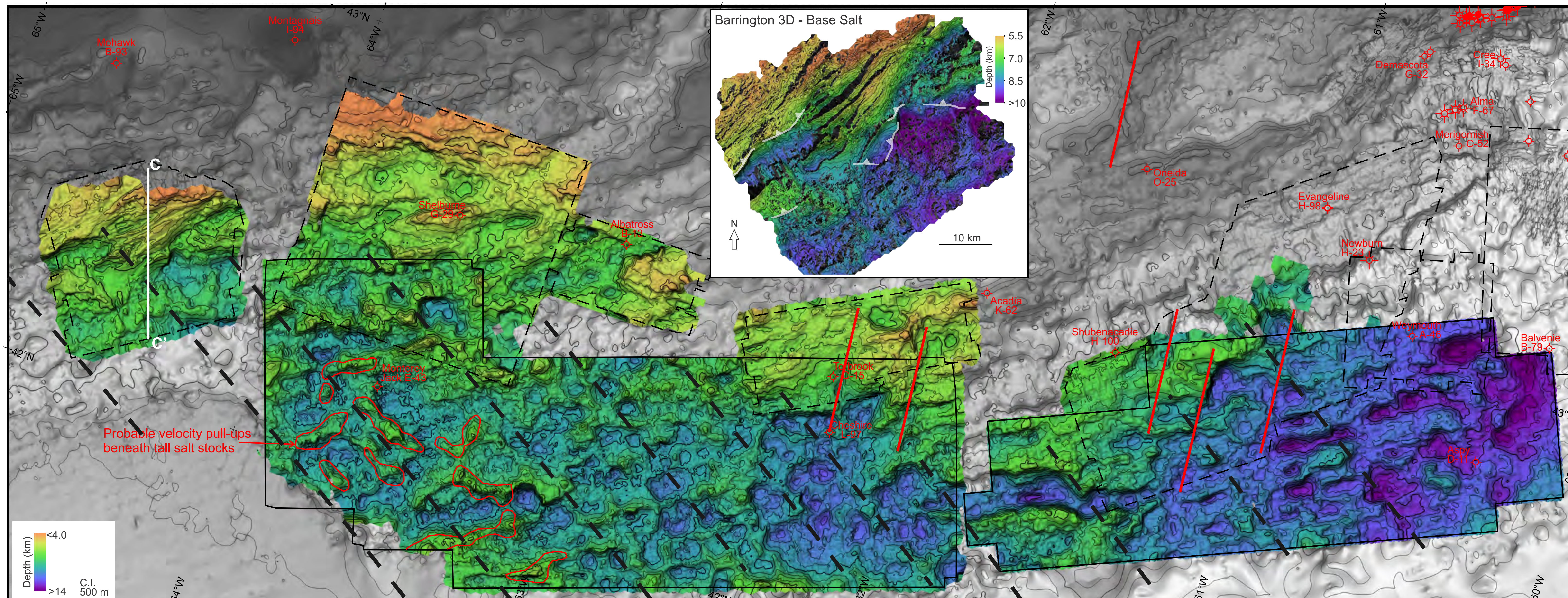
Base Autochthonous Salt

The term "autochthonous salt" or "primary salt" refers to salt that is still attached to its original depositional surface, and although the layer may be variably deformed, it is still situated in its original stratigraphic position. In the study area, the top basement surface is commonly veneered by variably imaged layered stratigraphic successions. They can exceed 4 km thick in proximal rift basins of the LaHave Platform (e.g. Deptuck and Altheim 2018), thinning substantially moving across the necking domain and towards hyperextended crust (e.g. Profile C-C'). The primary salt layer, composed mainly of incoherent to transparent seismic facies, is located above this heavily faulted, generally reflective layered pre-salt succession. The base salt surface is equivalent to the Tr220 marker that was carried through the Mohican, Oneida and Acadia grabens (Deptuck and Altheim 2018). No wells in the study area penetrate it and it is possible that the onset of salt deposition varied across the margin (e.g. beginning earlier in the Mohican Graben, and later further seaward, for example). Although the base salt surface could be diachronous, the *interface* between chaotic to transparent seismic facies associated with deformed evaporites and more reflective pre-salt strata of unknown composition, was correlated with a higher degree of confidence than the top basement surface.

The base salt surface is widely offset by basement faults implying that salt accumulated during active lithospheric extension (i.e. the salt is syntectonic). In the Barrington and WG surveys, most basement faults dip in the landward direction, offsetting the layered stratigraphic successions above basement and intervals of Late Triassic or earliest Jurassic evaporites. Maximum throw along the base salt surface exceeds 1.5 km, making the surface highly rugose, and exerting a strong influence on later salt expulsion. In addition to NE-SW fabric associated with rift extension (offset by NW-SE lineaments associated with synrift transfer faults shown as black dashed lines), a number of N-S lineaments are also apparent along the base salt surface, particularly in the eastern study area (red lines).

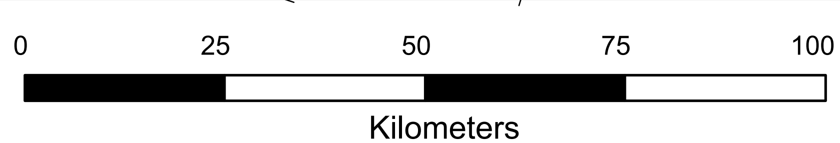
Like the top basement surface, some of the base salt rugosity in the western parts of the Shelburne survey appear in part to be artefacts caused by poor handling of salt velocities in the psdm volume available to us (i.e. velocity pull-ups beneath the salt remain in the depth-migrated volume - see red polygons that outline a number of tall vertical salt bodies that coincide closely with base salt highs).





Background image is "top basement"

ANGLE OF ROTATION 18.96 DEGREES



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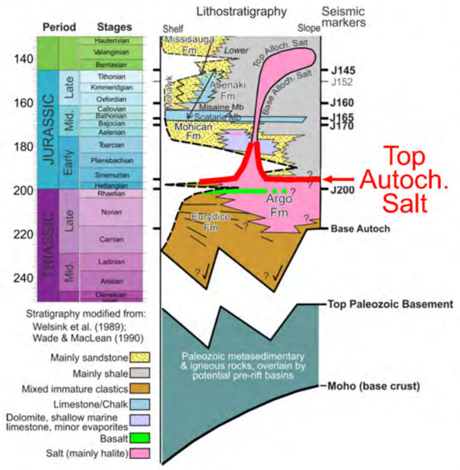
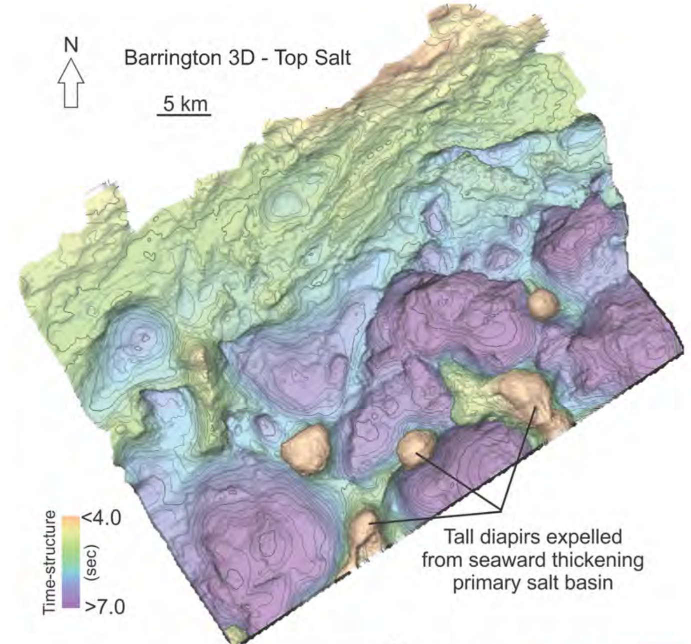


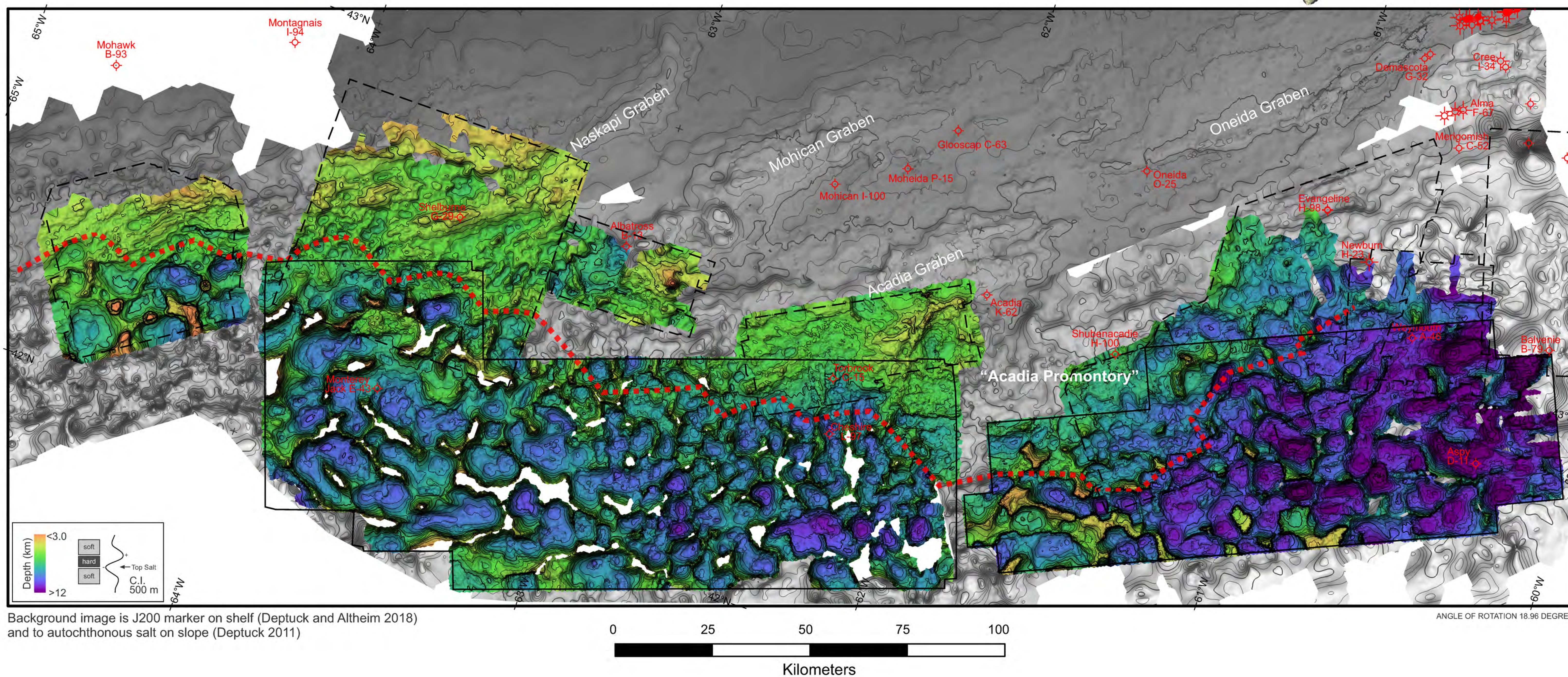
Top Autochthonous Salt

Above the interval of strongly faulted layered reflections is a distinct interval of chaotic to reflection free seismic facies interpreted as deformed Late Triassic to Lower Jurassic evaporites of the Argo Formation (Wade and MacLean 1990). Where these evaporites are still located in their original stratigraphic position, and overlain by younger Jurassic strata, they are capped by a broad variable amplitude, but commonly strong trough, in turn overlain by a narrower moderate to strong peak. The strong soft loop capping this interval is produced by the lower density and velocity of deformed evaporites beneath denser Jurassic strata (commonly carbonates). This strong trough defines the top of the primary salt layer.

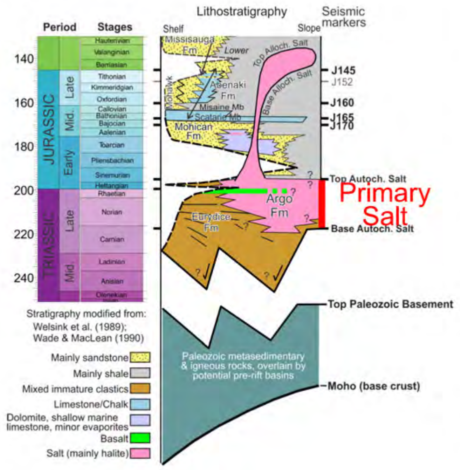
No wells in the study area penetrate this surface, but in the Mohican Graben to the north, Glooscap C-63 penetrated a 152 m basalt (CAMP) capping a 441 m thick Late Triassic interval of layered evaporites (halite) and fine grained red beds (Weston et al. 2012). However, the section is incomplete at Glooscap C-63, with an unconformity capping the volcanics and eroding candidate Lower Jurassic strata that thicken away from the borehole (Deptuck and Altheim 2018). As such, the age of the top salt marker is not known, but could be younger. Like the base salt surface, the top salt marker could be diachronous, and though it is capped by CAMP basalt flows on the platform (at Glooscap C-63), salt deposition may have continued into the Early Jurassic further seaward, where increased accommodation also improved its preservation potential. This would place the top salt surface *above* CAMP volcanics (see Profile E - E' where a very bright marker near the base of the salt layer is a candidate CAMP basalt marker).

The top autochthonous salt surface is structurally complex, but can be broadly separated into a landward region and a seaward region (red dashed line - that broadly follows the 9-10 km crustal thickness isochron). North of this boundary it is widely welded-out (e.g. landward parts of the Barrington, WG, Torbrook, and western Thrumcap surveys). Aside from remnants of salt preserved in salt rollers or localized pods, its expression mimics that of the base salt surface. Further seaward, the surface is dominated by a polygonal network of subcircular to elongated minibasins haloed by salt stems formed during down-building in the Jurassic and Cretaceous. Taller salt bodies (stocks and walls) were widely expelled from these basins.





Background image is J200 marker on shelf (Deptuck and Altheim 2018) and to autochthonous salt on slope (Deptuck 2011)

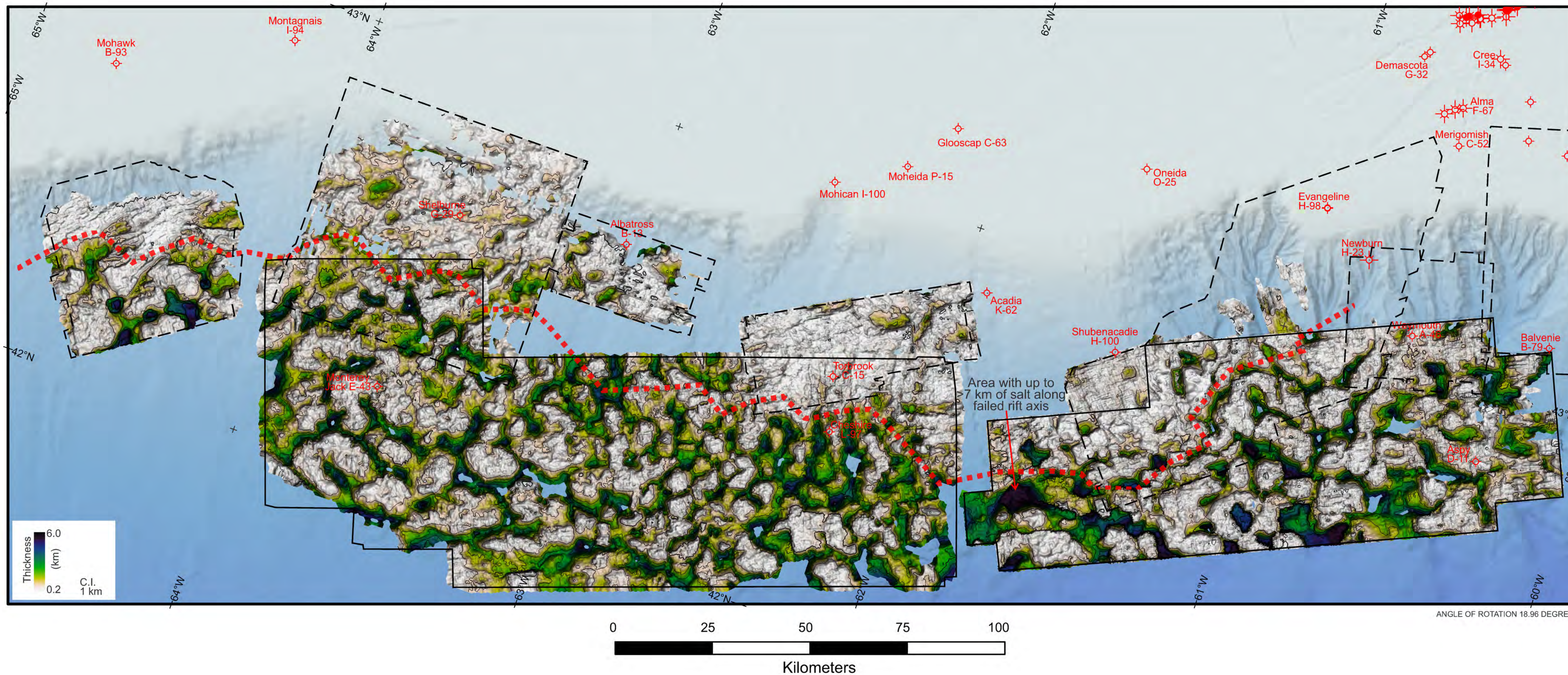


Thickness - Primary Salt Basin

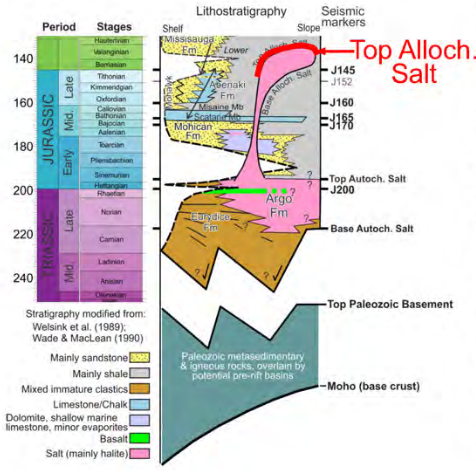
Salt thickness between the base and top of the primary salt layer varies widely across the study area, ranging from swells that are more than 7 km thick to welds with little or no salt. Whereas salt in proximal rift basins above the LaHave Platform was relatively thin (likely < 1 km thick near Glooscap C-63), clear changes in the salt-tectonic style are evident stepping off the LaHave Platform that, along with an number of other observations, imply more salt accumulated in the seaward parts of the study area.

Thickness distribution largely parallels the structural character of the top autochthonous salt surface described in the previous panel as well as clear proximal to distal changes in salt tectonic style. The thinnest remnants of salt are preserved in the landward parts of the Barrington, WG, Torbrook, and western Thrumcap surveys. Here, fragmented slabs (or rafts) of mainly Jurassic cover strata are offset along low-angle listric faults and associated salt rollers and pillows. Gravity gliding dominates. Some slabs are more heavily rotated where their seaward translation was hindered by an underlying basement high. Reactive diapirs are common, as are narrow linear salt highs associated with strike-slip offset between adjacent rafts. Sediment loading and minibasin development is only locally important (e.g. in the Mamou survey, at the mouth of the southwest plunging Mohican graben), and tall salt bodies are largely absent. We link this salt tectonics style to the necking domain where underlying crust is generally thicker than 10 km, and infer that the original primary salt layer was relatively thin, or was tapered in the landward direction, above crust that provided only limited accommodation space for salt to accumulate.

There is a sharp increase in the density of well-developed minibasins flanked by taller salt stocks and walls in the seaward parts of the Barrington, WG, Thrumcap, Weymouth, Shelburne and Tangier surveys. It was not possible to confidently correlate the top or base salt surfaces in the Veritas, or landward parts of the Thrumcap and Weymouth surveys. The halos of inflated primary salt surrounding largely welded-out minibasins in the Shelburne and Tangier surveys form an intricate polygonal network of salt thicks - many of which correspond to the roots of much taller salt stocks or walls, and increasingly salt tongues and salt stock canopies to the east. The red dashed line shows the approximate boundary between thicker crust of the necking domain and thinner crust of the hyper-extended domain (crust is thicker than 9 km north of this line). That the thickest remnants of salt and long-lived largely welded-out minibasins are present in regions of thinner crust south of this line, implies the primary salt basin was thicker here. The earliest welded minibasins (pre-J165) also thicken abruptly stepping across this stepped crustal domain boundary, with a number of basins accumulating up to 4 km of early post-salt strata. This implies there was an abrupt seaward increase in salt thickness stepping off necking domain crust and onto hyper-extended crust, and that increased crustal thinning favoured the accumulation of thicker intervals of salt. A pod of swelled primary salt > 7 km thick remains along the axis of a failed rift immediately seaward of the Acadia Promontory. The underlying crust here is < 3 km thick above a prominent Moho high. Highly thinned crust, and by inference increased salt accommodation, continues towards the eastern Tangier survey where complex salt canopies developed, fed by seaward-leaning salt feeders.



Mark E. Deptuck and Kristopher L. Kendell



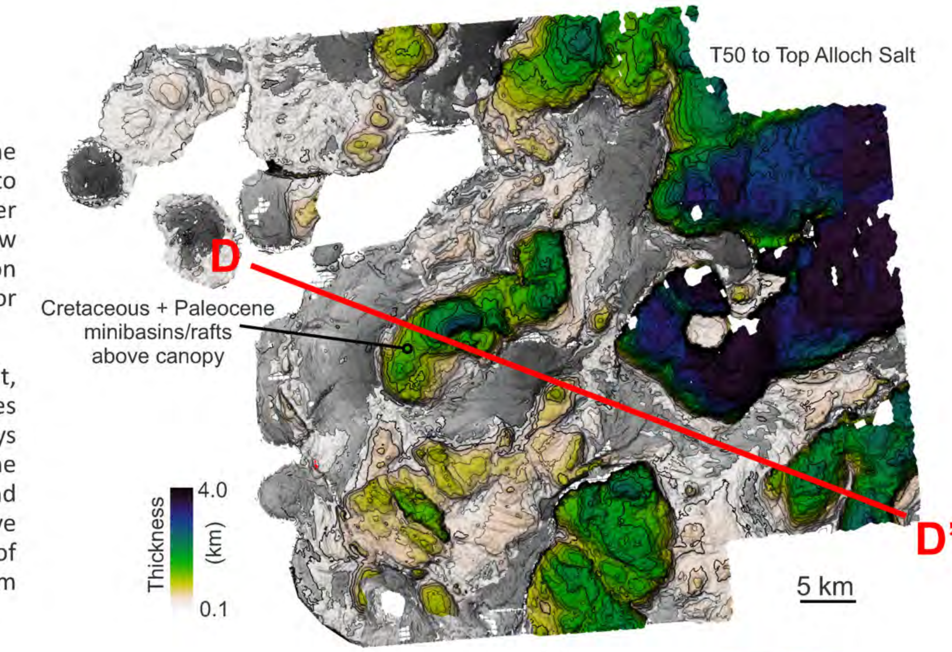
Top Allochthonous Salt Bodies

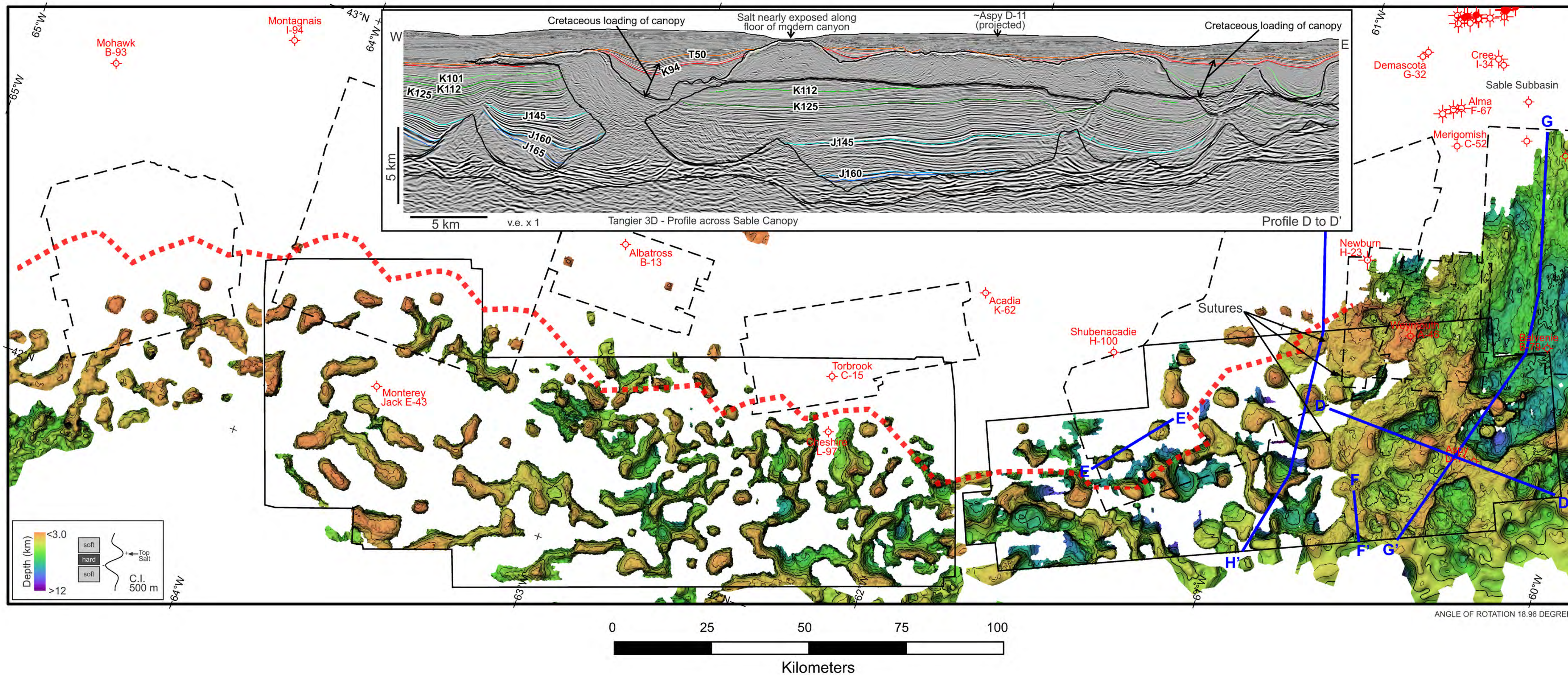
Widespread expulsion of salt took place in the seaward parts of the Barrington, WG, and Thrumcap surveys, and throughout the Shelburne, Tangier, Weymouth and Veritas surveys. The red dashed line shows the approximate boundary between thicker crust of the necking domain and thinner crust of the hyper-extended domain (crust is thicker than 9 km north of this line). Also shown are salt bodies mapped and gridded from 2D seismic profiles. The top reflection above shallow salt bodies commonly corresponds to an impedance increase, and has been correlated as a hard peak across the study area.

There are wide variations in the style of allochthonous bodies, but they generally form isolated salt walls and stocks in the west and salt tongues and amalgamated salt stock canopies in the east. Most salt diapirs are bulbous or mushroom shaped, with minor salt overhangs. Salt overhangs are most prevalent in the eastern part of the Shelburne and throughout the Tangier, Weymouth, Veritas, and southern Thrumcap surveys (see next panel and Profiles G-G' and H-H').

The crests of most salt bodies range from 2800 to 3600 m below sea level. The amount of overburden above them however, varies between more than2.0 km to less than 300 m, with salt bodies in the distal parts of the Shelburne and Tangier surveys commonly buried by the least amount of sediment (< 1 km). Shallow buried diapirs are located in areas where there was either focused erosion (removing overburden), or recent expulsion (locations where even the seafloor marker shows subtle expression of the underlying salt diapirs).

Internally, salt bodies in the Tangier survey shows clear layering within salt, highlighting internal compressional deformation within expelled salt tongues (Profile F-F' next panel) and diapirs (profile E-E' next panel). In most other surveys allochthonous salt bodies contain incoherent reflections or are transparent. In the eastern study area the salt canopies have been reactivated as Cretaceous and Cenozoic strata accumulated in minibasins, forming bowl-like depressions above the canopy (Profile D-D'). The thickness map on the right shows the distribution of Cretaceous strata above the canopy in the eastern Tangier survey. Maximum minibasin thickness exceeds 4 km.





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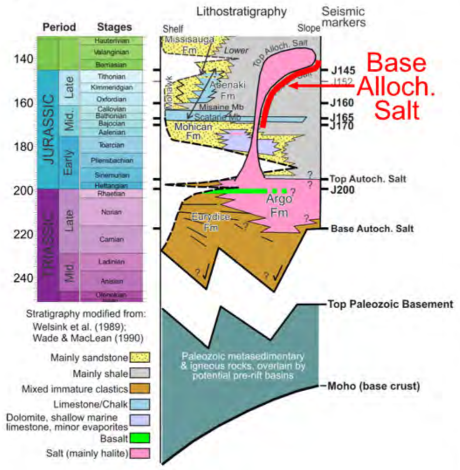
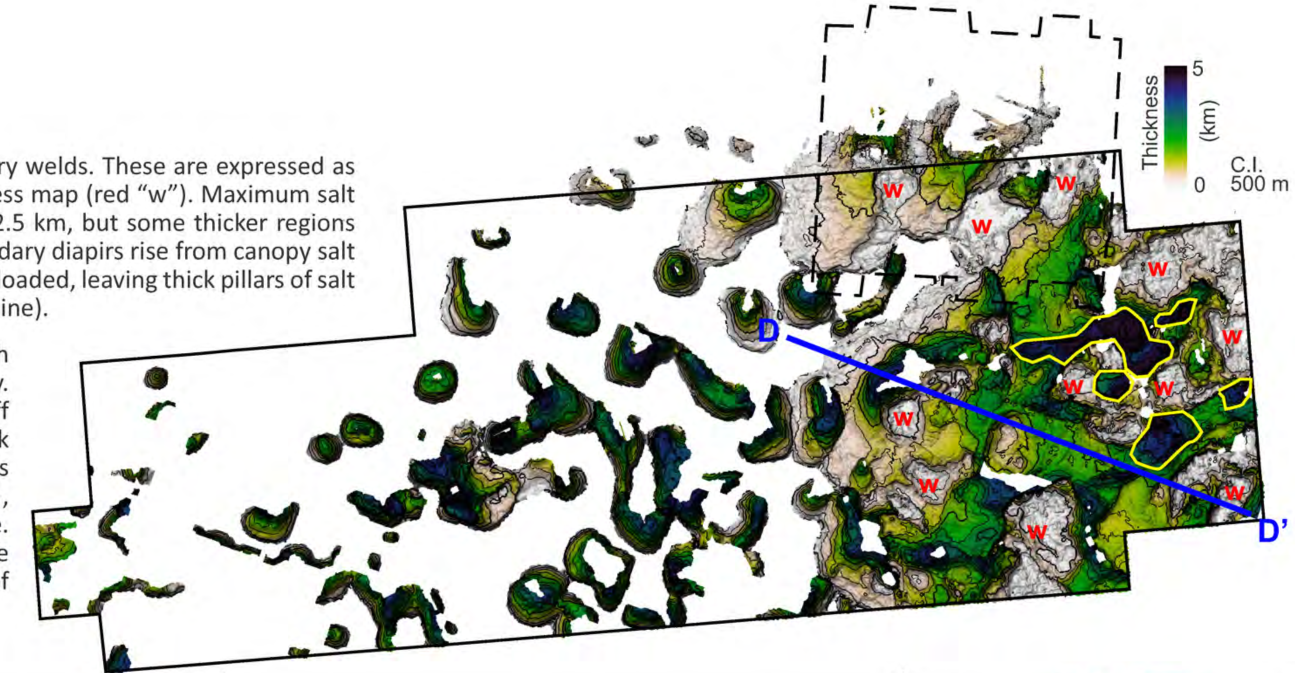


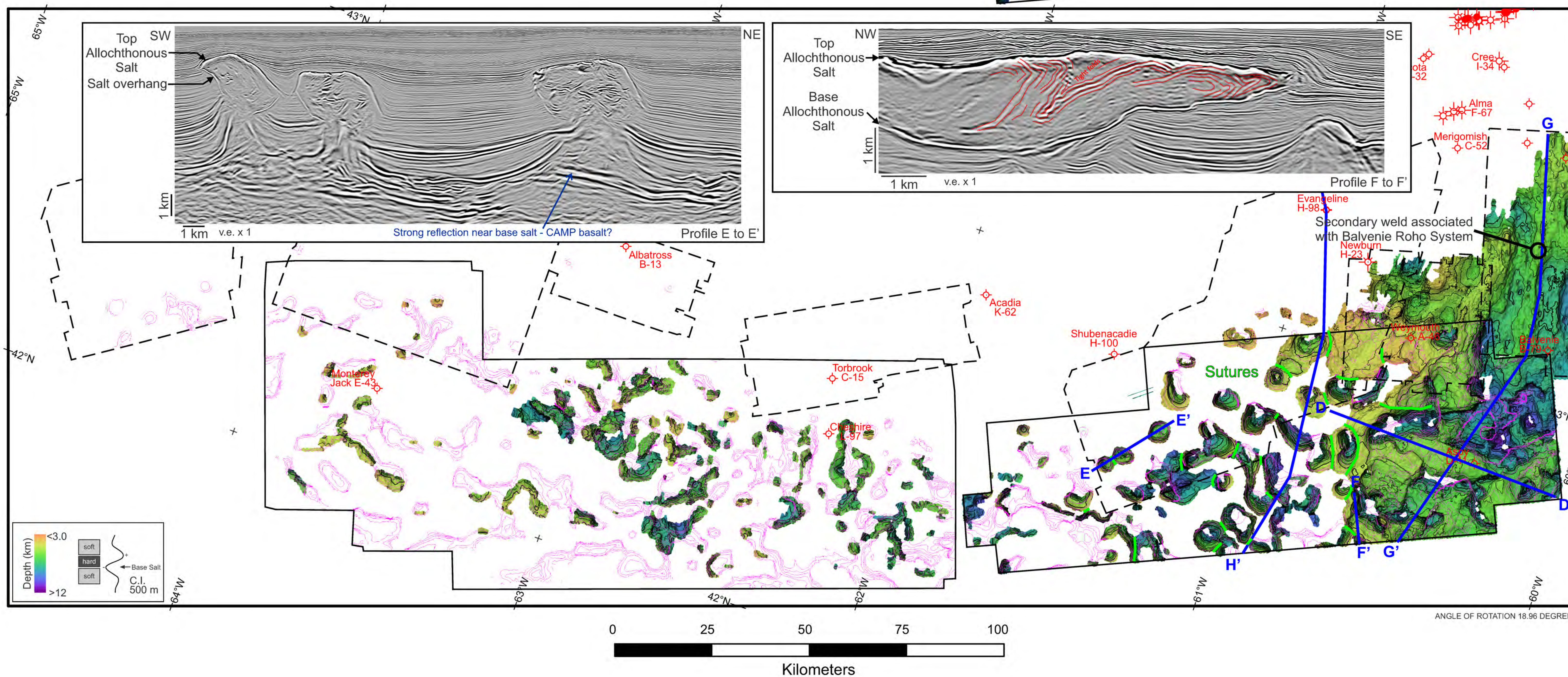
Base Allochthonous Salt Bodies and Salt Thickness

A number of salt bodies were expelled such that parts of them now lie above strata that is younger than the salt. Salt overhangs commonly produce a strong soft trough at shallow depths, changing to a hard peak in areas where the salt overlies older/denser strata. The distribution of salt overhangs is shown below, overlain by 1 km spaced structural contours from the top allochthonous salt surface (in pink).

Salt feeders are generally vertical in the Shelburne survey and western parts of the Tangier survey, with salt overhangs ranging from symmetrical to asymmetrical (skewed to one side of the salt body). The base allochthonous salt surface in a number of diapirs is funnel-shaped, reflecting salt bodies that are wider near their tops than along their stems or keels (see profile E to E'). Salt feeders increasingly lean to the south (ranging from southwest to southeast) in the eastern parts of the Tangier and Thrumcap surveys, as well as in the Weymouth and Veritas surveys. Adjacent salt bodies also increasingly intersect moving east, generating numerous complex salt sutures (shown in green). In a number of areas where salt canopies have been reloaded, the top allochthonous salt surface merges with the base allochthonous salt surface to produce secondary welds. These are expressed as thins in the adjacent allochthonous salt thickness map (red "w"). Maximum salt thickness in the canopy is generally less than 2.5 km, but some thicker regions exceeding 5 km thick also develop where secondary diapirs rise from canopy salt and in areas where primary salt feeders were reloaded, leaving thick pillars of salt that rooting to autochthonous levels (yellow outline).

Weymouth A-45 and Aspy D-11 drilled through 1507 m and 2155 m of canopy salt, respectively. Both wells encountered primarily clear to off white halite, but Aspy also encountered thick intervals of reddish coloured carnalite, as well as thin layers of grey coloured claystone, siltstone/vfg sandstone, and potential anhydrite. It also encountered a 10 m section near the base of the salt body with potential 5 mm fragments of grey/black basalt (BP 2019 EOW Report).





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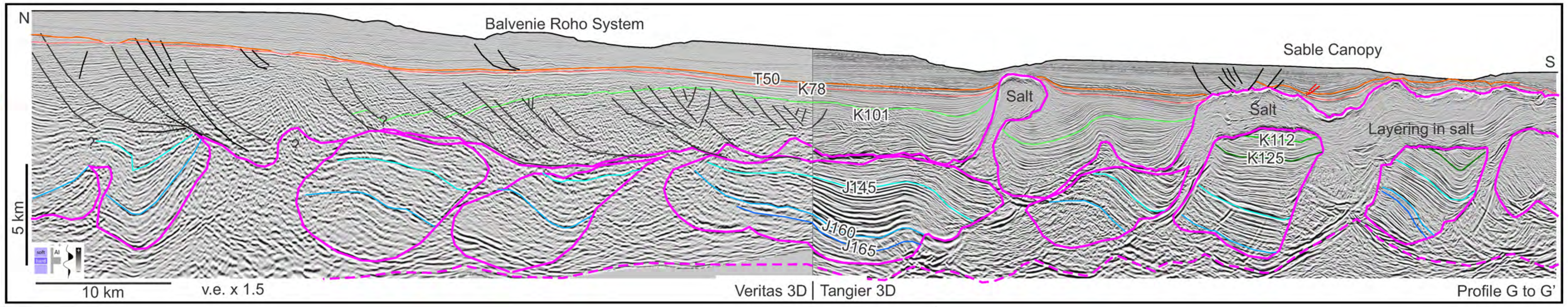
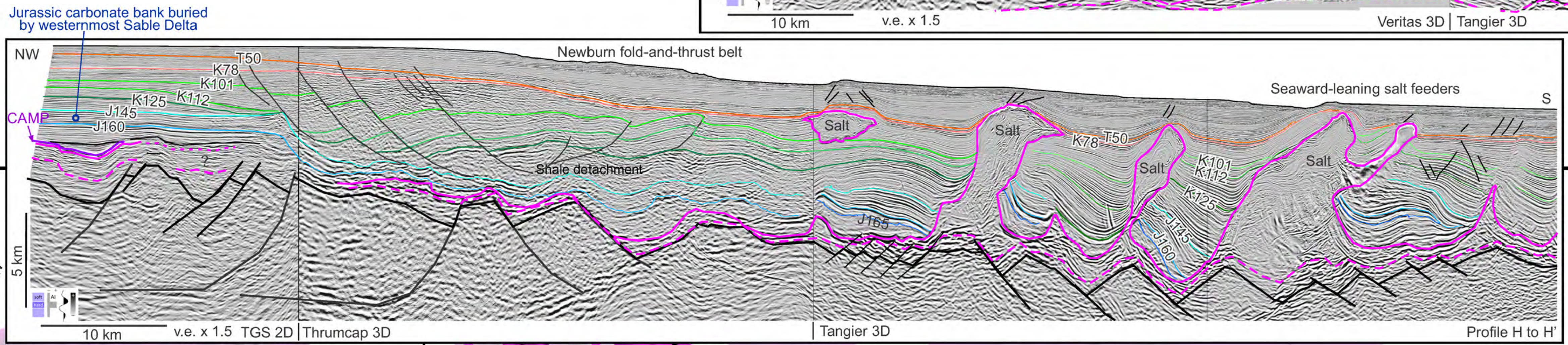
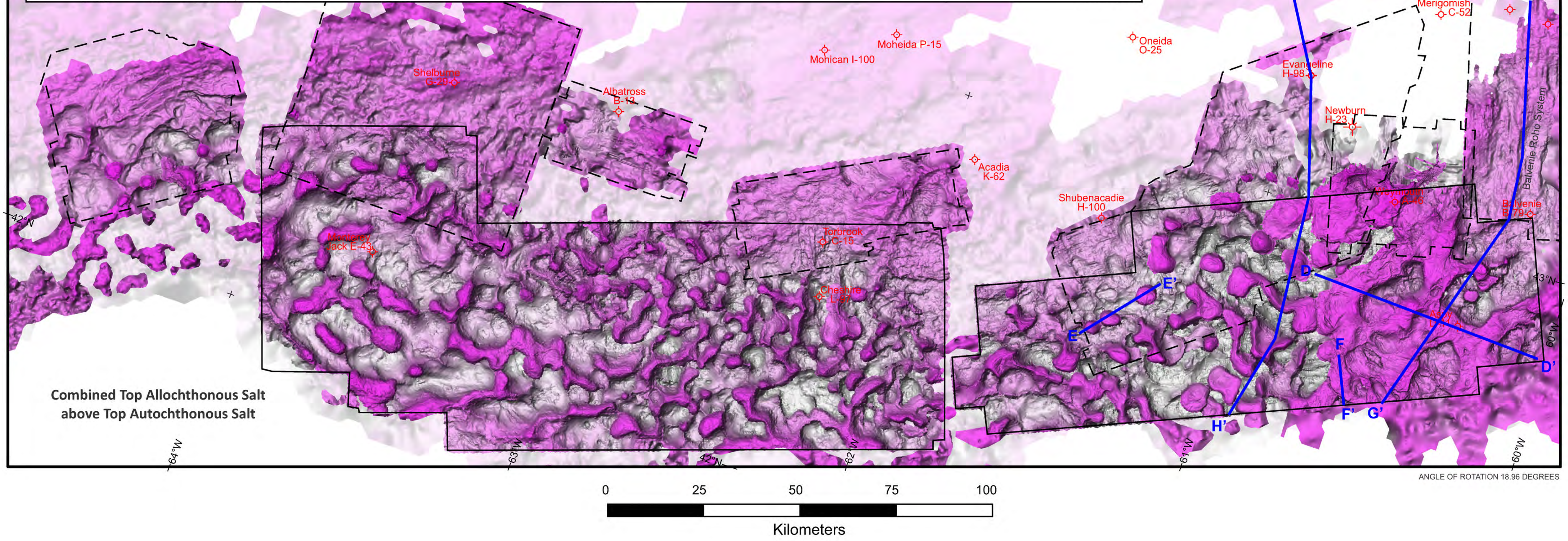
Regional profiles through complex allochthonous salt - eastern study area

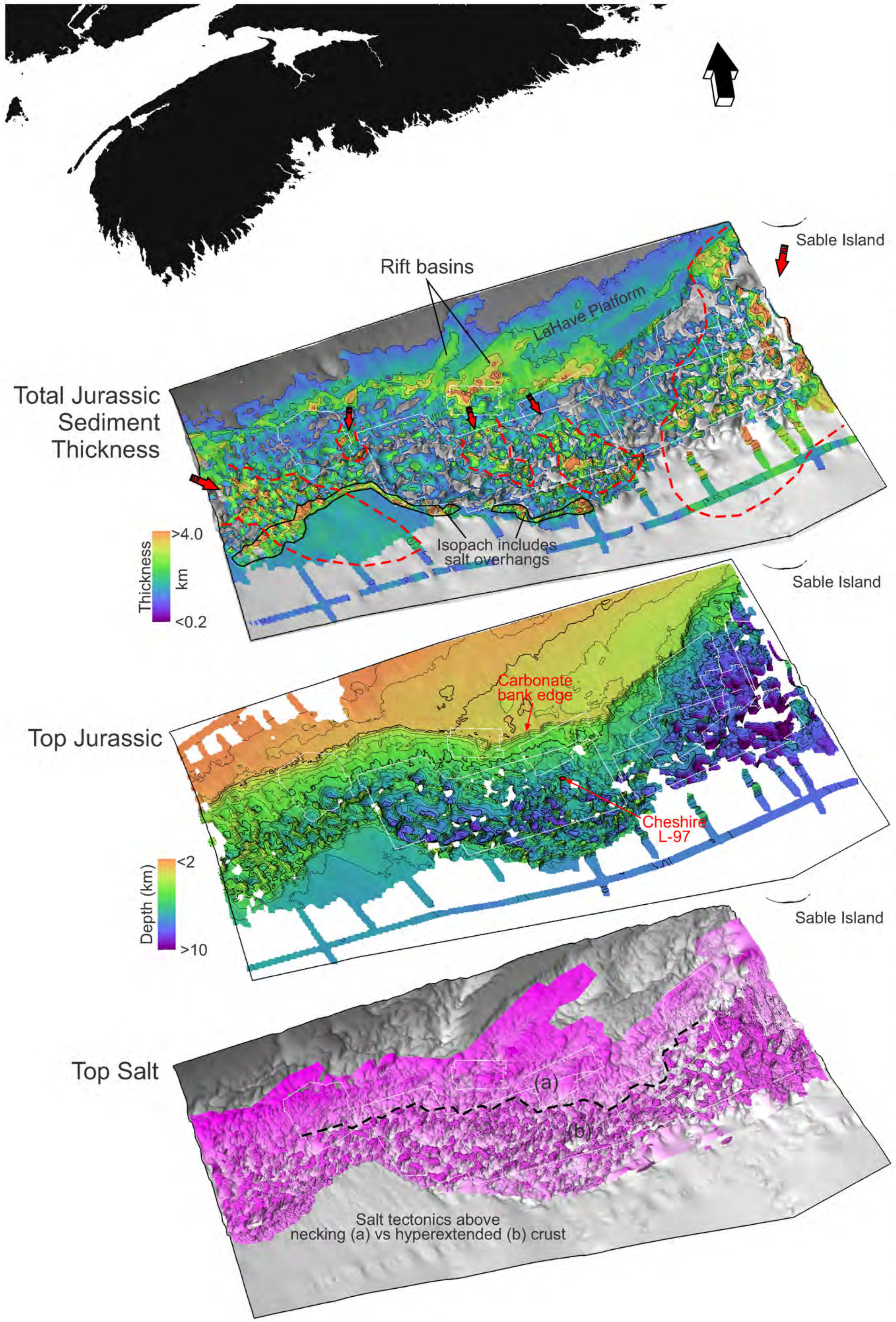






Atlas of 3D seismic surfaces and thickness maps, central and southwestern Scotian Slope

Chapter 3 – Jurassic



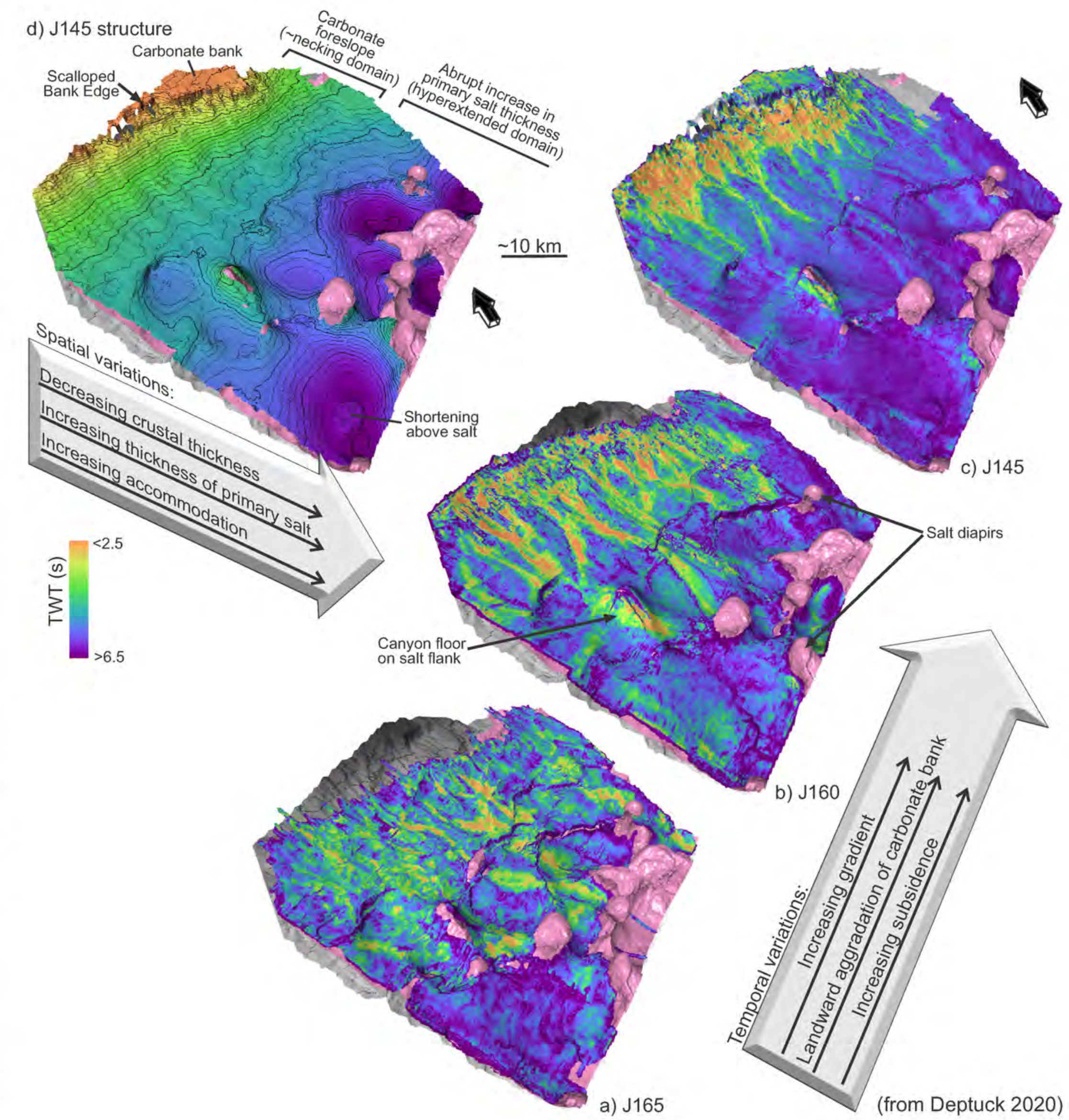
Jurassic sediment accumulation

Total Jurassic sediment thickness (top left) between the top of the autochthonous salt layer (lower left) and the top Jurassic J145 marker (middle left) shows the sharply contrasting sediment accumulation modes on the platform versus the slope. On the platform, up to 4 km of Jurassic strata accumulated above the top salt surface (or where salt is absent a combination of top CAMP volcanic J200 marker or the postrift unconformity that truncates it; Deptuck and Altheim 2018), with sedimentation focused above earlier northeast-trending rift basins that formed in the Triassic. No wells calibrate Lower Jurassic sediments in these rift basins, but Middle to Upper Jurassic immature clastics of the Mohican Formation or dolomites of the Iroquois Formation, or some combination, were encountered at the base of a number of wells. These pass up-section into widespread carbonates of the Abenaki Formation (Wade and MacLean 1990). Greater accumulation took place near the mouths of the Naskapi, Mohican, and Acadia grabens where there was increased salt withdrawal-related accommodation, and perhaps also tectonic subsidence stepping off the platform and onto more attenuated crust. On the slope, sediment accumulation is strongly localized in salt withdrawal minibasins - some exceeding 4 km in thickness. Thicker Jurassic minibasins are located in the east, approaching the Sable Subbasin where the carbonates of the Abenaki Formation transition into mixed carbonates and clastics of the Mic Mac Formation (Wade and MacLean 1990). Further west, thicker minibasins are clustered along three or four main corridors that may link to increased sediment accumulations on the platform (with sediment delivery guided through the axial parts of rift basins).

Basement morphology and crustal architecture both directly and indirectly influenced Jurassic sedimentation on the slope. Using the thickness of welded-out Jurassic minibasins as a proxy, the primary salt layer appears to have thickened abruptly stepping seaward off necking domain crust and onto hyper-extended crust thinner than 9-10 km. This produced a sharp contrast in the style of Jurassic salt tectonics that coincides with changes in underlying crustal domains; increased down-building and expulsion of tall salt bodies was mainly focused in areas underpinned by the thinnest crust, and early welds above thinner salt, accompanied by thin-skinned detachment and raft tectonics, was mainly focused above necking domain crust.

There is also a sharp change in the style and distribution of earlier versus later Jurassic strata across the study area that probably reflects regional tectonic controls and their impact on the distribution of tectonic subsidence. Pre-J165 sedimentation was focused along the remnant relief of rift basins on the platform extending seaward into widespread salt-withdrawal minibasins on the proto-slope. Recent paleoenvironmental results from Cheshire L-97, show that pre-J165 water depths were less than 100 m deep in the Bajocian (marginal marine to middle neritic environment; RPS 2018). In contrast, post-J165 sedimentation was focused above the platform, marked by widespread aggradation of the Abenaki carbonate bank, development of a sharply defined bank edge, and a thin, eroded succession further seaward interpreted as a carbonate foreslope. The carbonate bank preferentially aggradded above crust thicker than 20 km, with the sharply defined bank edge roughly coinciding with the 20 km crustal thickness contour. Seaward of it, the heavily eroded carbonate foreslope developed above seaward-thinning, and presumably more rapidly subsiding, crust of the necking domain, consistent with increasing water depths recorded in the latter part of the Jurassic in Cheshire L-97 (RPS 2018), located roughly 40 km seaward of the carbonate bank edge .

It appears that enhanced post-J165 subsidence above the necking domain not only controlled where platform versus slope carbonates were deposited, but it is also responsible for increasing the gradient of the proto-continental slope, a process recorded in the geomorphology of some Jurassic slope channel systems (figure to the right; Deptuck 2020), leading to the development of a bypass slope with long-term implications extending well in to the Cretaceous. A little surprising, however, is the shallow water depth recorded in the pre-J165 succession at Cheshire L-97, in an area underpin by crust that is probably less than 9 km thick (Chapter 2), and an interval that would traditionally be considered to be well into the "post-rift". These observations suggests something propped the distal part of the margin up, delaying thermal subsidence until after the Bajocian.



This chapter includes seven panels that summarize Jurassic mapping results from nine semi-contiguous 3D reflection seismic volumes on the central to western Scotian Slope. Starting with the composite J170/165 surface - the deepest marker we were able to carry regionally above the primary salt layer - we describe three Jurassic surfaces and intervening thickness maps. To provide a more complete picture, we also incorporate 2D seismic-based mapping results from the LaHave Platform that was done in an earlier project (from Deptuck and Altheim 2018).

Recommended citation:
Deptuck, M.E. and Kendell, K.L. 2020. SCOPE Project, Chapter 3 - Jurassic, In: Atlas of 3D Seismic Surfaces and Thickness Maps, Central and Southwestern Scotian Slope, Canada-Nova Scotia Offshore Petroleum Board Geoscience Open File Report: 2020-004MF, 8 panels.

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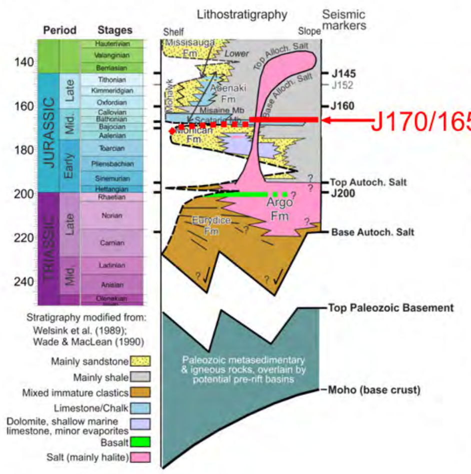
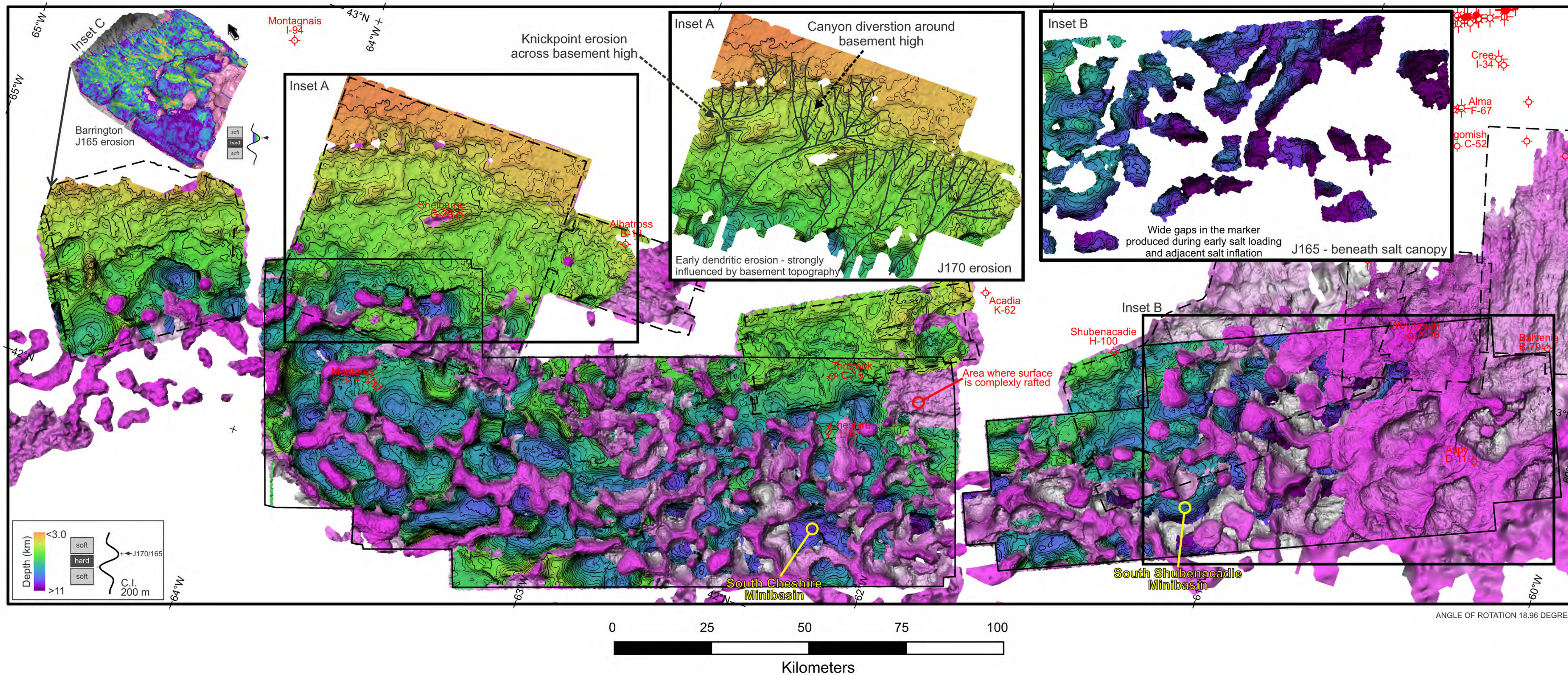


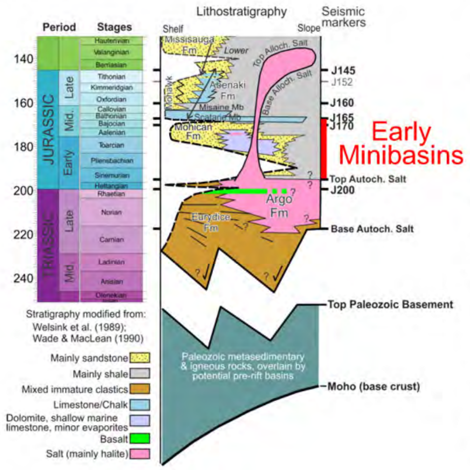
J170/165 Pre-Bathonian/Bathonian

The J165 marker is the oldest and deepest calibrated seismic marker in this study, corresponding to the base of a Callovian clastic-dominated succession and top of a thick Bathonian limestone unit at Cheshire L-97. It corresponds to a moderate to strong peak above a moderate to strong trough. No other wells calibrate this marker on the slope. The bright trough that underlies the J165 peak corresponds to the Bathonian limestone, the base of which corresponds to a thin shale unit that contains the Late Bajocian MFS near the wells TD (RPS 2018). The J165 peak was correlated with a moderate to high degree of confidence through the Shelburne and Tangier surveys. In both surveys the marker merges in the landward direction (through onlap) with a slightly older heavily eroded surface (where the surveys overlap with the WG, Torbrook and Thumcap surveys). We did not initially recognize that the landward unconformity was a separate surface, but it is clear that it continues below the J165 marker in the Thrumcap/Tangier surveys, although it cannot be correlated far in the seaward direction. As such, the landward unconformity has not been calibrated at Cheshire L-97, but we have notionally named it the J170 marker (but it could be somewhat older), and the composite surface the J170/J165 marker.

Proximal erosion along the J170 marker is widespread; it commonly caps (and erodes) a series of brittle rafted fragments of mainly Lower Jurassic strata identified in the Barrington, Torbrook, and Thrumcap surveys. The marker also caps intervals of expanded pre-J170 strata deposited in areas with sufficient salt-related accommodation. In planview, erosion produces a series of curvi-linear down-slope oriented channels in the Barrington survey (see amplitude extraction in Inset C; Deptuck 2020), with a clear dendritic pattern of erosion through the WG, Mamou and Torbrook surveys (Inset A). The pattern of erosion is strongly influenced by basement topography, with canyons diverted around the basement highs through relay ramps (e.g. near the Shelburne G-29 well), or entrenchment via knickpoint erosion across basement highs. The J170 unconformity marks the first widespread period of incision with downslope sediment transport along the proto-Scotian Slope, perhaps recording the early phases of rapid deepening and seaward tilting of necking domain basement off southwestern Nova Scotia (Deptuck 2020).

The J165 marker forms the top of two to four subtle onlapping markers that merge with the J170 erosive surface in the landward direction. J165 is widespread throughout the western parts of the Shelburne survey where it is preserved between mainly vertically rising salt diapirs or is preserved above steeply tilted flanks of distal diapirs (forming part of widespread salt megaflaps here). The marker is widely absent moving east and into the Tangier survey (see Inset B), where large gaps were produced by early expelled salt bodies (above which the marker is absent). Early salt bodies in the eastern Tangier survey lean increasingly seaward and underwent a much more complex evolution. As such, the wide gaps in the J165 marker are commonly occupied by Late Jurassic or Cretaceous minibasins, rather than vertically rising diapirs as observed further west. The marker is also challenging to correlate into some distal basins where Jurassic strata are expanded. In the "South Cheshire" minibasin, for example, the marker could instead be carried higher, above an expanded interval, which would increase the thickness of pre-J165 strata above the primary salt layer at this location.





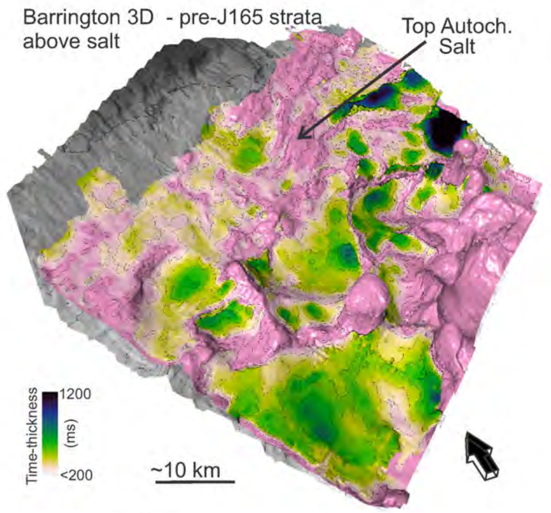
Thickness - Top Autochthonous Salt to J170/J165

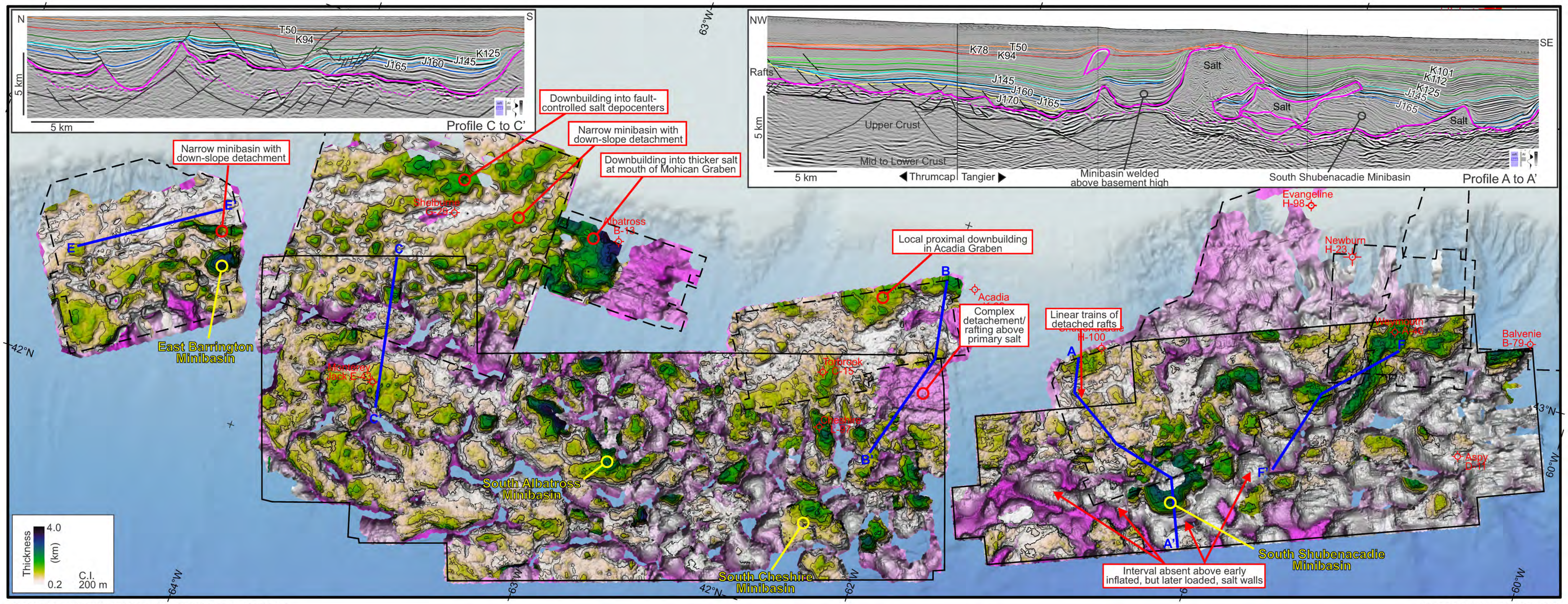
The Top Autochthonous Salt to J165 succession remains largely uncalibrated in the study area. Cheshire L-97A encountered ~320 m of Bathonian to Bajocian oolitic to bioclastic limestone and marl, with thin intervals of grayish black silty claystone in the uppermost parts of this interval. These rocks were likely deposited in an inner to middle neritic marine setting (paleo water depth < 100 m; RPS 2018). The pre-J165 succession is typically less than 2 km thick across the study area, thinning substantially above salt or basement elements, or associated with detachment faults above the primary salt layer. Seismic facies are commonly lower amplitude in the lower part of the succession, increasing towards the upper part of the succession (likely due to increased carbonates).

Pre-J165 strata deposited above the primary salt layer are preserved in three main salt tectonic-related settings: (i) as fragmented rafts deformed and faulted during gravity gliding; (ii) as thicker minibasins that formed through downbuilding or as localized expulsion rollovers in areas where the primary salt layer was thicker; and (iii) as continuous strata preserved in salt megaflaps, found mainly in the distal parts of the Shelburne survey.

Pre-J165 cover strata are commonly segmented into small pods or angular fragments floored by low angle seaward-dipping listric faults that sole out into the primary salt layer, in the opposite direction of most rift-related basement faults (see profiles A-A', B-B', and C-C'). This reversal in fault polarity is attributed to the onset of post-rift thermal subsidence with enhanced gravity-driven thin-skinned detachment facilitated by salt. The same episode of subsidence likely prompted erosion along the J170 unconformity.

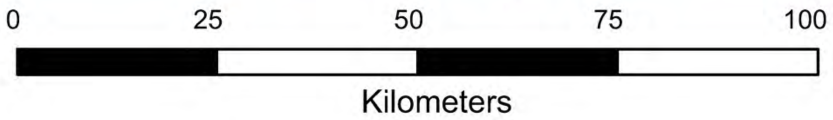
Some thicker accumulations of pre-J165 strata are found in more proximal settings where they occupy fault bound grabens that once held thicker intervals of salt (e.g. near the western limits of the Naskapi, Mohican, and Acadia grabens (Deptuck and Altheim 2018 - see next panel also). For example, more than 3.5 km of pre-J165 sediment accumulated in the Mamou survey that covers part of the Mohican Graben. Thicker accumulations are also found immediately seaward of the necking domain, along the leading edge of the diapiric province where early complex salt bodies - commonly with seaward leaning feeders - were expelled. In the South Albatross and South Shubenacadie minibasins in particular, expulsion roll-overs imply a pulse of sediment was delivered to deeper basin underpin by hyper-extended crust (see seaward part of Profile A-A'). Up to 4 km of strata were deposited in the East Barrington, South Albatross, South Cheshire, and South Shubenacadie minibasins identified below.





Underlying pink surface is top of the autochthonous salt layer..

ANGLE OF ROTATION 18.96 DEGREES



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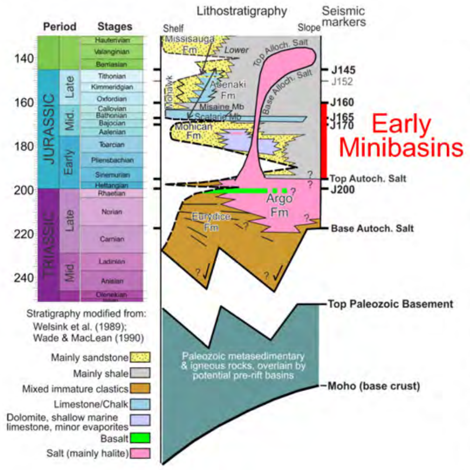
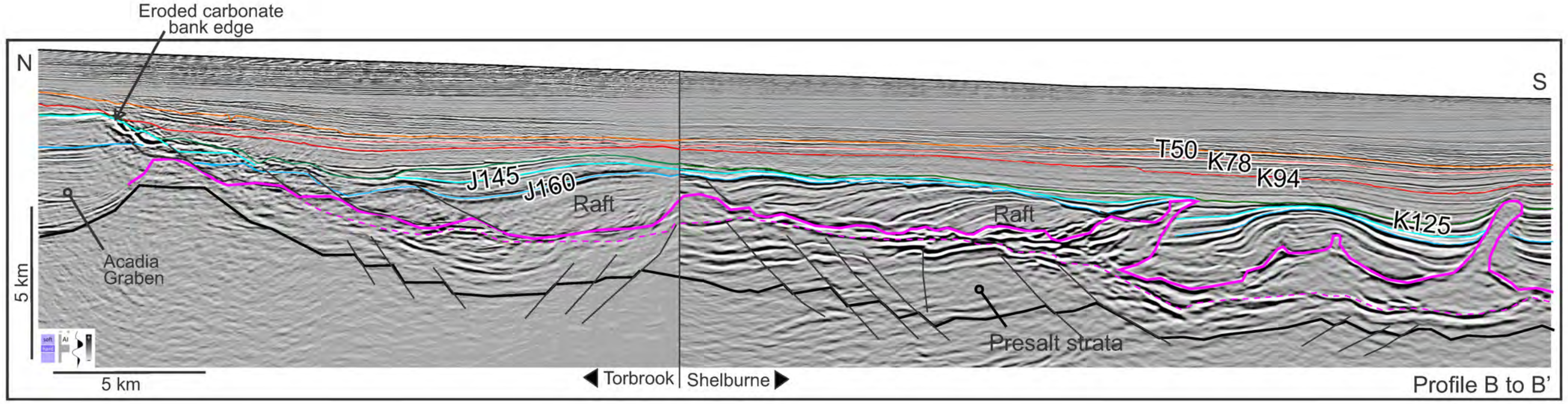
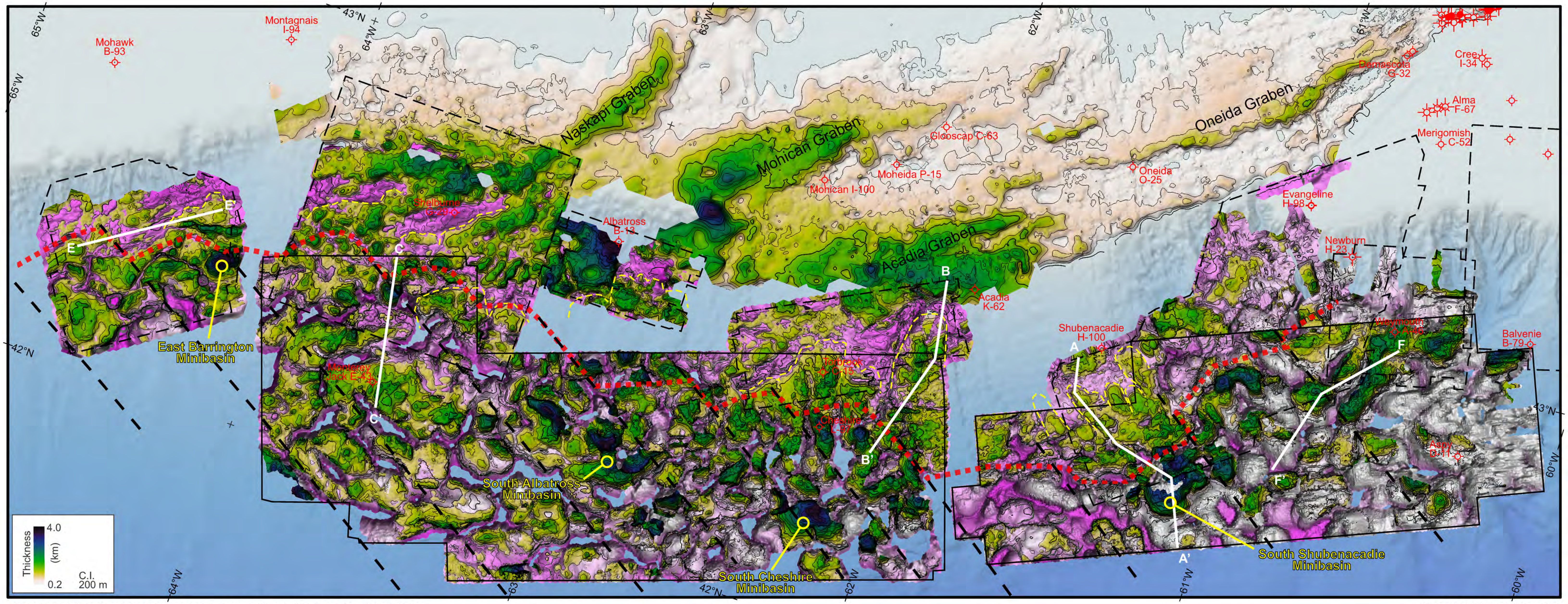


Thickness - Top Autochthonous Salt to J160

Improved continuity of the J160 marker (described in the next panel), provides a more complete picture of Middle to Lower Jurassic sediment distribution above the primary salt layer. Strata thinner than 300 m were turned transparent to highlight areas where the interval is largely absent or highly thinned (mainly above important basement elements like the high that underlies Shelburne G-29). Yellow dashed lines show areas where pre-J160 cover strata detached above the primary salt layer. Profiles A-A', B-B', and C-C' show several examples of raft tectonics involving mainly pre-J160 strata in the study area.

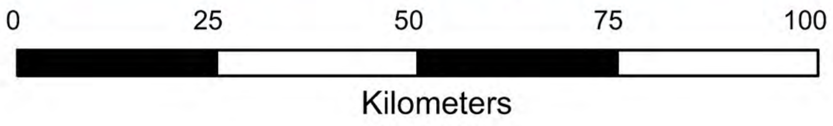
Also shown is the J200 (top CAMP basalt, and a good proxy for the top salt equivalent surface) to J163 (top Scatarie limestone) thickness map from the LaHave Platform (Deptuck and Altheim 2018). Lower to Middle Jurassic strata thicken along the axes of the Naskapi, Mohican, Acadia, and Oneida grabens. Red dashed line shows the approximate stepped boundary between necking domain and hyperextended crust. Grey dashed lines show the location of transfer fault/accommodation zones that may have segmented hyperextended crust.

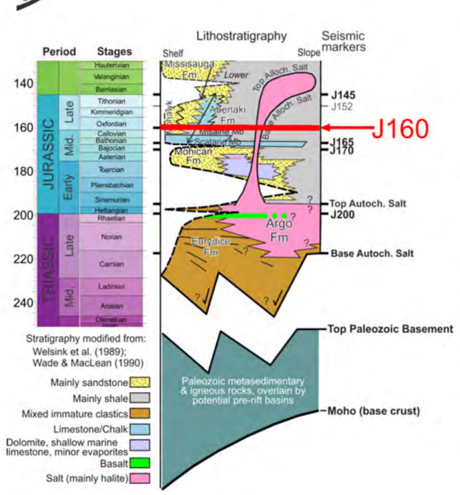




Underlying pink surface is top of the autochthonous salt layer. Shown on the platform is the J200 to J163 isopach from Deptuck and Altheim (2018).

ANGLE OF ROTATION 18.96 DEGREES





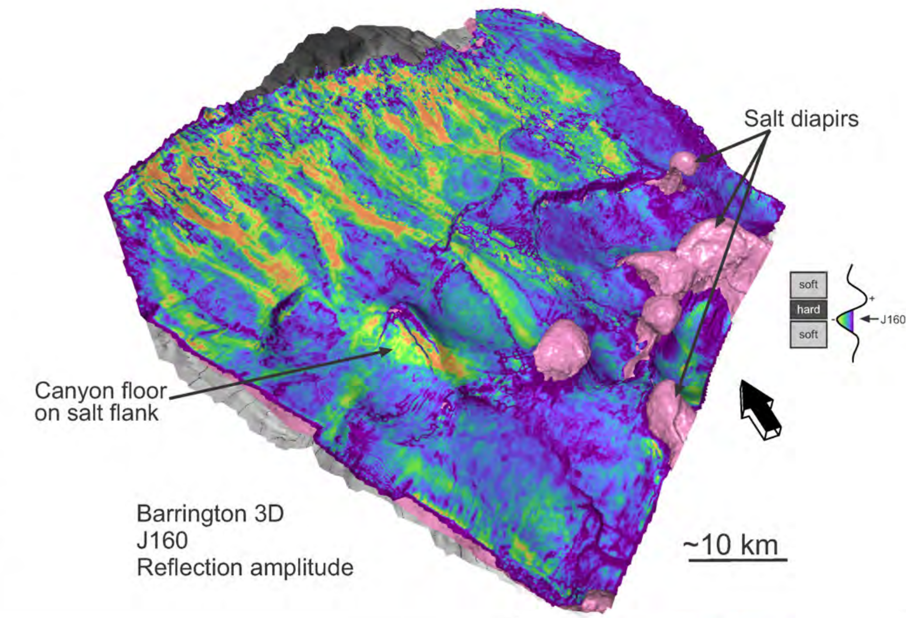
J160 - Callovian

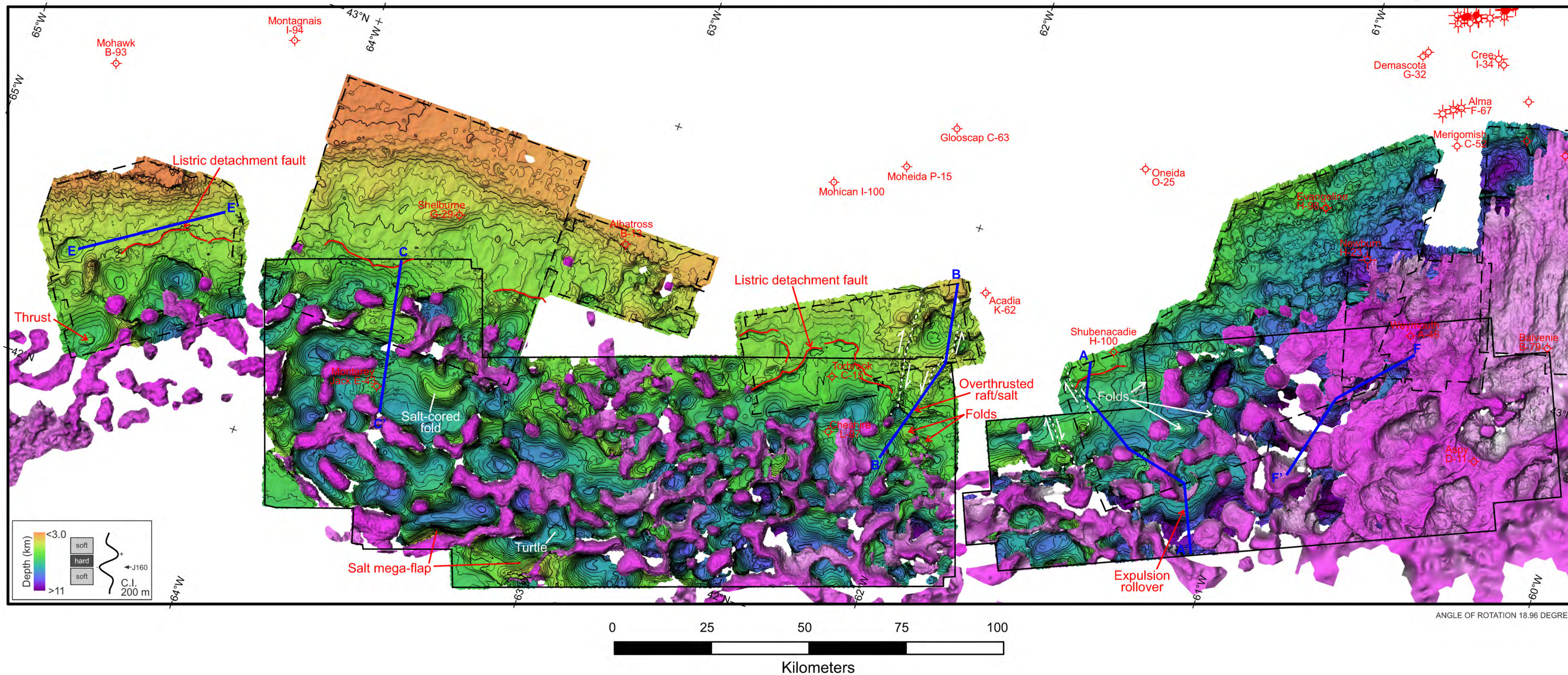
The J160 marker is a strong regional trough, the centre of which ties to the base of a carbonate section and top of a Callovian clastic dominated succession at Cheshire L-97A. As such this soft marker is lithologically equivalent to the top of the Misaine Member (base of the Bacarro Member; Wade and MacLean 1990) penetrated in a number of wells on the LaHave Platform. The zero-crossing below the strong trough ties closely with the ?Late Callovian MFS at Cheshire L-97A (RPS, 2018).

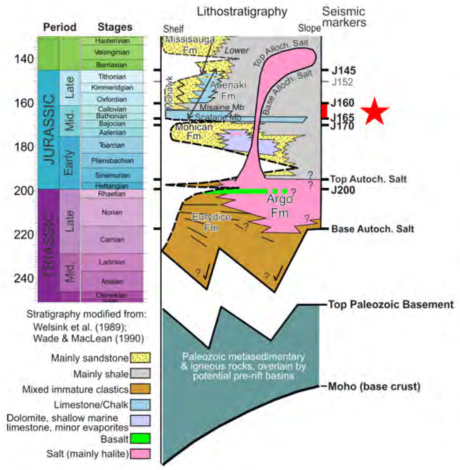
The marker was picked with a high degree of confidence in most areas, except approaching regions of more complicated allochthonous salt in the eastern parts of the Tangier and Thrumcap surveys and in the Weymouth and Veritas surveys where it was picked with a moderate degree of confidence. The marker is locally eroded from above by canyons associated with the J152, J145, or K125 unconformities - mainly in the most landward parts of Barrington, WG, Mamou and Torbrook. In a small number of isolated minibasins there is more than one candidate J160 marker. The strongest trough was selected in these uncommon scenarios.

The marker is increasingly erosive moving landward where it locally merges with the underlying J170/J165 surface. The erosional style is similar to that of the J170/165 unconformity in the WG and Mamou surveys, with basement elements still exerting a control on canyon morphology. An RMS amplitude extraction from the Mamou survey captures the dendritic head of a canyon system, whereas the Barrington survey captures numerous curvi-linear canyons or broad channels with more subtle dendritic heads (see image to the right). Both indicate that a slope was well established by the Callovian, and that a shelf edge had developed near the margin hinge by this time.

The marker is offset across a number of thin-skinned listric faults that sole into the primary salt layer in the landward parts of the Barrington, WG, and Thrumcap surveys. Like the J170/165 marker, there is an abrupt downslope change in surface structure, where the marker accumulated in the lower parts of salt withdrawal minibasins in the Shelburne survey. There is also widespread evidence for both extension and shortening in the Barrington, Shelburne, Tangier and Thrumcap surveys with squeezed diapirs, salt-cored folds, thrusts and reverse faults (e.g. Deptuck et al. 2009), as well as strike-slip faults between adjacent rafts.



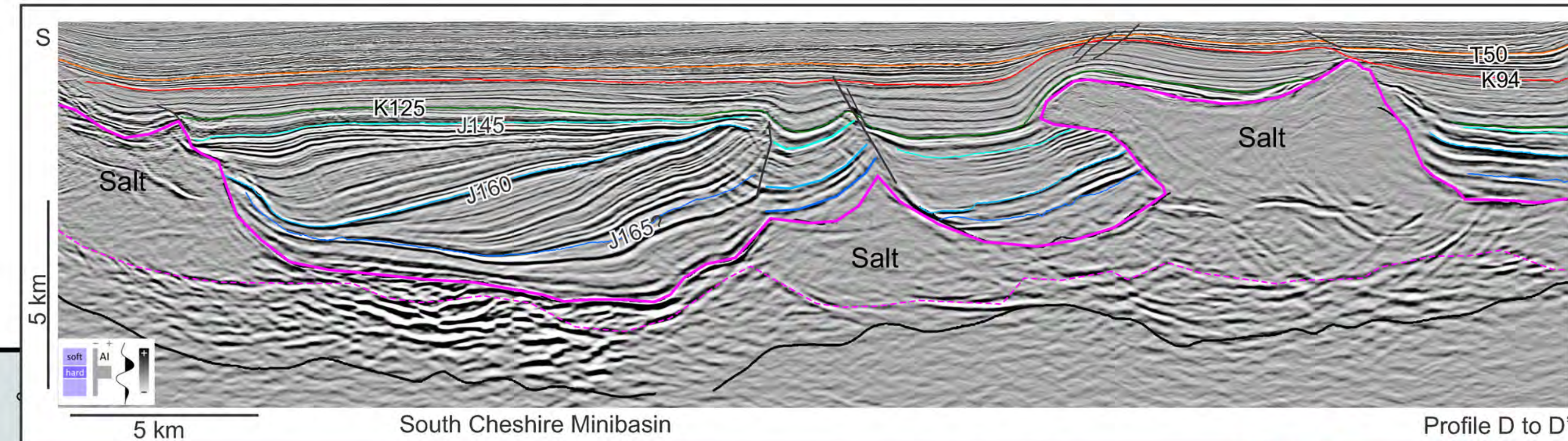


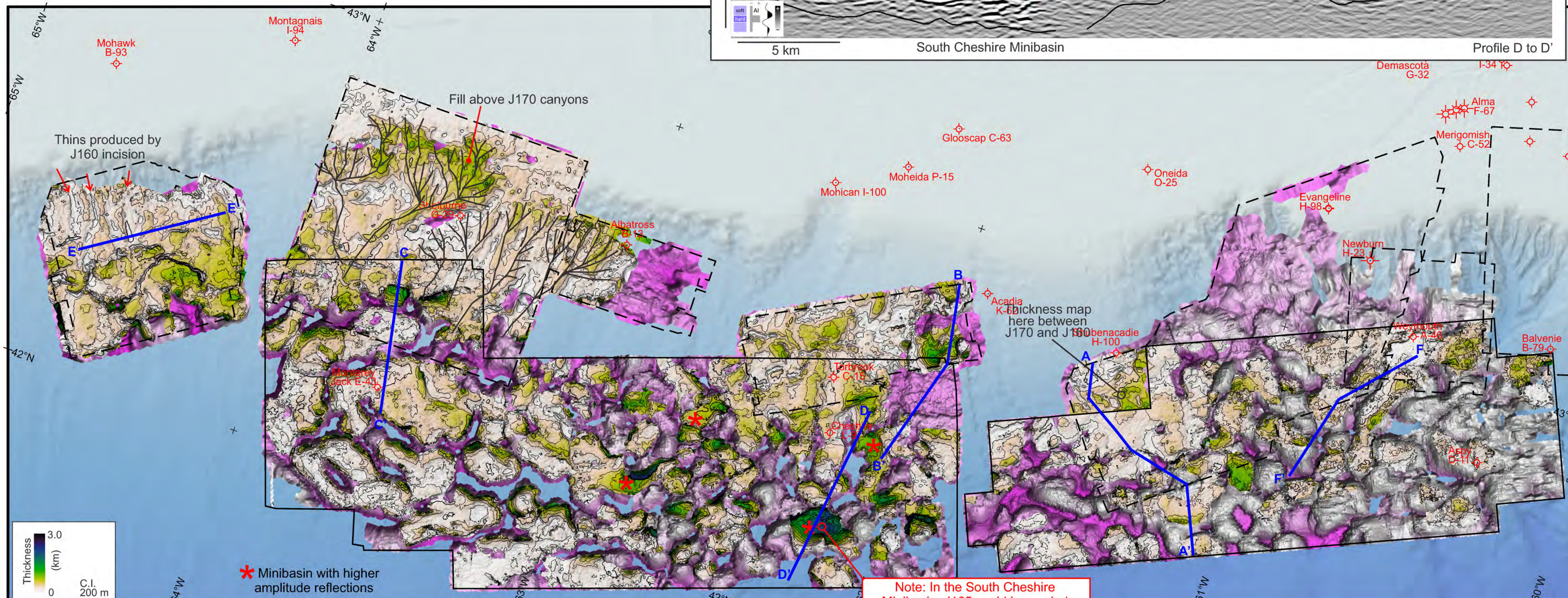


Thickness - J170/165 to J160 (Bathonian to Callovian)

The J170/165 to J160 interval marks a sharp change in the thickness and distribution of Middle Jurassic strata compared to the underlying interval. The succession was sampled at Cheshire L97A where it encountered 337 m of Callovian to Late Bathonian (RPS 2018) clastics composed of claystone, shale, and siltstone, with a number of very fine grained quartz-rich sandstone stringers, and rare interbedded marls. The unit is equivalent to the clastic dominated Misaine Member of the Abenaki Formation encountered in a number of wells on the shelf (Wade and MacLean 1990).

Overall the succession comprises lower amplitude seismic facies that blanket the J170/165 unconformity. In landward surveys like Barrington, WG and Mamou, it is thickest (locally > 700 m) where it infilled the erosional relief of J170 canyons, thinning along linear downslope-oriented bands where incised by younger J160 canyons. The succession is generally thinner than 300 m where it could be mapped above the platform in the northern parts of the WG survey. It is also generally thinner than 300 m in distal minibasins in the Shelburne and Tangier surveys, where it has a draping morphology. The interval does thicken locally along a number of corridors in the central to eastern parts of the Shelburne survey (in particular). Seismic amplitudes along these corridors and within minibasins are generally higher in these areas (basins identified with red asterix). The thickest accumulations took place in the South Cheshire Minibasin (see Profile D - D'). Difficulty correlating the J165 marker into this isolated minibasin provides scope to carry this marker shallower than what was done in this study, which could place part or most of this succession into the underlying thickness map.





Underlying pink surface is top of the autochthonous salt layer.

ANGLE OF ROTATION 18.96 DEGREES

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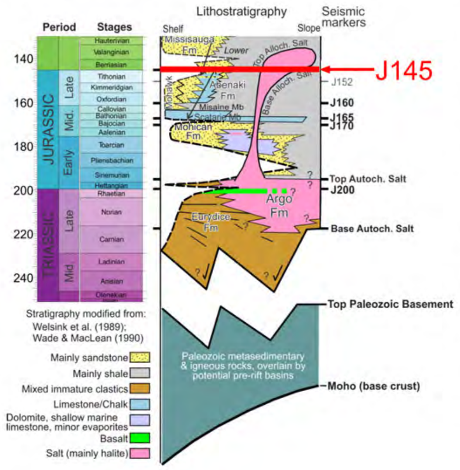


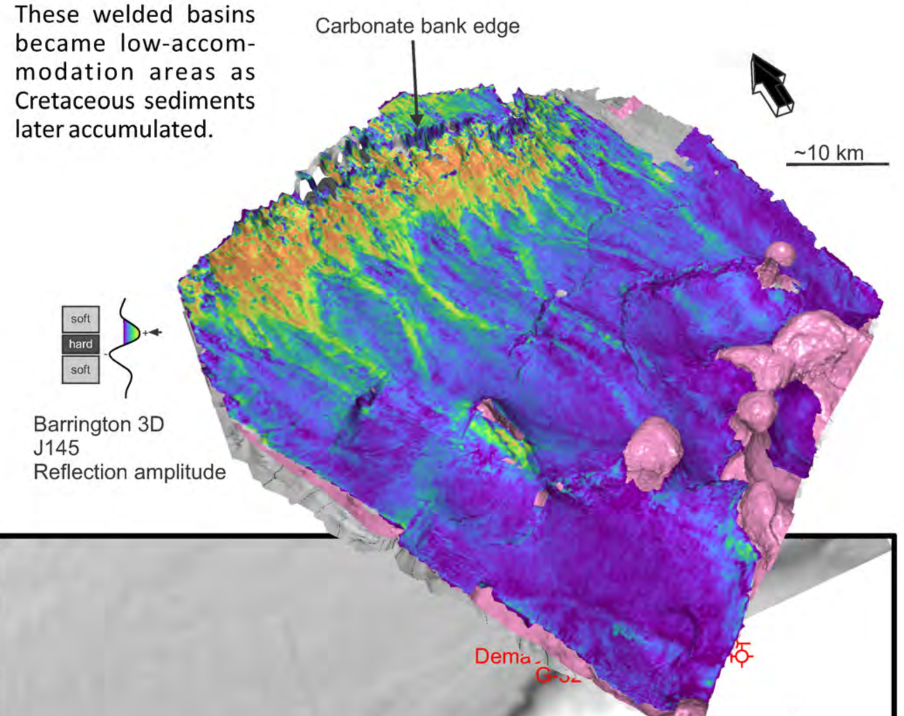
J145 - Late Tithonian/Berriasian Unconformity

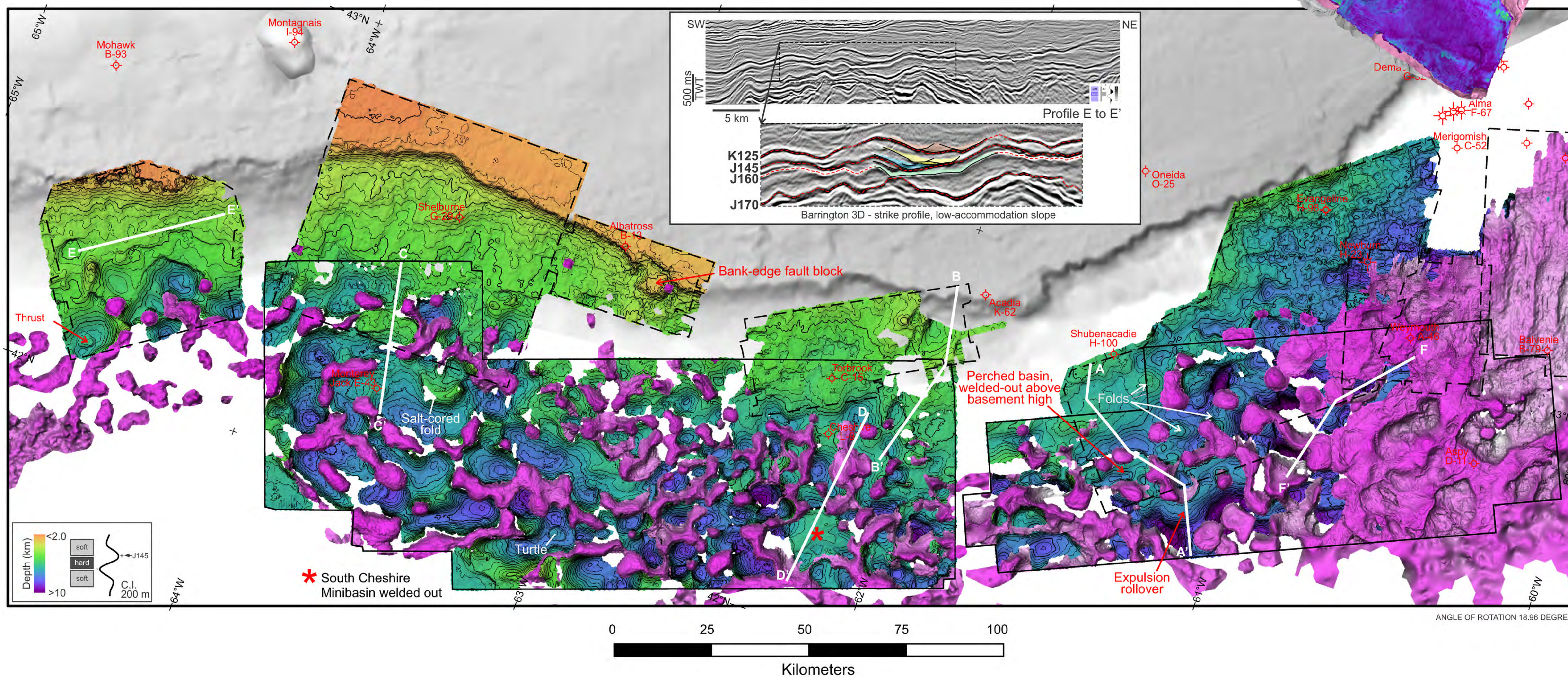
The J145 marker defines the top of the Jurassic succession, and forms a complex unconformity, in part because a number of erosive surfaces amalgamate above it. The marker closely matches the J265 marker defined by Deptuck (2008) in the Thrumcap survey area. On the slope it has been calibrated at Cheshire L-97 and Monterey Jack E-43 where it is located above Tithonian carbonates in both wells (and hence is more appropriately referred to as the J145 marker than the J150 marker as in previous studies).

The J145 marker corresponds to a peak above brighter amplitude seismic facies produced by carbonates. It was picked with a moderate to high degree of confidence throughout the Shelburne and western Tangier surveys, but untangling the J145 marker from shallower and deeper surfaces in the landward parts of the Barrington, WG, Mamou, and Torbrook surveys is challenging because a number of these surfaces form unconformities that converge above the steep carbonate foreslope that began to take shape in the Middle Jurassic. In the Barrington survey, prominent dendritic canyon heads erode the carbonate foreslope immediately seaward of the erosionally scalloped bank edge (see figure to the right). Overlapping networks of converging gullies merge downslope into a number of more widely spaced trunk channels/canyons that re-occupied underlying J160 channels. Here, the J145 marker forms a composite surface of erosion that formed during the northeast migration of these broad low-aggradational channels (see Profile E-E'). Further seaward in the Shelburne, Tangier, and Thrumcap surveys, the marker commonly caps a shingled interval of bright amplitude reflections, interpreted as calciclastic submarine fans.

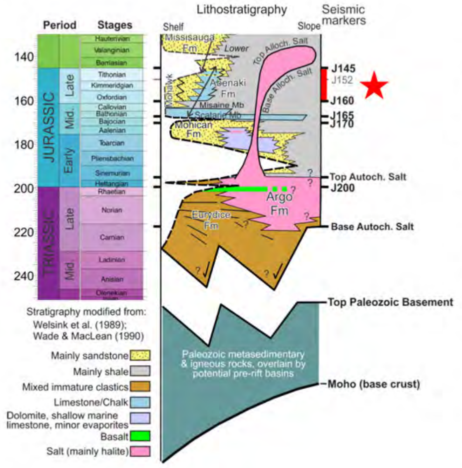
The J145 structure strongly resembles the underlying J160 marker, except a much sharper bank edge was established by the end of the Jurassic. In the Mamou survey, a large fragment of the carbonate bank detached along a listric fault that soles into the primary salt layer. Other low-angle detachment faults also offset the marker on the foreslope, and most of the folds that are present along the J160 surface are still present along the J145 surface. The South Cheshire Minibasin appears to have welded out by this stage; likewise, even some thinner minibasins located above basement highs had welded out by J145, leaving them perched above surrounding areas where salt withdrawal continued (see Profile A to A').

These welded basins became low-accommodation areas as Cretaceous sediments later accumulated.





Mark E. Deptuck and Kristopher L. Kendell

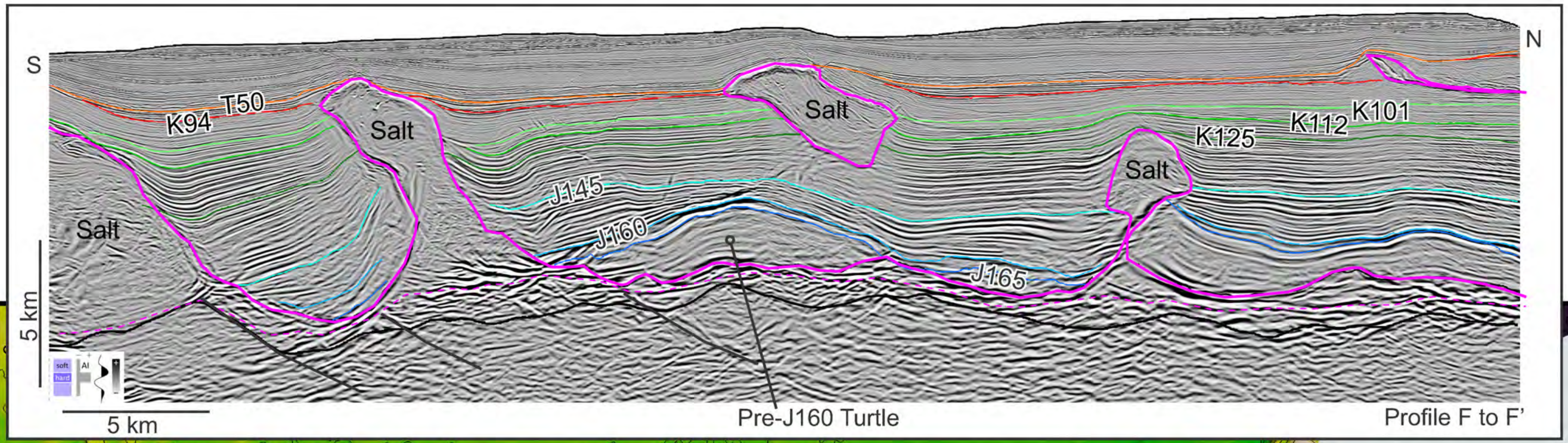


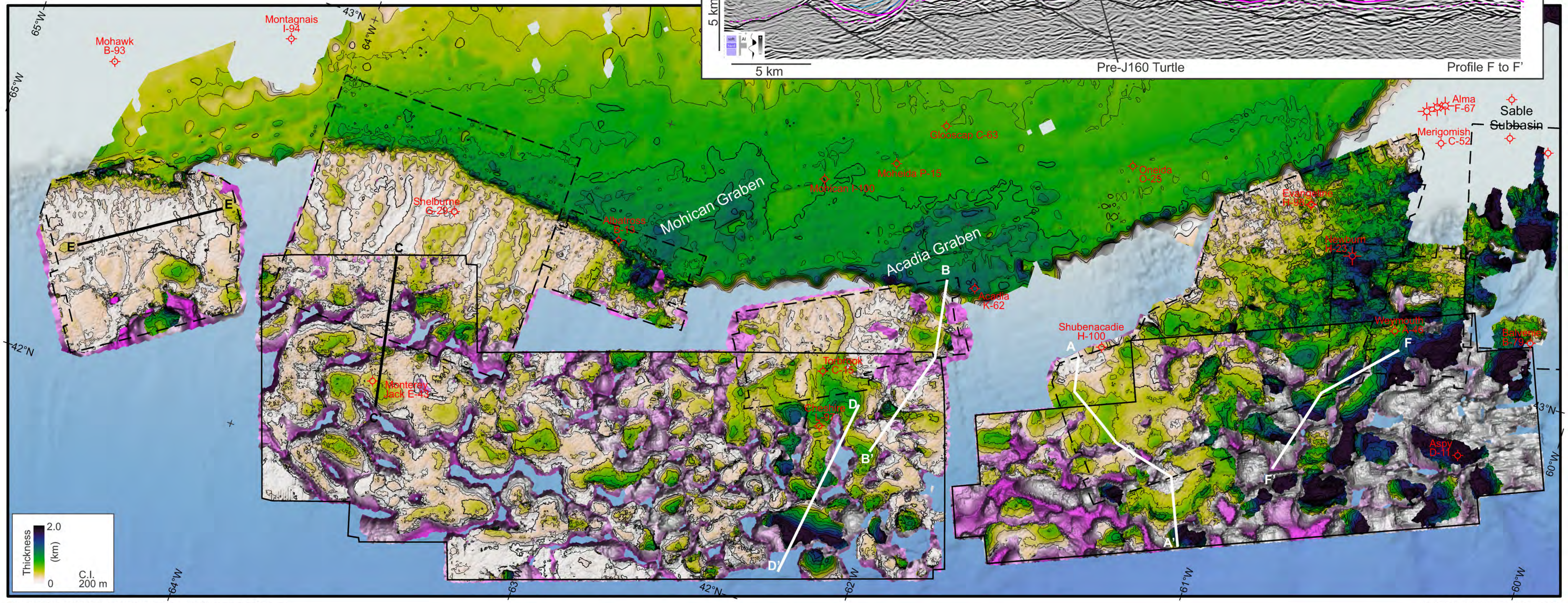
Thickness - J160 to J145 (Callovian to Tithonian)

Two thickness trends stand out on the J160 to J145 thickness map below. The first is the sharp increase in shelf aggradation compared to the underlying J160 to J170/165 interval. This is in response to growth of the Abanaki carbonate bank above the slowly subsiding LaHave Platform. The landward parts of the Barrington, WG, Mamou and Torbrook surveys cover parts of the carbonate bank. The second trend is the eastward increase in sediment accumulation on the slope towards the region of complex salt canopies. This trend reflects increased sediment input from the Sable Subbasin where the equivalent succession consists of mixed clastics and carbonates of the Mic Mac Formation, encountered in a number of shelf wells (Wade and MacLean 1990).

The thickest intervals are found in the Tangier, Weymouth, and Veritas surveys where up to 2.7 km thick of latest Callovian to Tithonian strata were deposited along narrow (8 to 15 km wide) south-oriented salt bound corridors. Seismic reflections in this interval range from moderate to high amplitude, with common onlaps onto the J160 marker, abrupt lateral thinning, and common turtles. The interval also abruptly thins where pre-J160 strata had already turtled. These successions now mostly underlie the salt canopy (see Profile F - F').

A second notable corridor is present on the slope seaward of the Acadia Graben, terminating in the South Cheshire Minibasin (see Profile D - D'). A particularly pronounced latest Kimmeridgian unconformity is present within the J160 to J145 interval along this corridor. In the Torbrook survey, amalgamation between the J145 and J152 unconformities makes it difficult to separate these surfaces, but two distinct erosive surfaces are present downslope. Canyon erosion along the J152 marker produced an erosional remnant at Cheshire L-97, separated from the J145 surface by an interval of Tithonian carbonates.





Underlying pink surface is top of the autochthonous salt layer.

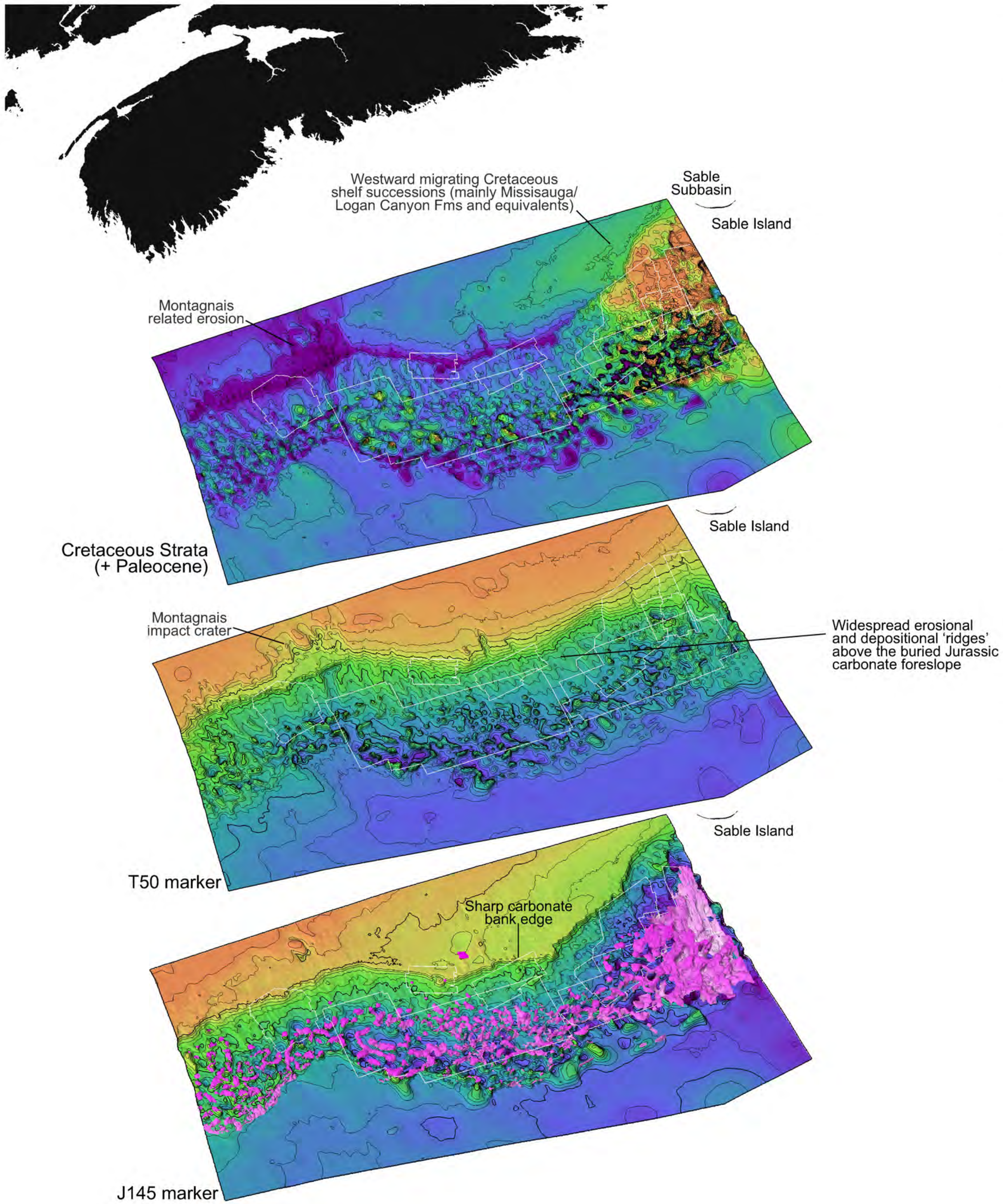
ANGLE OF ROTATION 18.96 DEGREES

0 25 50 75 100

Kilometers

Atlas of 3D seismic surfaces and thickness maps, central and southwestern Scotian Slope

Chapter 4 – Cretaceous



Gross distribution of Cretaceous strata off central and southwestern Nova Scotia

The total Cretaceous sediment thickness (top left) between the end Jurassic J145 marker (lower left) and Early Eocene T50 marker (middle left), shows that sedimentation was heavily skewed towards the Sable Subbasin in the northeastern study area. Here, it is made up mainly of clastic-dominated shelf successions that also host most of the discovered hydrocarbon reservoirs produced off Nova Scotia. They are mainly found in fluvial-deltaic reservoirs of the Missisauga and Logan Canyon formations that were deposited during southward progradation of the sand-prone Sable Delta, along the eastern edge of the carbonate bank (Wade and MacLean 1990). The thickest deposits here are more than 6 km thick, and are closely associated with complex salt tectonics and development of extensive salt canopies (Shimeld 2004; Kendell 2012; Deptuck and Kendell 2017). Marginal marine strata progressively aggraded and prograded towards the southwest, mirrored closely by clastic-dominated slope successions that follow the trajectory.

Further west, Cretaceous clastics were deposited above the Upper Jurassic carbonate bank, eventually building south and west towards the bank edge and foreslope, where its steep gradient profile left a lasting impact. Through the Lower Cretaceous, erosion, or highly condensed sedimentation, was focused above the outer parts of the carbonate bank and the steep slope seaward of it, as clastic depositonal systems attempted to erase or regrade the bank edge to establish a more suitable graded slope profile. Locally thicker Cretaceous intervals are preserved in vertically subsiding salt withdrawal minibasins on the slope, where a number of prominent unconformities and associated canyons were incised, transferring sediment seaward of the study area.

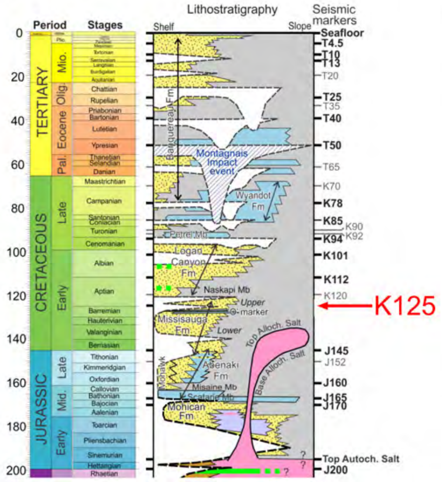
Distinctive downslope-oriented 'thicks' are preserved at many Cretaceous stratigraphic levels, aggrading and migrating above the carbonate foreslope. Their consistent northeast migration direction above the steep, buried Jurassic carbonate foreslope, and striking similarity to migrating sediment waves on strike-oriented profiles, imply that the Cretaceous slope was swept by persistent southwest-flowing ocean currents (probably an ancestral western boundary current). Currents were guided along the steep slope where they molded fine-grained sediments on the seabed into long-wavelength sediment-wave-like ridges. Through the Cretaceous, these ridges progressively migrated up-current, towards the northeast, periodically interrupted by downslope sediment transport that exploited the negative bathymetric relief between ridges. Their crests acted to focus upper slope sediment transport, and during the passage of more vigorous flows, also focused erosion. In the mid-Jurassic through Aptian these ridges showed little aggradation (or preservation) between regional unconformities , but upper slope aggradation rates increased abruptly in the early Albian, perhaps related to the voluminous supply of sediment made available to the slope as progradation of the Logan Canyon Formation reached the edge of the underlying carbonate bank, delivering muddy hypopycnal plumes to deepwater where they could be entrained into southwest flowing ocean currents. Evidence for southwest-flowing contour currents is less obvious further seaward, either indicating they were less important here or that the stratigraphic expression is complicated in areas also impacted by salt-related deformation.

In the westernmost study area, the Montagnais impact event, and associated erosion, probably had the strongest impact on gross sediment thickness along a part of the margin that was already sediment starved compared to the Sable Subbasin. The impact event excavated more than a kilometer of mainly Cretaceous strata from the outer shelf, triggering a massive slope failure. Note that the "Cretaceous" sediment thickness map also includes Paleocene strata, but these contribute little to the overall thickness of the succession.

This chapter includes thirteen panels, stepping through the K125, K112, K101, K94, K92, K90, and K78 markers from nine semi-contiguous 3D seismic volumes along the central and western Scotian Slope, and the intervening thickness maps between them, as well as several amplitude extractions. Where possible, we have also included thickness maps from roughly time equivalent strata on the LaHave Platform, mapped in previous studies using variable-quality 2D seismic profiles. The location of the thickest deposits on the LaHave Platform shows remarkable correspondence to the thickest deposits on the slope

Recommended citation:
Kendell, K.L. and Deptuck, M.E. 2020. SCOPE Project, Chapter 4 - Cretaceous, In: Atlas of 3D Seismic Surfaces and Thickness Maps, Central and Southwestern Scotian Slope, Canada-Nova Scotia Offshore Petroleum Board Geoscience Open File Report: 2020-005MF, 13 panels.

Kristopher L. Kendell and Mark E. Deptuck

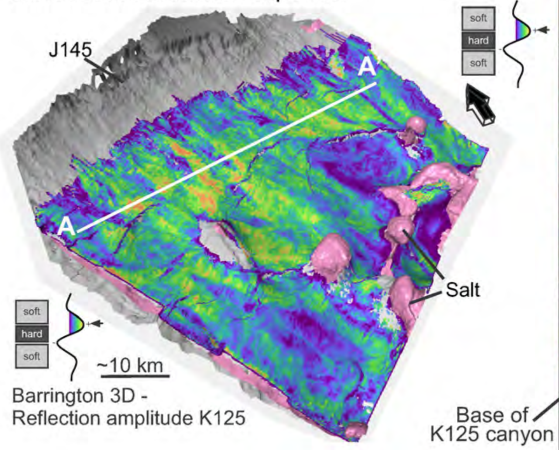


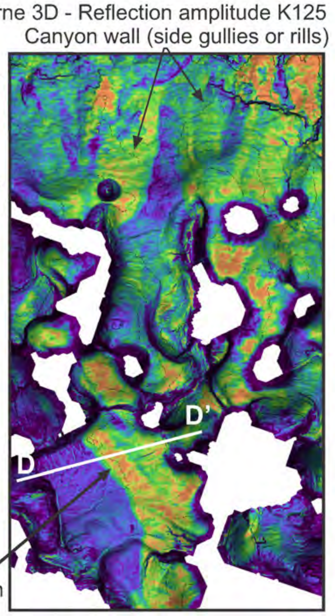
K125 - Aptian/Barremian Unconformity

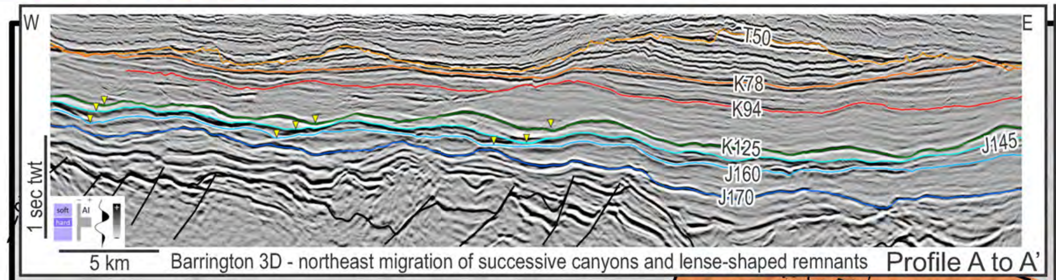
The K125 marker is a moderate to high amplitude peak (downward increase in impedance) that forms a widespread erosive surface, with common truncation of underlying seismic markers on the slope. It has been calibrated at Newburn H-23, Weymouth A-45, Cheshire L-97, and Monterey Jack E-43, where it lies within a marine clastic succession and corresponds to an unconformity separating Aptian strata above from Barremian or older strata below (depending on the amount of erosion into older intervals) (Weston et al. 2012; RPS 2018). K125 was picked with a very high level of confidence everywhere except three regions: (i) moderate confidence above the steepest parts of the J145 carbonate foreslope where, because numerous surfaces amalgamate, it is challenging to correlate; (ii) moderate confidence in the eastern study area approaching the Sable Slope Canopy (Kendell 2012; Deptuck and Kendell 2017), where Lower Cretaceous strata expand and K125 is less distinct (Weymouth A-45 and Newburn H-23 help constrain the marker here); (iii) beneath the Balvenie Roho System in the Veritas survey where the marker could not be carried.

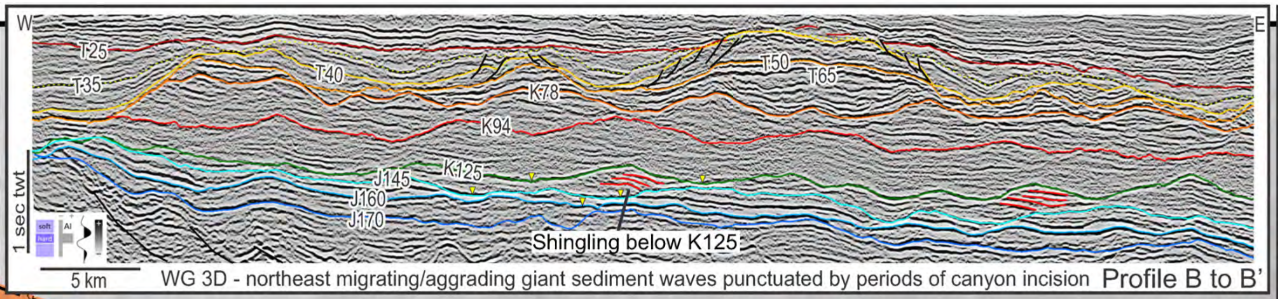
Similar to deeper markers, K125 shows a pronounced change in structure stepping off the platform, where the slope is heavily eroded in the Barrington, WG, Mamou, and Torbrook surveys. In the landward parts of the Barrington 3D survey for example, K125 merges and erodes the J145 marker, making the surfaces difficult to distinguish. Further down the slope, the marker defines a number of canyons separated by down-slope oriented erosional remnants that form intercanyon highs. Amplitude extractions from the Barrington, Torbrook, and Shelburne surveys show widespread rill patterns along canyon margins, but there is no amplitude response to suggest the canyon fill has any reservoir potential. Where there are anomalous amplitudes along the erosive base of K125 canyons, they appear to be associated with tuning effects where the incision surface merges with underlying strata (carbonates?) (Inset A; see Profile D - D').

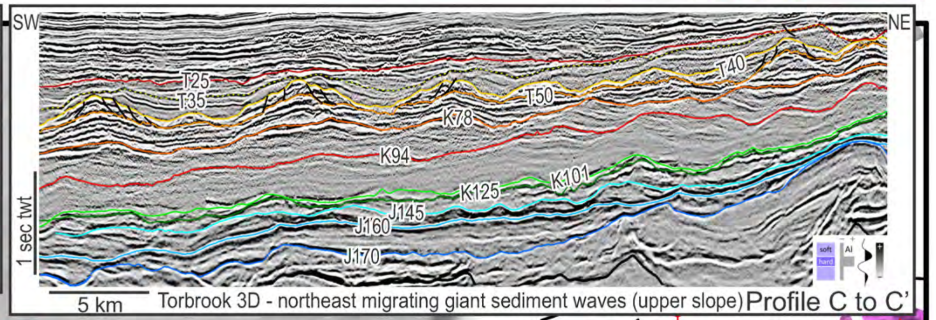
In the distal parts of the Shelburne survey, K125 passes into a conformable surface outside canyon axes, where it caps a high-frequency lower to mixed amplitude layered succession that probably corresponds to chalks or marls. The surface is increasingly conformable both seaward and eastward in the Tangier, Thrumcap and Weymouth surveys, where the underlying Cretaceous succession expands.

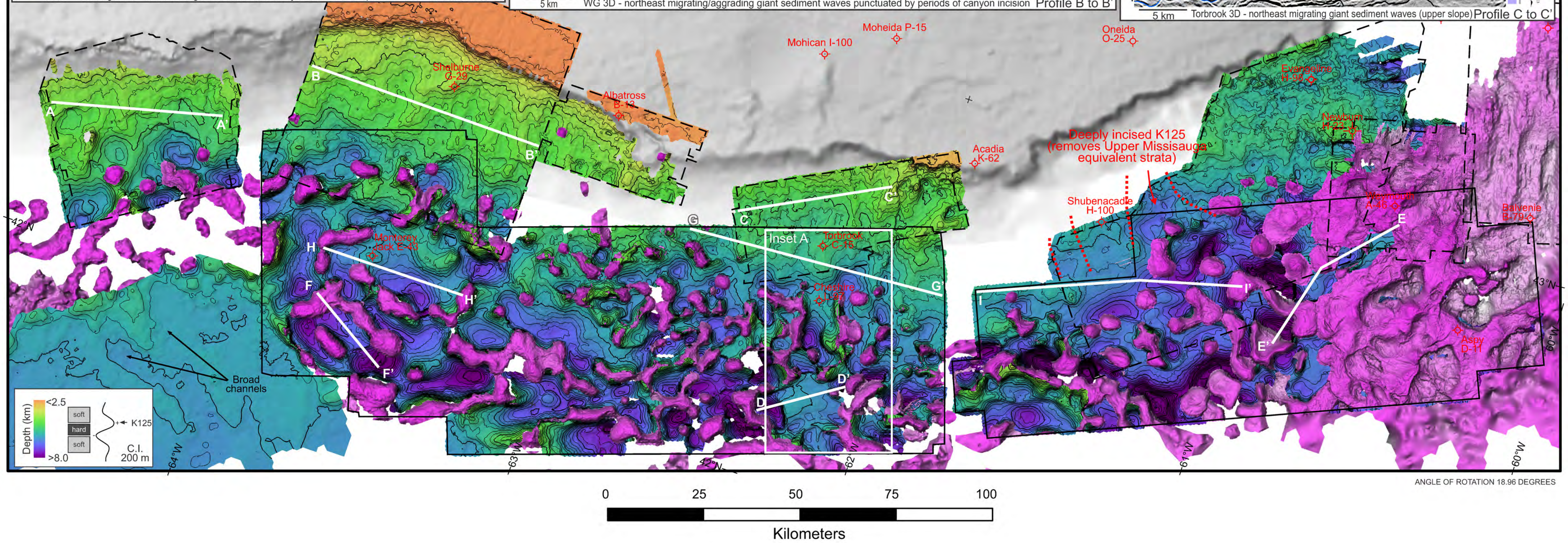




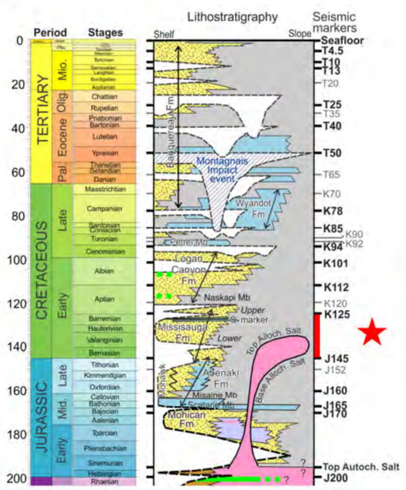








ANGLE OF ROTATION 18.96 DEGREES

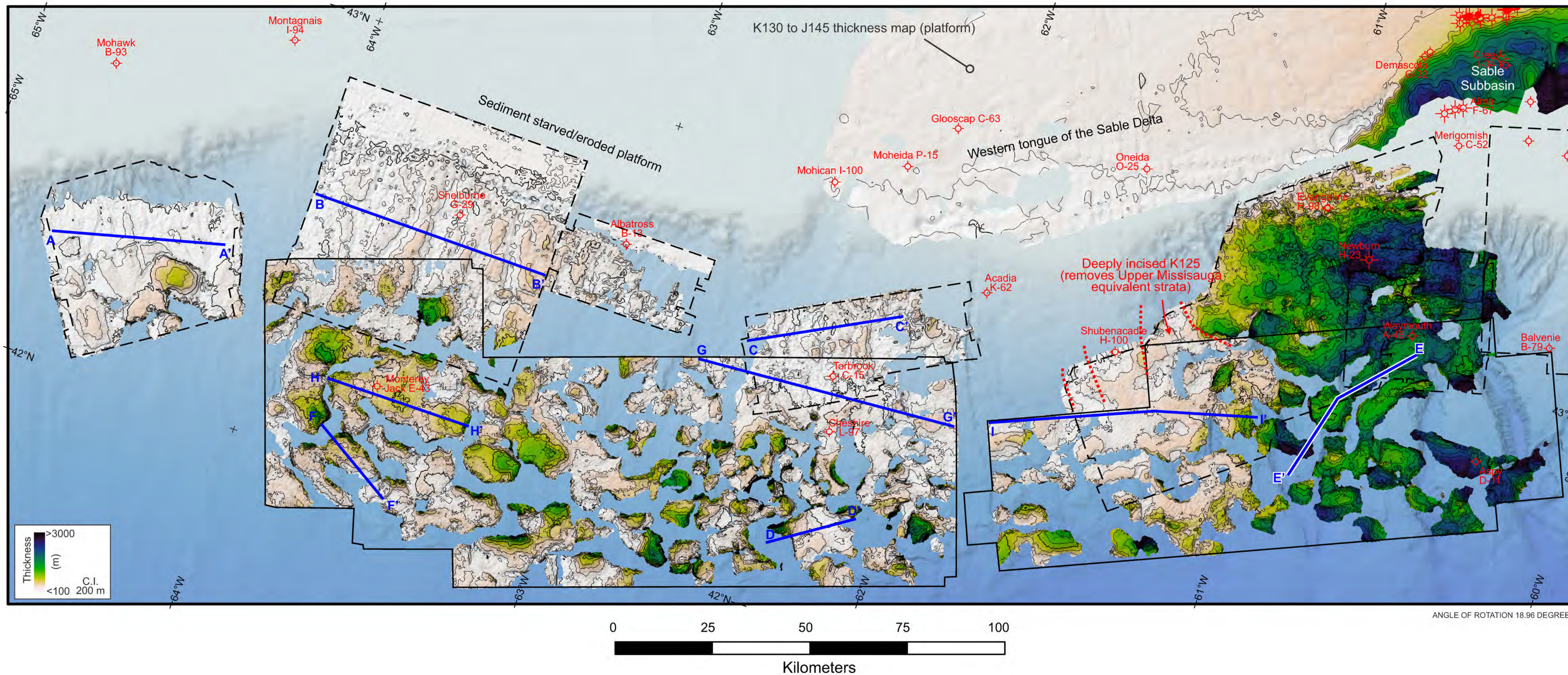


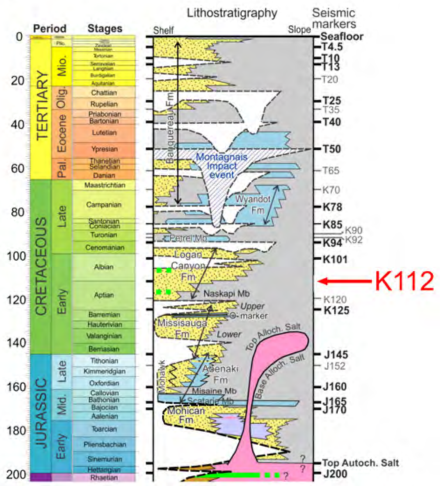
Thickness - J145 to K125 (Berriasian to Barremian)

Overall, the J145 to K125 interval is thickest in the east and thinnest in the west. In the west, the interval is mainly represented by a highly condensed surface (single seismic loop) or an unconformity above the carbonate platform. Increasingly thicker intervals of J145 to K125 strata are preserved stepping off the platform, down the underlying Jurassic carbonate foreslope in the landward parts of the Barrington, WG, Mamou and Torbrook surveys. Clear down-slope oriented thicks are present here corresponding to strata preserved between K125 canyons (see Profiles A - A', B - B', and C - C'). In the Barrington and WG surveys, J160, J145, and K125 canyons shifted 1-2 km to the northeast between periods of erosion, preserving eroded lens-shaped remnants that, when stacked, strongly resemble northeast migrating sediment waves on strike-oriented profiles (with downslope-oriented crests). Monterey Jack E-43 penetrated a 550 m pre-K125 erosional remnant composed of Barremian to Berriasian claystone, with minor marls and very fine grained sandstone. Internal mixed-amplitude reflections in the remnant, however, are not layer cake, but instead are complexly stacked with shingling. Other remnants further up the slope contain similar internal reflections (highlighted in red on Profile B - B'). Both the external stacked geometry, and internal seismic facies, imply that this part of the margin was swept by southwest-oriented ocean currents, interrupted periodically by periods of downslope sediment transport and canyon erosion (e.g. during K125 erosion).

Reflection amplitude diminishes downslope and to the east, but increases again in the Thrumcamp, Weymouth, and eastern Tangier surveys where numerous bright amplitude reflections are present within minibasins that formed above salt expelled from welded and commonly turtled Jurassic minibasins; the thickest pre-J145 strata commonly coincide with the thinnest Early Cretaceous strata. By far the thickest J145 to K125 succession is preserved in the eastern parts of the Tangier and Thrumcap surveys, where it is more than 2.5 km thick approaching the Sable Subbasin and the sand-rich Sable Delta)(Profile E - E'). Some of the elevated amplitudes in this interval may be associated with marl, siltstone and calcareous shale - as encountered in Weymouth A-45, however, Newburn H-23 also encountered two 6 m thick gas charged turbidite sands (5402-5408 m and 5958-5964 m MD; Kidston et al. 2007; Deptuck 2008), and Aspy D-11A encountered a 19 m Barremian sequence (7115-7134 m MD) containing three upward-coarsening turbidite sands interbedded with shale and siltstone, and a 2 m sand at 7400 m. Porosities reach 18%. Both these wells only tested the upper part of the interval.

The thickness distribution on the slope mirrors that on the shelf. Strata are thinnest above the LaHave Platform immediately landward of the WG, Mamou, and Torbrook surveys, where K125 converges with J145 above the carbonate bank. The J145 to K125 succession thickens above the platform towards the Sable Subbasin, where the Aptian/Barremian unconformity marks the top of the Missisauga Formation and the boundary between Naskapi shales above and Missisauga fluvial deltaic sandstones below (Wade and MacLean 1990; Weston et al. 2012). A 60 m upward-coarsening Barremian sandstone interval at Oneida O-25, and a number of thin Lower Cretaceous regressive sands in Glooscap C-63, Moheida P-15, and Mohican I-100 demonstrates that by the end of the Barremian the Sable Delta had expanded towards the southwest, across the LaHave Platform, but pinches out (or was removed by erosion) 10 km or more before reaching the carbonate bank edge near the Torbrook, Mamou and WG surveys. A thickness map between the K130 and J145 markers from Deptuck and Altheim (2018) provides a good proxy for the southwest extent of the Missasauga Formation, at least to the Hauterivian.





K112 - Aptian/Albian boundary

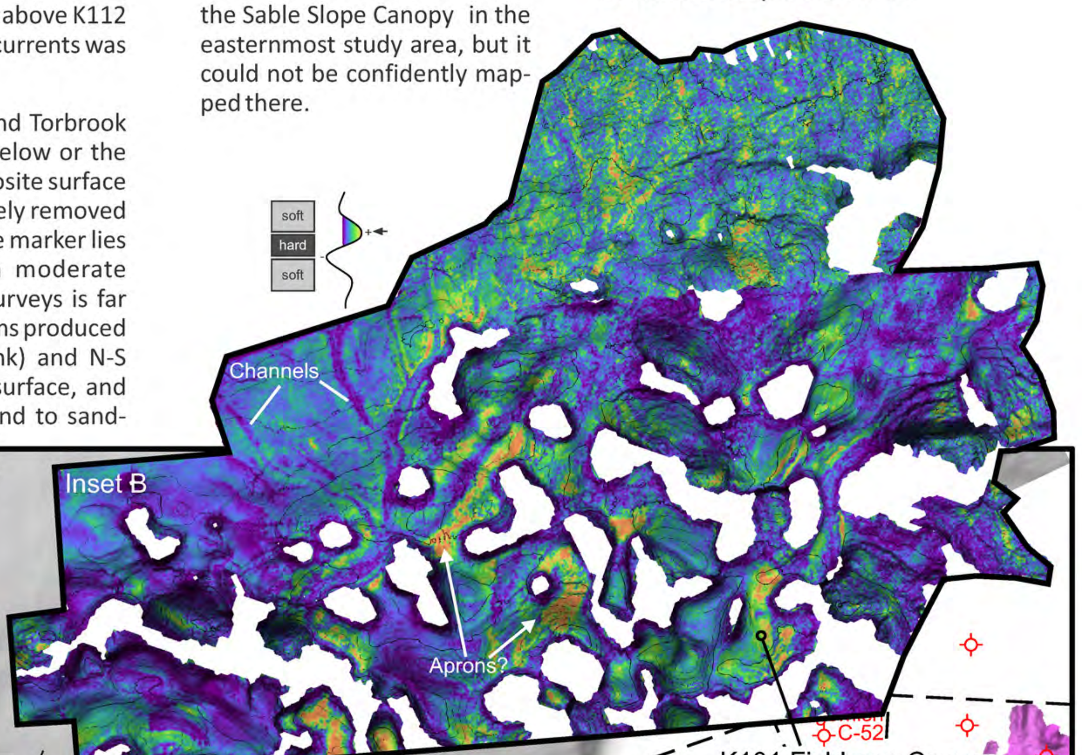
The K112 marker is a moderate to low amplitude peak (downward increase in impedance) that displays subtle scouring into underlying intervals but otherwise is a highly continuous event. It lies within a succession of gray marine claystone, near the top of the Aptian section. At Monterey Jack E-43 and Newburn H-23, the marker is located in a relatively conformable succession separating Aptian and Albian strata (Aptian/Albian MFS, Weston et al. 2012). At Cheshire L-97, K112 corresponds to an unconformity with a 12 Ma stratigraphic gap (mid-Albian strata overlie Aptian strata; RPS 2018). Likewise, at Weymouth A-45 the marker merges with a mid-Albian unconformity.

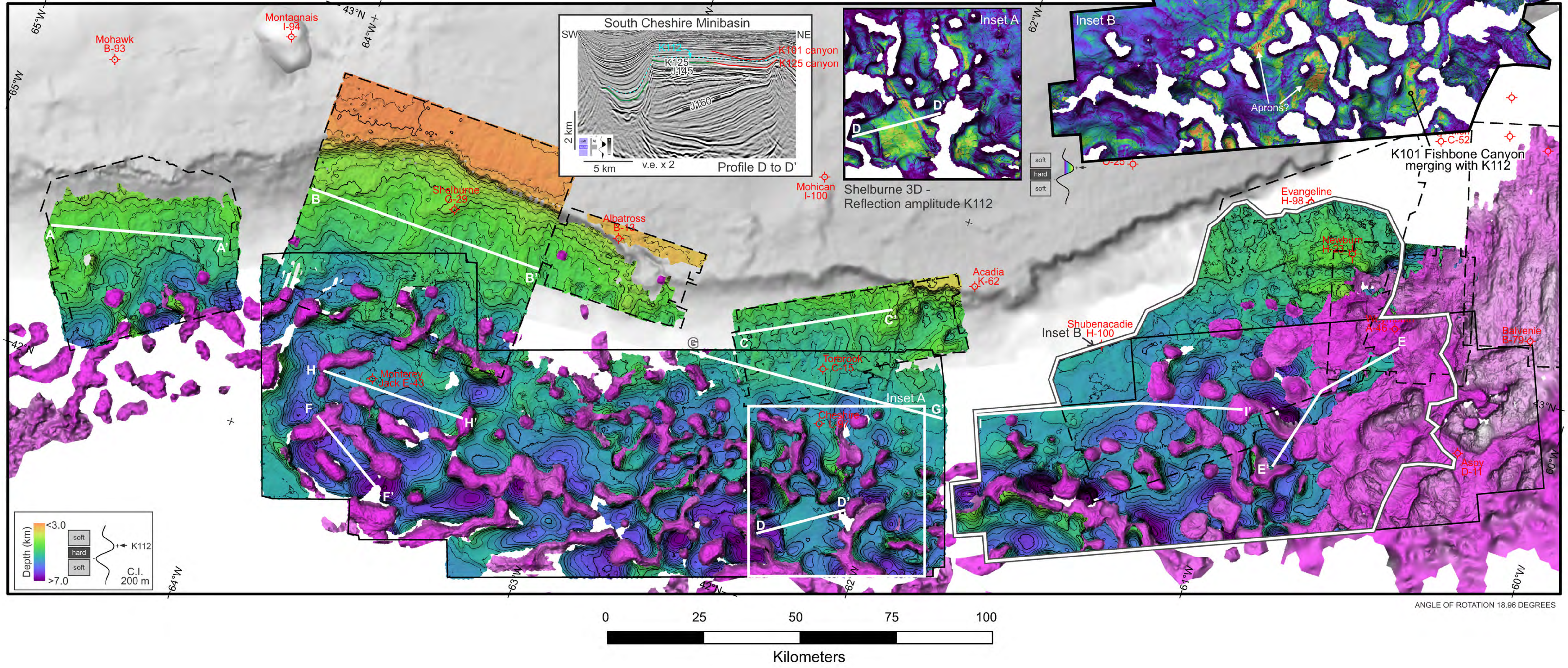
K112 was picked with a high level of confidence throughout the Shelburne and western Tangier surveys where it corresponds to the first brighter peak above K125. Subtle scouring here is observed along K112 on seismic profiles, causing underlying strata to pinch and swell, but despite the large stratigraphic gap at Cheshire L-97, K112 is not noticeably 'canyoned' across most of the Shelburne survey, and as such is unlike either the underlying K125 or overlying K101 surfaces.

Amplitude extractions along this surface are relatively featureless, with subtle anomalies in areas where overlying surfaces, like K101, merge with it. Its amplitude is elevated above the welded-out South Cheshire Minibasin (Inset A), with northeast-oriented lineations found in the soft loop immediately above K112 that may have formed where scouring from southwest-flowing ocean currents was enhanced above this low-accommodation paleo-bathymetric high.

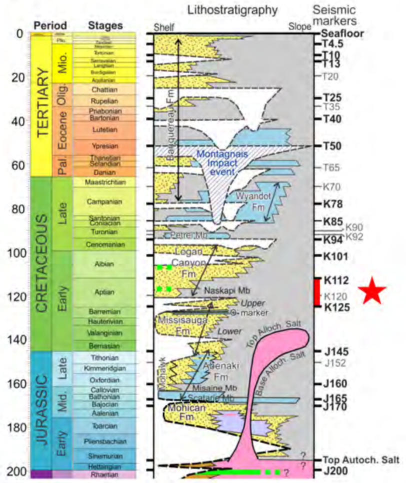
In the Mamou survey and landward parts of the Barrington, WG, and Torbrook surveys, K112 cannot be distinguish from either the K125 surface below or the K101 surface above, because these surfaces converge to form a composite surface (K125 is used as a proxy for it here). Erosion along the K101 surface likely removed the marker, if it was present above K125 to begin with. Further east the marker lies within an expanded section where K112 was correlated with moderate confidence. Its amplitude response in the Thrumcap and Tangier surveys is far more variable than in the Shelburne survey, with subtle curvi-linear dims produced where overlying E-W oriented channels (normal to carbonate bank) and N-S oriented channels (normal to Sable Delta clinoforms) cut into the surface, and where several additional anomalies are present that may correspond to sand-prone aprons (Inset B). The marker is probably also present in the thicker minibasins above the Sable Slope Canopy in the easternmost study area, but it could not be confidently mapped there.

Thrumcap and Tangier 3D - Reflection amplitude K112





Kristopher L. Kendell and Mark E. Deptuck



Thickness - K125 to K112 (Aptian)

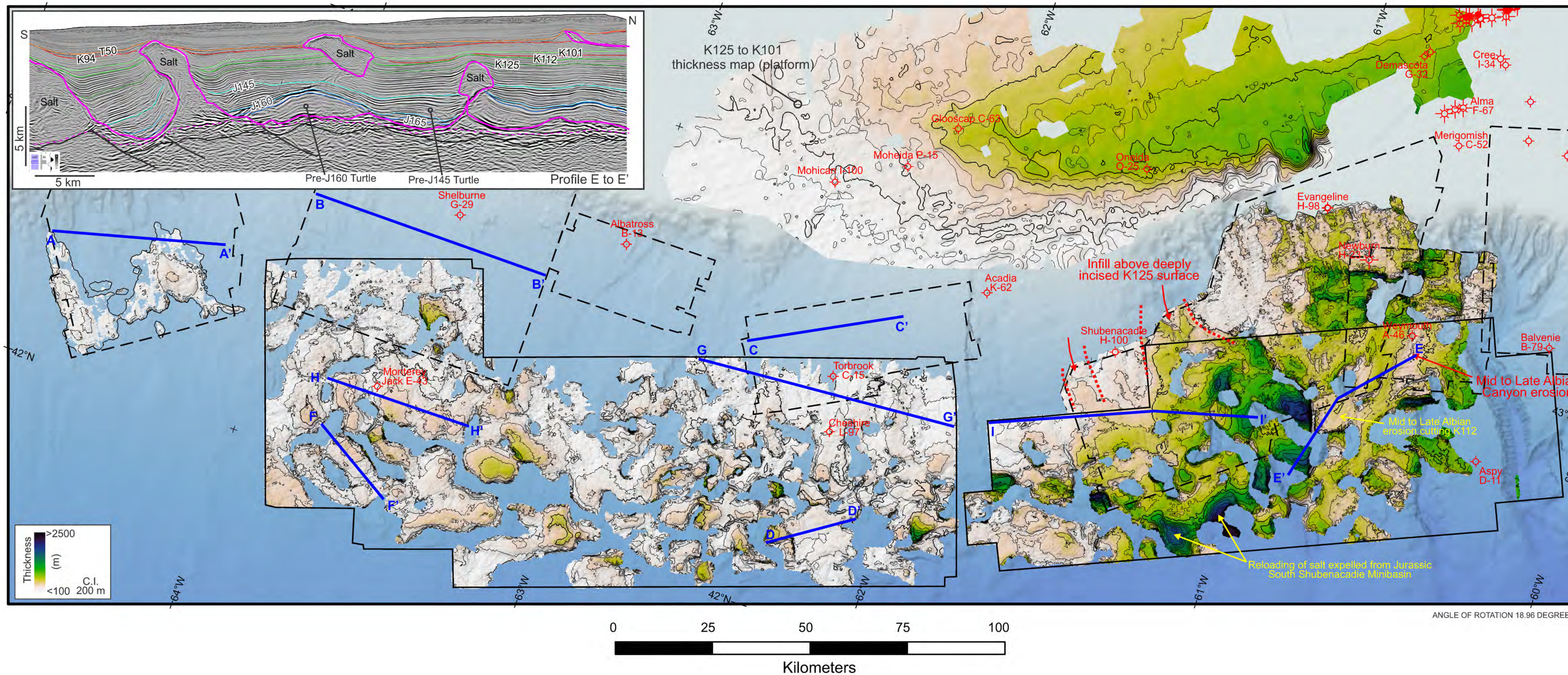
Similar to older Cretaceous strata, the K112 to K125 interval is thickest in the eastern half of the study area and thinnest in the west. It reaches a maximum thickness of just over 2.2 km in a series of localized salt withdrawal minibasins in the Tangier survey, approximately 50 km south-southeast of Shubenacadie H-100. One of these minibasins formed via re-loading of salt originally displaced by the Jurassic South Shubenacadie Minibasin. One notable thicker corridor passes through the Thrumcap survey 20 km east of Shubenacadie H-100. Sediments here filled in a deeply eroded K125 corridor that had removed underlying strata equivalent to the Upper Missisauga Formation.

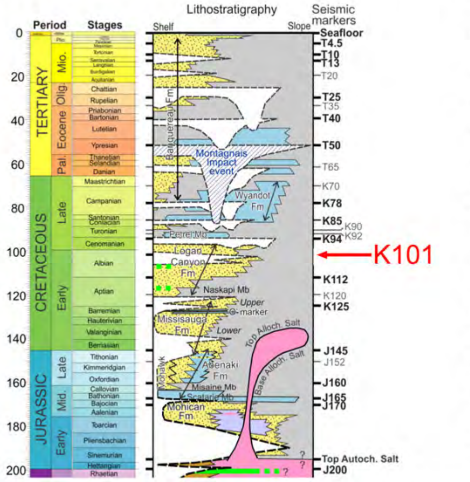
To the west, the interval is generally less than 200 meters thick (202 meters encountered at Cheshire L-97 and 186 meters at Monterey Jack E-43), thickening locally above a number of minibasins where K125 to K112 strata are up to 750 meters thick. Here, it consists of low amplitude continuous reflections, with a moderate increase in reflection amplitude where the interval thickens in minibasins across the central part of the Shelburne survey. This interval in landward parts of the Shelburne, Torbrook, Mamou, WG and Barrington surveys onlaps the carbonate foreslope, converging into a single seismic reflection, so there is no appreciable stratigraphic thickness here. Several other Cretaceous stratigraphic intervals also thin above the Jurassic carbonate foreslope that, along with the heavily scalloped bank edge, was an important geomorphic element throughout the Cretaceous.

Other notable thinner areas include a north-south trending thin approximately 5 km in width that tracks though the Weymouth survey, continuing south to the edge of the Tangier survey. The thin was produced by a combination of canyon erosion along a Middle Albian unconformity and the Late Albian (K101) unconformity, both identified in Weymouth A-45 (Weston et al. 2012). The erosionally thinned K125 to K112 succession at Weymouth A-45 consists of 427 m of claystone and shale, similar to what was encountered in Cheshire L-97 and Monterey Jack E-43. Aspy D-11, located ~36 km southeast of Weymouth, penetrated 635 m of mainly claystone and shale, with some thin sandstones between 6300-6900 m (TVD SS) reported in the cuttings descriptions.

Across the study area, the K125 to K112 interval commonly thins and onlaps salt bodies and salt feeders. Further east, in the eastern Tangier, Thrumcap and Weymouth surveys, the interval contains high amplitude continuous reflections mixed with lower amplitude, discontinuous reflections, with subtle onlap relationships between loops (Profile E - E').

K125 to K112 thickness distribution on the slope is mirrored by the thickness distribution between the K125 and K101 markers on the shelf. Note that the shelf succession includes Albian strata between K101 and K112, so it is not exactly time equivalent, but shows nicely the southwestward advance of the Logan Canyon Formation in the mid-Cretaceous, compared to the J145 to K125 succession in the previous thickness panel.



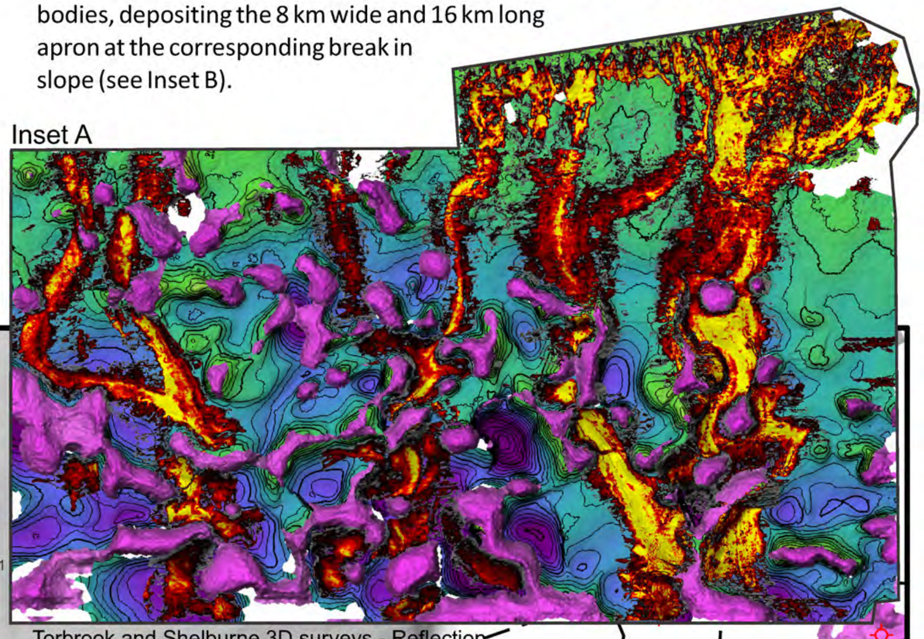


K101 - Late Albian Unconformity

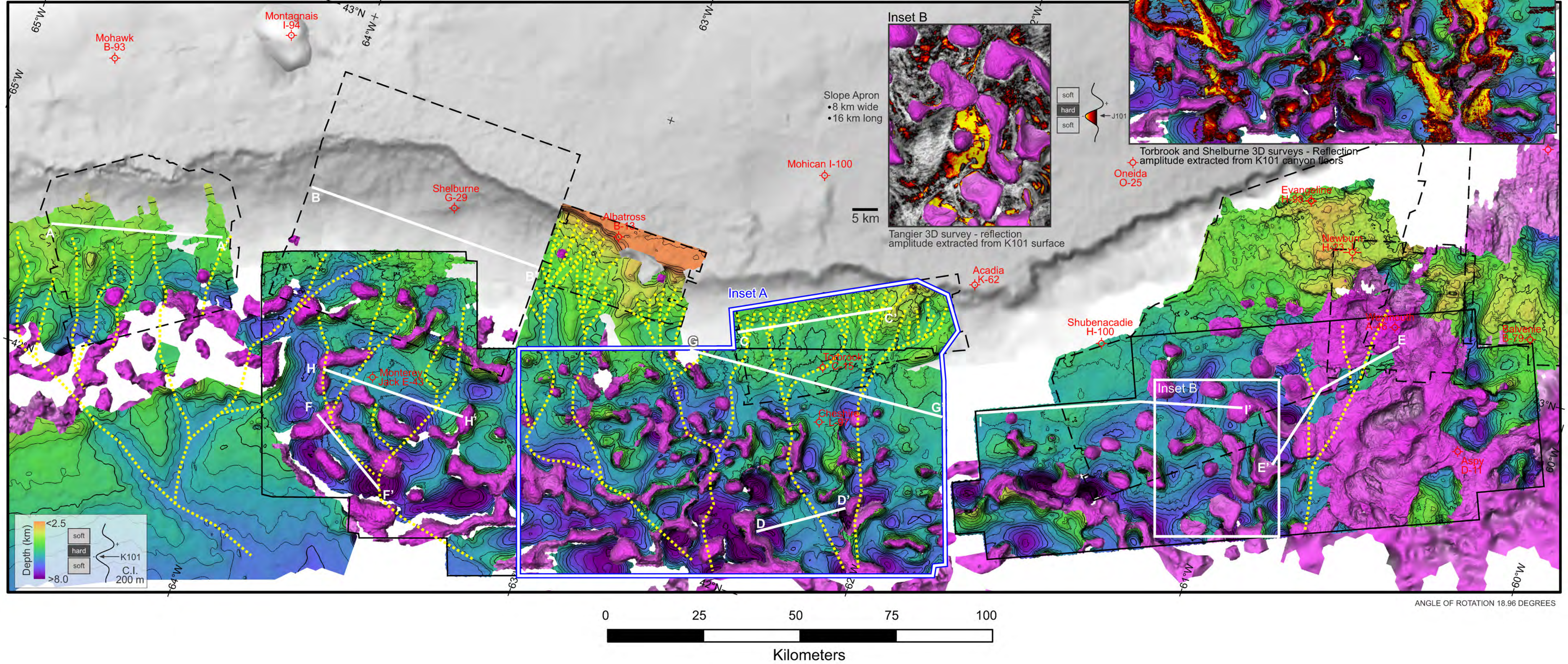
The K101 marker is a moderate to high amplitude trough (downward decrease in impedance) mapped regionally. It records slope erosion along the axes of numerous canyons whose floors produce a particularly bright soft reflection within a generally low amplitude K112 to K94 succession. K101 ties to the Late Albian Unconformity (Weston et al. 2012; RPS 2018) at Monterey Jack E-43, Cheshire L-97, Evangeline H-98, Newburn H-23, Weymouth A-45, and Balvenie B-79, and has been correlated with a high degree of confidence in most areas. Some mapping uncertainty arises where younger periods of erosion re-occupied K101 canyons. For example, at Cheshire L-97, the K101 marker forms a bright trough roughly 3 km east of the borehole. Correlating this trough (the axis of a canyon) "low" ties the marker to the K101 unconformity at the borehole; correlating this trough "high" along the youngest incision, brings the marker into slightly younger lastest Albian strata at the borehole. So although canyoning appears to have begun at the K101 unconformity, the canyons themselves are diachronous and remained active through the remainder of the Albian.

K101 canyons locally cut as deep as the K125 marker in the Shelburne survey. In the landward parts of the Torbrook and Mamou surveys, the two surfaces are nearly indistinguishable (e.g. Profile C-C'), except for the bright negative character of K101, and a distinctive mass transport deposit that plugs one K101 canyon along the eastern part of the Shelburne survey and landward into the Torbrook survey. The K101 surface could not be correlated into the WG survey. It is, however, the oldest marker we were able to correlate into minibasins that loaded the salt canopy in the eastern study area.

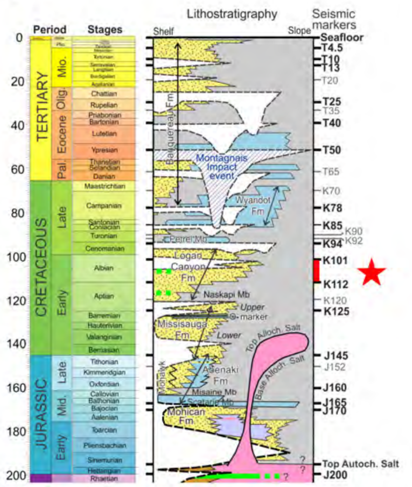
K101 canyons in the eastern part of the Shelburne survey show elevated reflection amplitude along their axes (Inset A), with a strong trough overlying the canyon thalweg. Incision depths reach 400 m, while canyon widths can exceed 10 km. Several canyon reaches eroded and unroofed previously stalled diapirs, so salt-related morphology probably impacted how the canyons filled. Canyon fill ranges from a single bright amplitude trough immediately above the canyon floor, to clear lense shaped accumulations of transparent to chaotic facies corresponding to mass failure deposits plugging the lower canyon fill, to slightly elevated amplitude convergent thinning deposits that plug the upper canyon fill. Dendritic gullies in the heads of several canyons are imaged in the Torbrook and Mamou surveys. These pass downslope into 19 tributary canyons that dissect the slope from the Barrington survey in the west to the Tangier survey in the east, that in turn converge into eight main canyons in the seaward study area (including the abyssal plain outboard the salt basin in the southwest). In addition to canyons, there is at least one slope apron along the K101 surface in the Tangier survey. It is fed by a narrow bifurcating channel that passed between two converging salt bodies, depositing the 8 km wide and 16 km long apron at the corresponding break in slope (see Inset B).



Torbrook and Shelburne 3D surveys - Reflection amplitude extracted from K101 canyon floors



Tangier 3D survey - reflection amplitude extracted from K101 surface



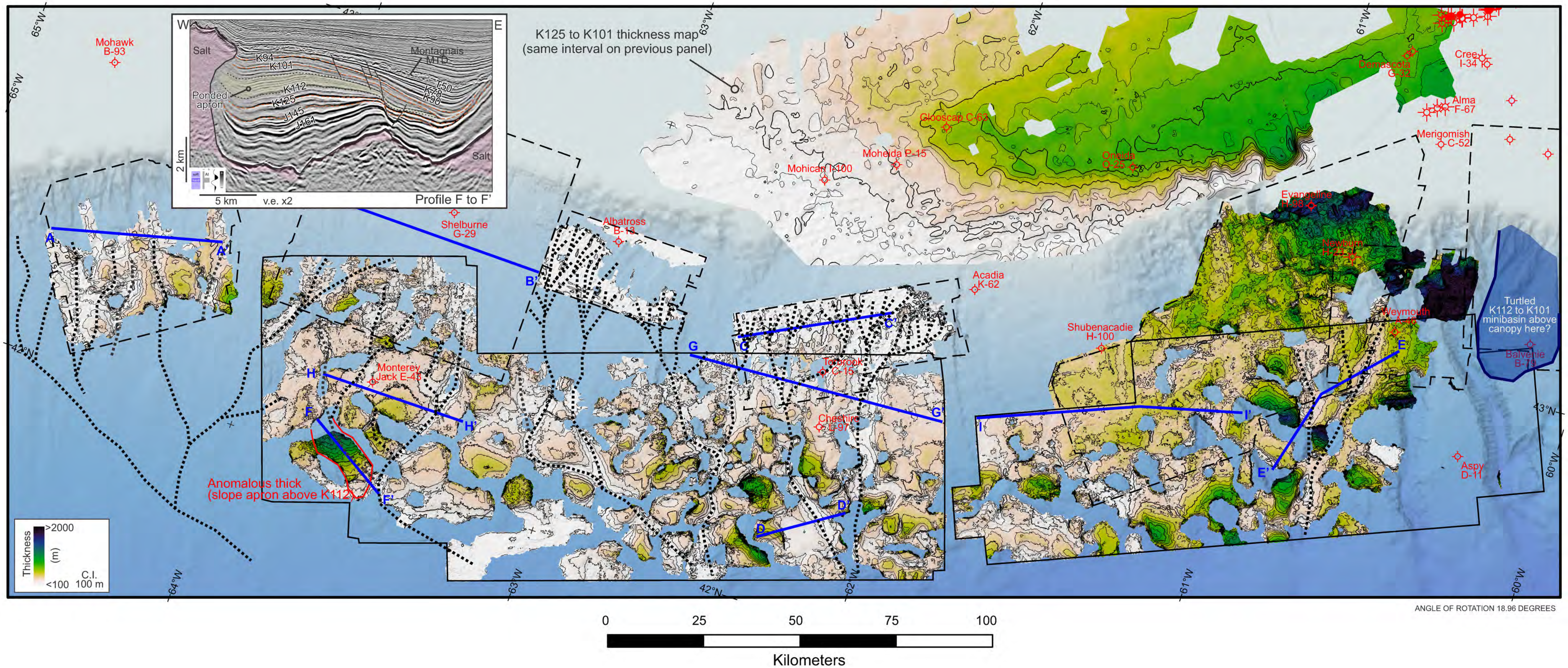
Thickness - K112 to K101 (Albian)

The K112 to K101 interval is generally thickest in the northeastern parts of the study area within the Tangier, Thrumcap, Weymouth, and probably Veritas surveys. Here, salt-based detachments are common, as strata translated downslope during development of landward growth faults. The anomalously thick region in the northeast part of the Weymouth survey was produced by K112 to K101 loading above one or more salt feeders here. Because K112 could not be carried above the canopy with confidence in the northeast study area, it is not possible to generate a thickness map here. However, there are several turtled minibasins above the salt in the blue shaded area probably containing Albian strata. The interval also locally thickens within salt withdrawal minibasins in the Shelburne survey. One anomalous thick - made up of layered onlaping packages of moderate amplitude reflections - was deposited above the K112 marker, but below a clear K101 channel axis in the southwestern part of the Shelburne survey (Profile F - F'). The deposit tapers seaward and strongly resembles a ponded slope apron, now turtled. It was probably deposited in the mid-Albian.

The interval is generally thin or absent across the landward parts of the Barrington, WG, Mamou and Torbrook surveys and on the outer shelf immediately landward of these surveys. Widespread thins from K101 canyon erosion are visible across all surveys on the slope (canyon axes identified in black stippled lines). In the east, a major branching canyon system passes west of Weymouth A-45 and continues across the full width of the Tangier survey. Although it is difficult to differentiate the different periods of canyon incision here due to complex salt tectonics, erosion likely began in the Middle Albian with a subsequent younger period of canyon incising across the same region in the Late Albian. In the west, canyon incisions across the Shelburne, Torbrook, Mamou and Barrington(?) surveys are mostly related to the K101 unconformity, and are expressed as clear thins on the K112 to K101 thickness map.

The K112 o K101 interval is sampled at multiple slope wells. At Weymouth A-45 it is 1142 meters thick and composed mostly of shale and claystone with some minor siltstones. At Newburn H-23 it is 760 meters thick. The upper section is predominantly shale but there are two sands at the base just above the K112 marker. The shallower sand, sand 1 (4306-4326 m), is about 20 m thick, with the bottom 8 m of section producing a blocky gamma ray response and the upper 12 m producing a more serrated upward-fining gamma ray response. Two sidewall cores from the lower blocky interval (4323 and 4317 m) contain pebble conglomerates interpreted as channel lag deposits from a submarine channel that transported sands further into the basin. Average porosity is 18% (Kidston et al., 2007). The second slightly deeper sandstone (sand 2) is about 9 m thick and is gas bearing. It consists of very fine to fine grained sandstone with an average porosity of 13.5% (Kidston et al., 2007). This interval does not appear to be present in Aspy D-11, though correlations into this area are challenging, and age control is limited. In the west, penetrations of this interval at Monterey Jack E-43 and Cheshire L-97 are much thinner (230 m and 183 m respectively) and the interval is mainly claystone.

K112 to K101 thickness distribution on the slope is mirrored by the thickness distribution on the shelf, where it is **equivalent to Cree Member of the Logan Canyon Formation (Wade and MacLean 1990). Although the** K125 and K101 thickness map shown on the shelf below includes Aptian strata that are not included on the slope, it provides a good proxy for the distribution of the Cree Member and its shelf equivalents.



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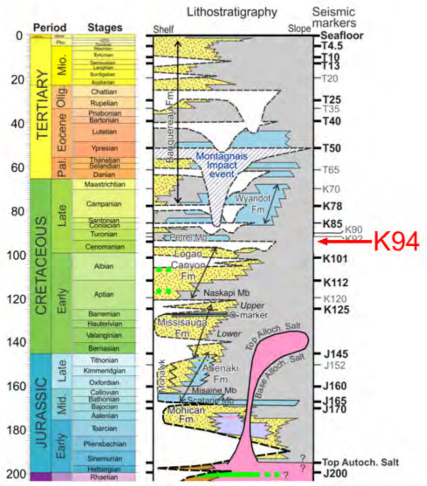


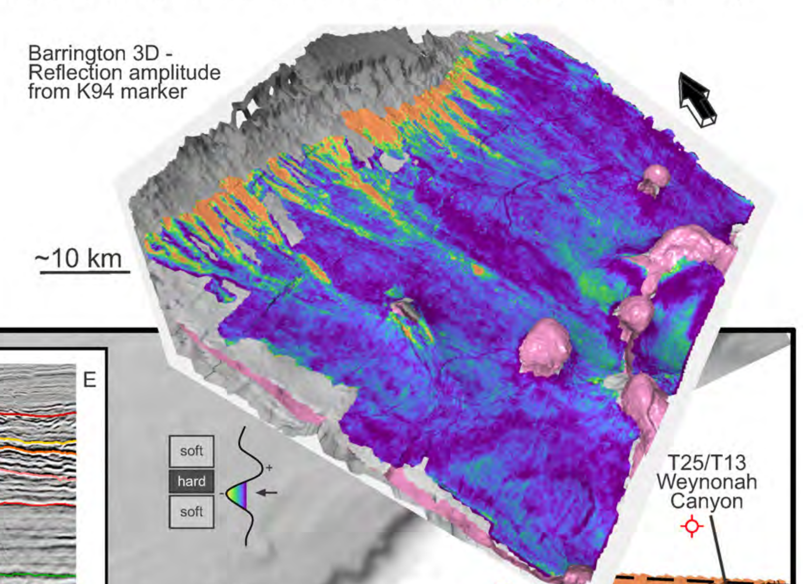
K94 - Cenomanian/Turonian Unconformity

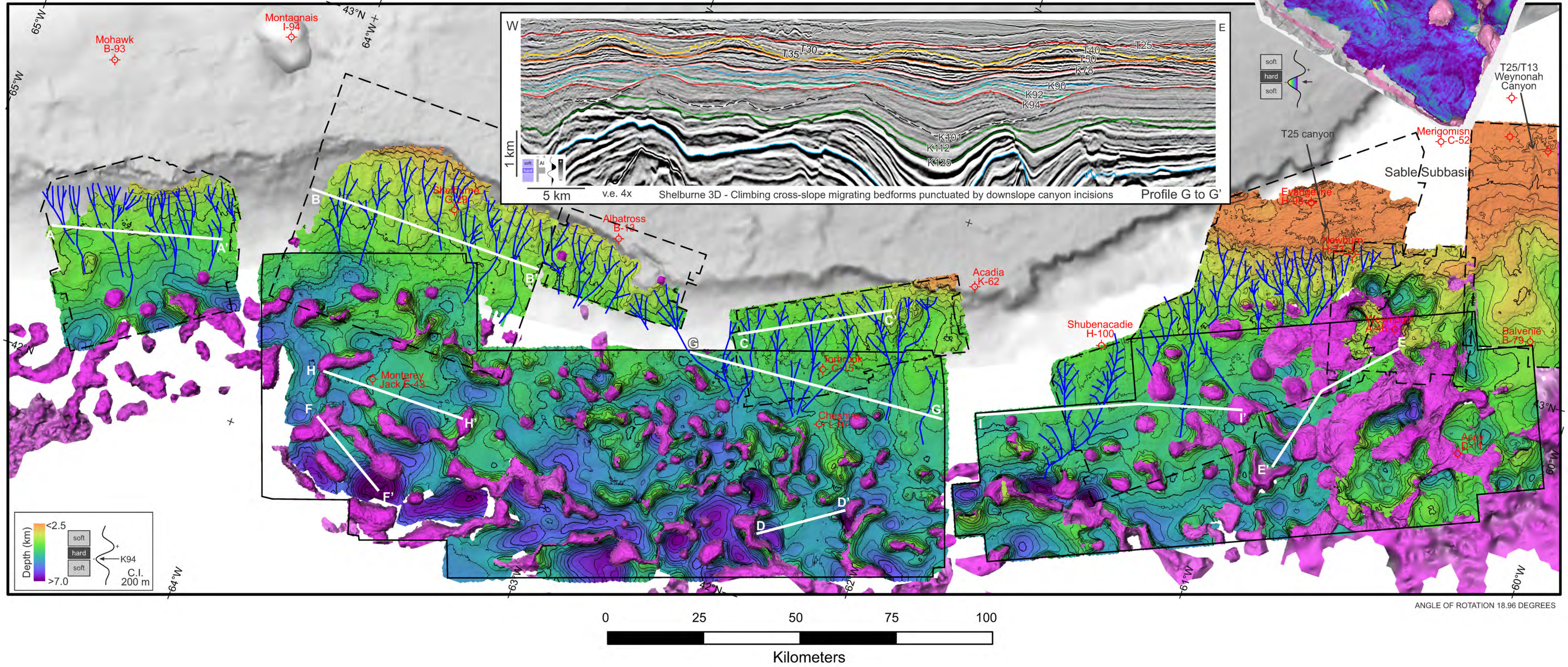
The K94 marker is a moderate to high amplitude trough (downward decrease in impedance) mapped regionally. It ties to either an unconformity or a correlative conformity at the Turonian/Cenomanian boundary (just beneath the Petrel Member, if present) at Monterey Jack E-43, Cheshire L-97, Shelburne G-29, Shubenacadie H-100, Evangeline H-98, Newburn H-23, Weymouth A-45, and Balvenie B-79 (Fensome et al. 2008; Deptuck 2008; Weston et al. 2012; RPS 2018), and has been correlated with a high degree of confidence in most areas. The marker separates generally low amplitude reflections below from a number of shingled/climbing/migrating, brighter amplitude reflections above (e.g. K92 and K90 markers described later). At Shelburne G-29 and Shubenacadie H-100, K94 coincides with a subtle lithological change from shale below to shale, siltstone, and minor marls above. It is the oldest marker widely correlated above the salt canopy.

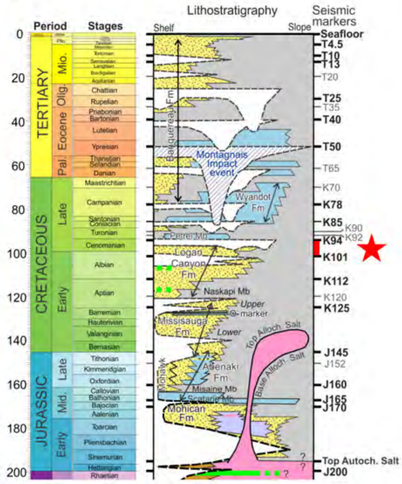
Some mapping uncertainty arises with how deep to carry K94 where it is most erosive and overlies K101 canyons. K94 generally lies above K101 canyon fill, and does not appear in most cases to deeply re-incise its fill. Correlation into the landward and eastern parts of the Thrumcap survey, and landward parts of the Barrington survey, is challenging due to poor imaging and the lower amplitude of the marker here.

Like K101, it records slope erosion along the axes of numerous canyons, particularly in the landward parts of the WG, Mamou, Torbrook and Thrumcap surveys, where they mimic the morphology of the large-scale climbing bedforms that aggraded above the K101 surface (see Profiles A - A' through C - C'). Canyon spacing and trajectory correspond closely with the spacing and trajectory of these large-scale northeast migrating bedforms, which appear to have guided the passage of turbidity currents traversing the slope. Amplitude extractions from the Barrington survey show a number of narrow high amplitude channels and gullies extending down the steep slope in a dendritic pattern seaward of the carbonate bank edge (see image on the right). Unlike K101 canyons that truncate underlying strata even in the seaward parts of the Shelburne and Tangier surveys, K94 canyons are difficult to follow further seaward. Instead the surface passes distally into a brighter, more continuous to striped negative reflection in several of the distal minibasins in the Shelburne survey (see amplitude extraction on next panel).

Further east, the marker is widespread above the salt canopy in the Weymouth and eastern Thrumcap and Tangier surveys. It also correlates near the base of the Upper Slope Slide Complex described by Deptuck and Campbell (2012), where it forms a detachment surface instead of a stratigraphic marker. K94 also truncates the folds associated with the Newburn fold-and-thrust belt in the eastern part of the Thrumcap survey that formed as a downslope response to rapid Albian sedimentation above growth faults in the Sable Subbasin (Deptuck et al. 2009).





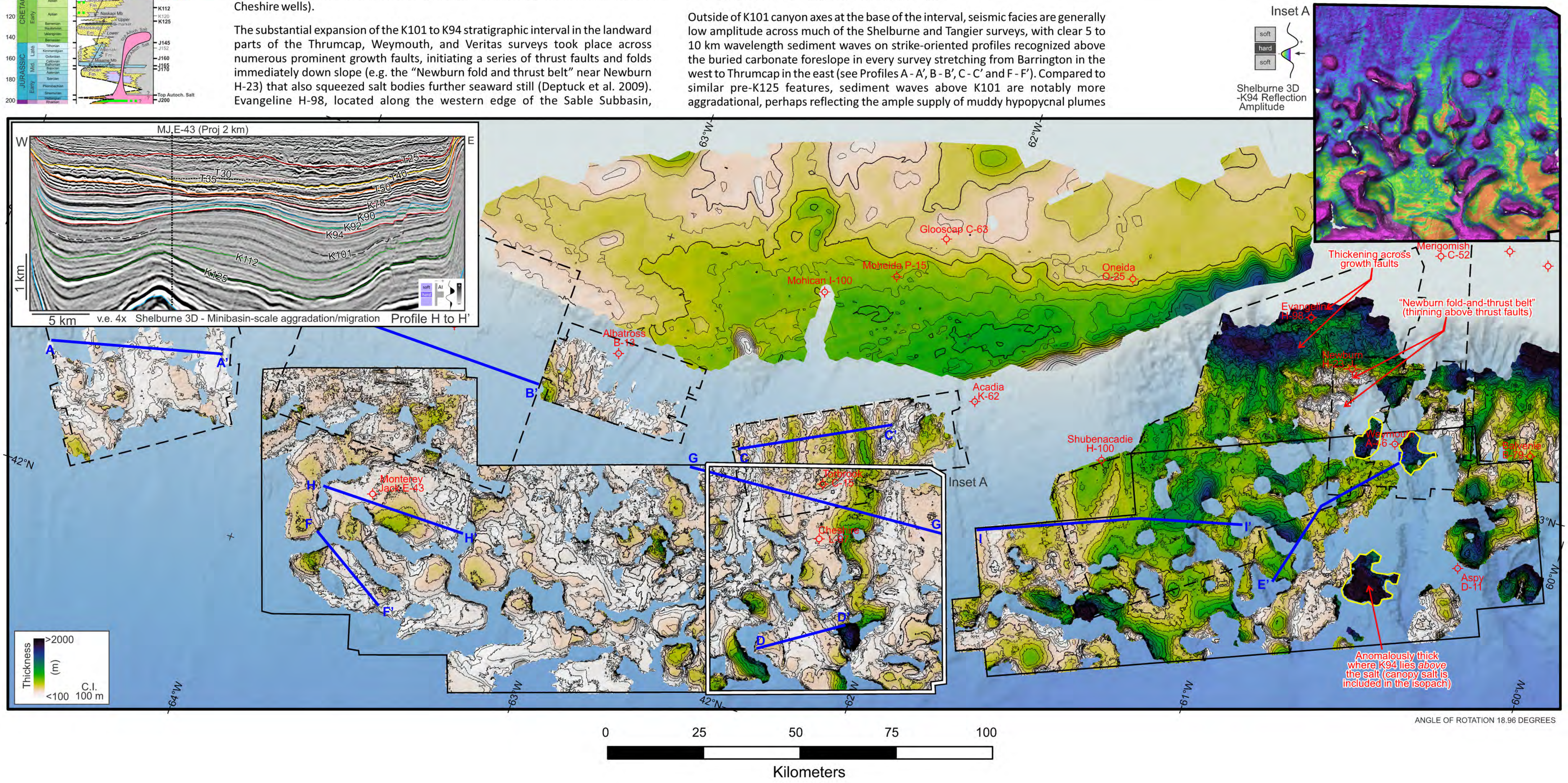


Thickness - K101 to K94 (latest Albian to Cenomanian)

Overall, the K101 to K94 interval is thickest in the east in the Tangier, Thrumcap, Weymouth and Veritas surveys, and thinnest in the west in the Barrington, WG, Mamou and western Shelburne surveys. Thickness distribution is strongly affect by canyon erosion from above along the K94 unconformity that causes the interval to thin, and by canyon erosion below, where the increased fill of K101 canyons causes the interval to thicken. Thinning from K94 canyons is particularly evident in the western Thrumcap and Tangier surveys, while thickening above K101 canyons is particularly evident in the eastern Shelburne survey (east of the Torbrook and Cheshire wells).

The substantial expansion of the K101 to K94 stratigraphic interval in the landward parts of the Thrumcap, Weymouth, and Veritas surveys took place across numerous prominent growth faults, initiating a series of thrust faults and folds immediately down slope (e.g. the "Newburn fold and thrust belt" near Newburn H-23) that also squeezed salt bodies further seaward still (Deptuck et al. 2009). Evangeline H-98, located along the western edge of the Sable Subbasin, penetrated a 1432 m interval dominated by shale across one of these growth faults, while Newburn H-23 penetrated a 587 m interval of similar strata above a thrust fault 17 km downslope. Although the thickest sediments are found in the Sable Subbasin, there is a pronounced westward and seaward shift in the thickest shelf sediments above the LaHave Platform (compared to the K125 to K101 interval), matching the westward migration of equivalent strata on the slope. Seismic profiles near Oneida O-25 show prograding clastics reached the edge of the underlying carbonate bank. Multiple seismically defined channels are recognized on the shelf, supplying clastics directly to the slope north and northwest of the Thrumcap and Torbrook surveys.

Outside of K101 canyon axes at the base of the interval, seismic facies are generally low amplitude across much of the Shelburne and Tangier surveys, with clear 5 to 10 km wavelength sediment waves on strike-oriented profiles recognized above the buried carbonate foreslope in every survey stretching from Barrington in the west to Thrumcap in the east (see Profiles A - A', B - B', C - C' and F - F'). Compared to similar pre-K125 features, sediment waves above K101 are notably more aggradational, perhaps reflecting the ample supply of muddy hypopycnal plumes coming from the Sable Subbasin. There is an increase in evidence for down-slope sediment transport in the K101 to K94 interval moving towards the Sable Subbasin, including broad incisions that are locally floored by higher amplitude reflections, filled with chaotic seismic facies resembling mass transport deposits, and flanked by wedge-shaped deposits that more closely resemble overbank deposits (levees) than sediment waves. Reflection amplitude also locally increases in some salt withdrawal minibasins, where bright localized reflectors might correspond to sandy slope aprons similar to the example in Inset B of the K101 panel.



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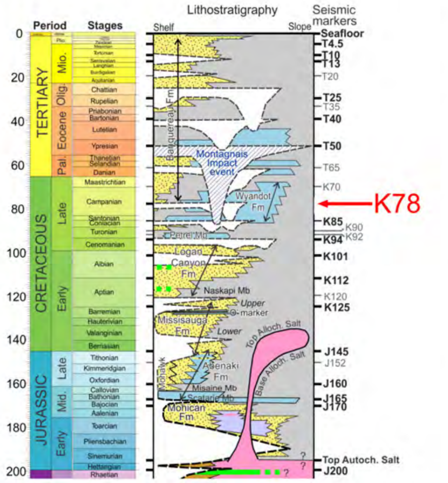
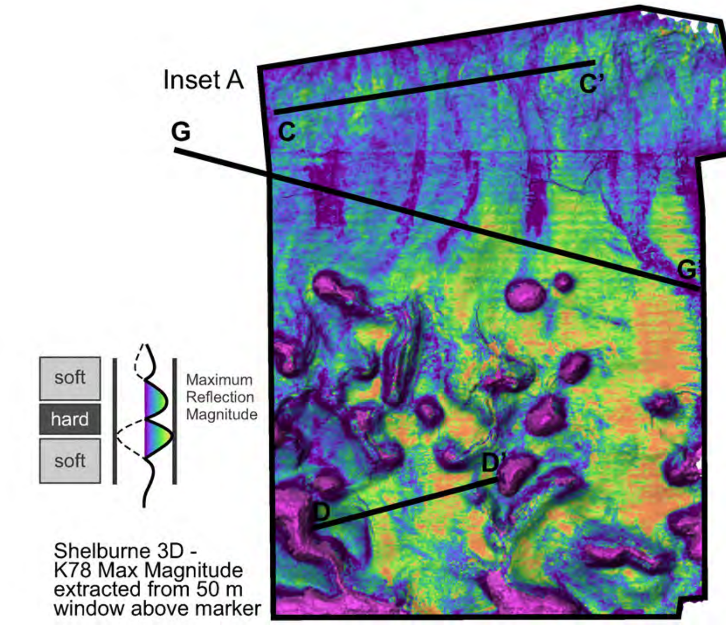


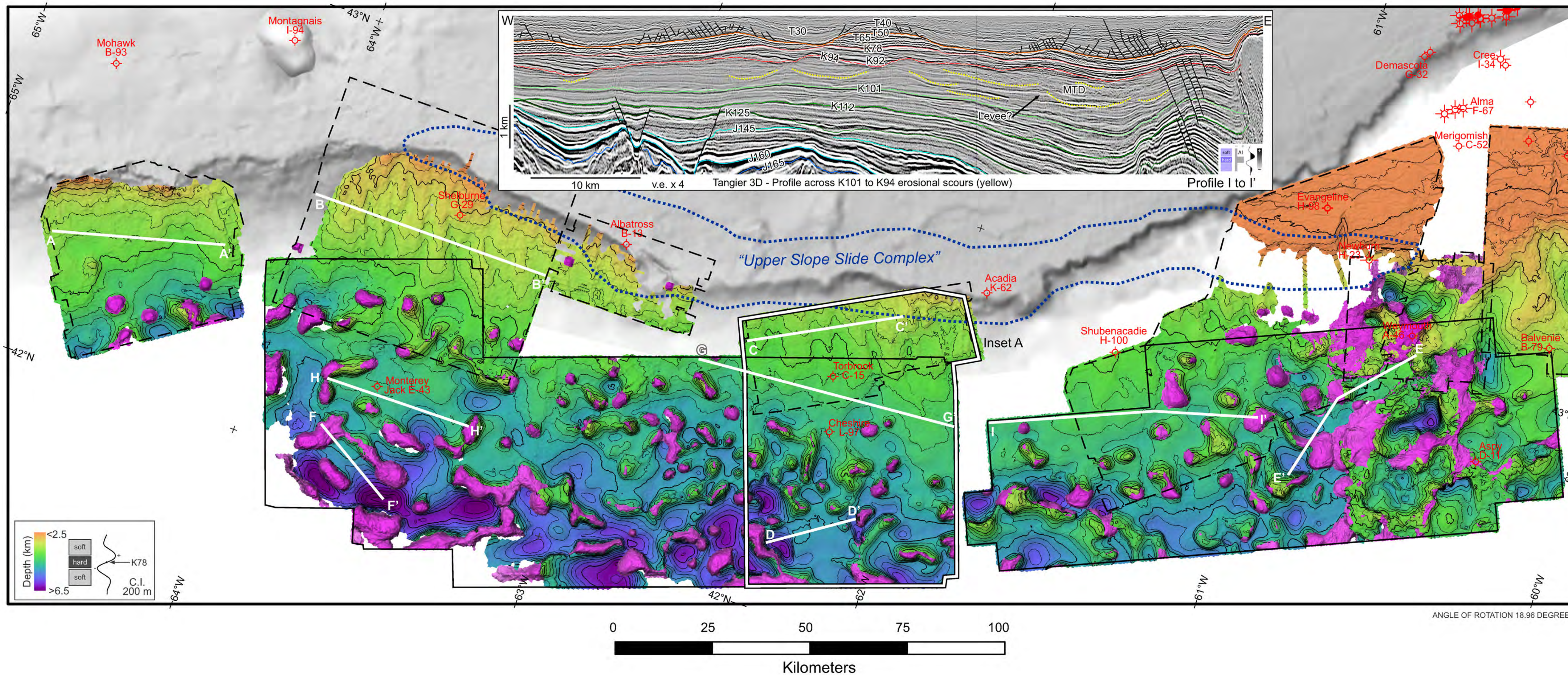
K78 - Campanian Unconformity

The K78 marker is a zero-crossing beneath a continuous peak and above a prominent trough that displays common lateral pinchout and merger with an underlying trough. It separates moderate amplitude commonly shingled reflections below, from a distinctive interval of high amplitude, commonly vertically aggrading and faulted reflections above. At Shelburne G-29 and Shubenacadie H-100, the K78 marker is located above a relatively thin interval of Campanian chalks, separated by an unconformity from an overlying thicker interval of inter-layered later Campanian to Maastrichtian chalks, marls, and calcareous mudstones (Fensome et al. 2008; Weston et al. 2012). On the shelf, the marker defines the top of the Campanian Wyandot Formation, whereas on the slope the marker is both underlain and overlain by chalks that lithostratigraphically could all be considered the Wyandot Formation (making K78 an "intra-Wyandot" unconformity in deepwater).

The marker can locally be difficult to pick from a slightly older unconformity that underlies the Campanian chalks (K85 marker of Deptuck and Campbell 2012). It is also locally difficult to pick in the eastern parts of the Tangier survey where the K94 to T50 envelope is much thinner and complexly deformed above salt tongues and canopies. Otherwise, K78 was correlated with a high degree of confidence across the study area.

Ultimately K78 is an unconformity, with numerous canyons cutting the slope in the WG, Mamou, and Torbrook surveys, several of which continue seaward crossing the Shelburne and Tangier surveys (see Inset A). The fill of these canyons is distinctly low amplitude to reflection free. Outside of canyons, the reflection amplitude of the interval immediately above the K78 zero-crossing is quite variable, but is generally lower in the western part of the Shelburne survey and higher in its eastern part and into the Tangier survey. Locally there is clear angular truncation adjacent to some diapirs where steeply inclined Cretaceous strata on the flanks of a number of salt diapirs (draping megaflap successions) are truncated along the K78 surface in the Shelburne and Tangier 3D surveys.





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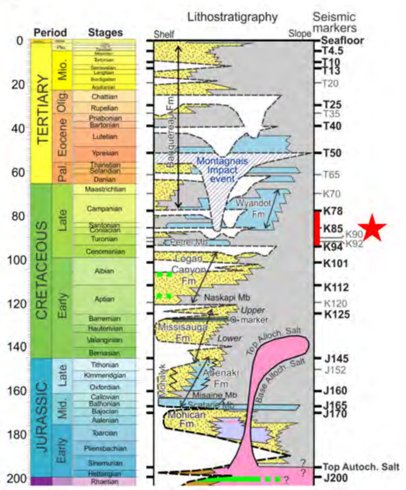


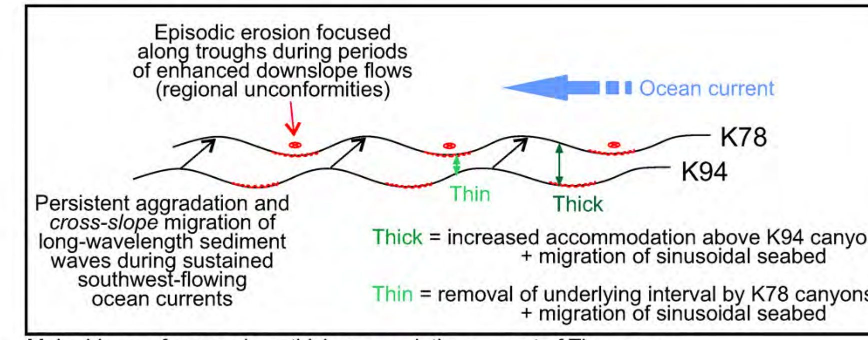
Thickness - K94 to K78 (Turonian to mid-Campanian)

Overall the K94 to K78 interval is thickest in the west and thins significantly to the east. Where it is thickest in the Barrington, WG, Mamou, Shelburne and Torbrook surveys, it forms downslope elongated bands - more numerous and tightly spaced on the upper slope, and fewer and broader further seaward. At least thirty 3 to 5 km wide and 7 to 10 km spaced bands of 500 to 950 m thick strata on the upper slope, broaden and merge into just seven 15 to 30 km wide and 20 to 40 km spaced bands of thicker strata in the Shelburne survey. No wells penetrate the thickest parts of this succession, but Shelburne G-29, Cheshire L-97, and Shubenacadie H-100 each sampled 433 m, 234 m, and 218 m, respectively, of predominantly claystones and shales of Turonian to Santonian age, capped by Campanian chalks (Fensome et al. 2008; Weston et al. 2012).

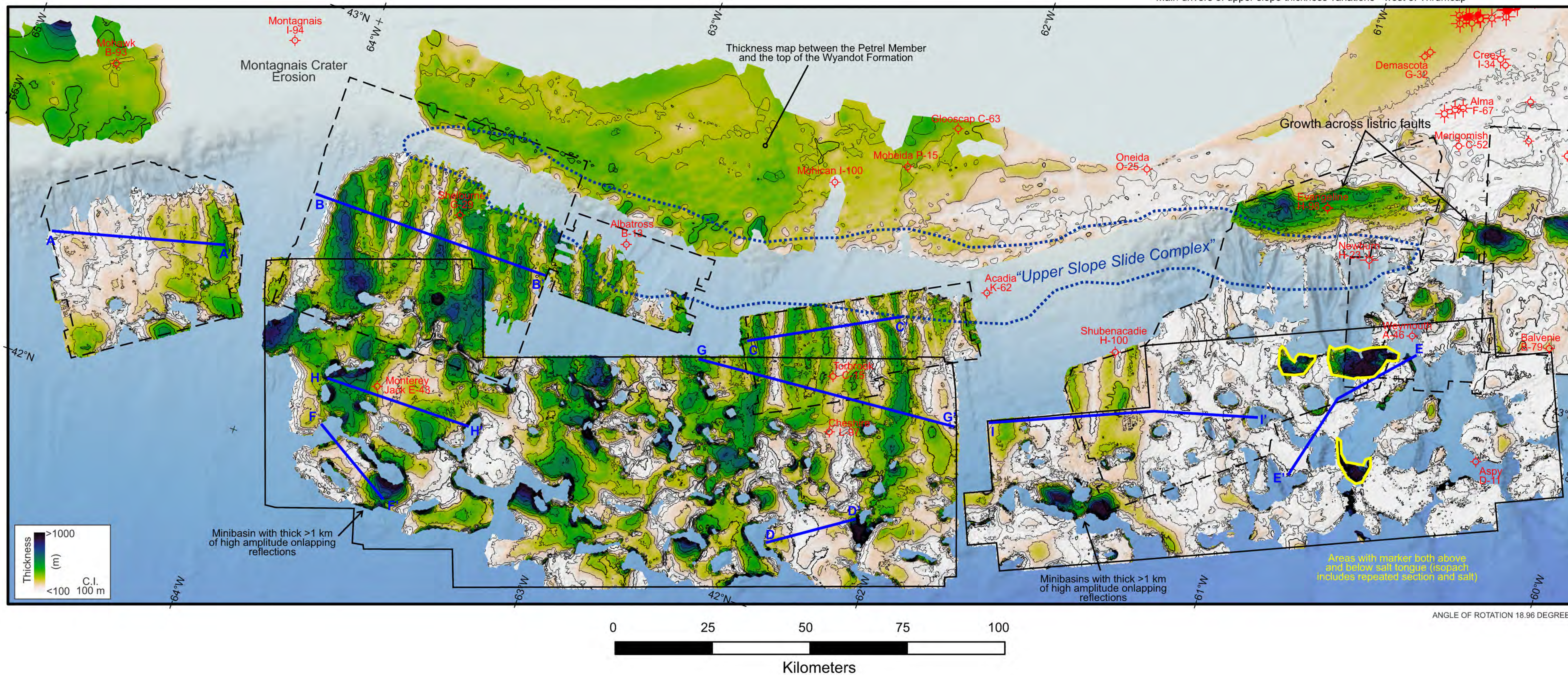
Like the interval between the K101 and K94 markers, the thickness of the K94 to K78 interval is strongly affect by overlying K78 canyons that cause the interval to thin, and by canyon erosion below, where the increased accommodation above K94 canyons causes the interval to thicken. Almost every thicker band on the upper slope coincides with the axes of K94 canyons, with the overlying K78 canyon axes shifted consistently to the northeast coinciding with thins (see Profiles A - A', B - B', C - C', and G to G'). Some thickness variations also take place independent of canyon erosion, as the offset stacking (migration) of successive sinusoidal surfaces naturally produces both thins and thicks in the intervening interval (see the figure to the right and the next panel).

Four or five other anomalous accumulations are present in isolated minibasins in the seaward parts of the Shelburne and western Tangier surveys, where the K94 to K78 succession is more than 1 km thick and is characterized by high amplitude onlapping reflections of unknown composition. K94 to K78 strata are generally thin across the eastern parts of the Thrumcap and Tangier surveys, thickening in the landward parts of the Thrumcap and Veritas surveys across growth faults where the interval can exceed 750 m thick, and locally in two minibasins above the salt canopy in the Weymouth survey. Three other areas show anomalous thicks above the canopy are regions where the K94 marker underlies the salt, but K78 overlies it, with intervening canopy salt included in the thickness map (identified in yellow).

Strata between the Petrel Member (Turonian limestone) and the top of the Wyandot Formation (Coniacian to Campanian chalk) on the shelf is roughly equivalent to the K94 to K78 interval on the slope. Like other shelf intervals, there is close correspondence between the thickest deposits on the platform and the thickest deposits on the slope.



Main drivers of upper slope thickness variations - west of Thrumcap



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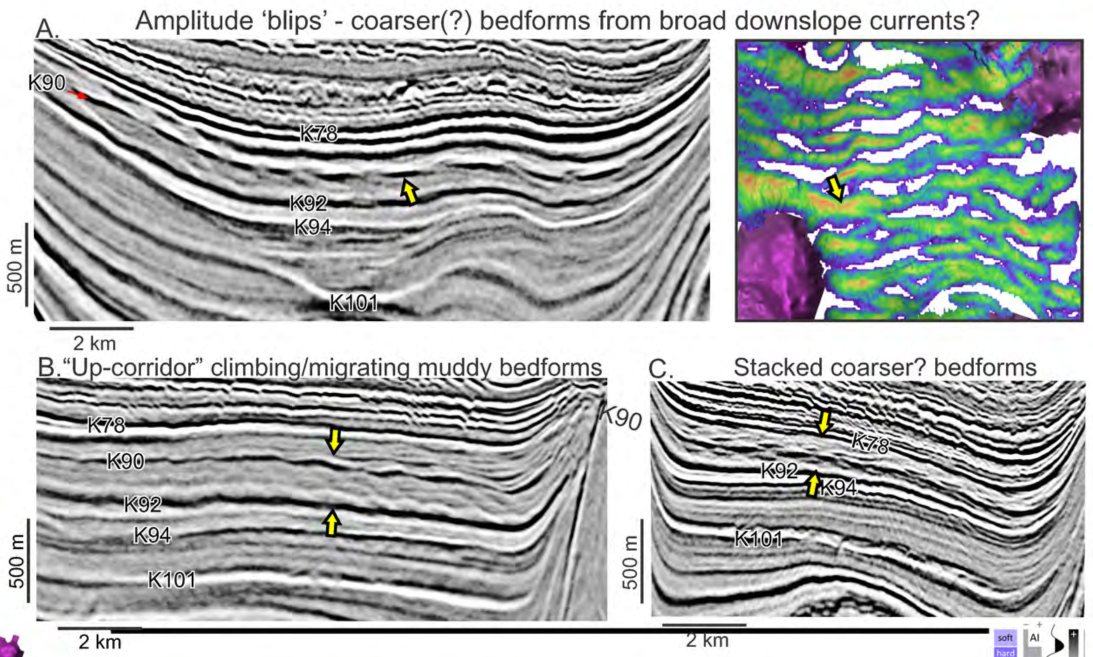
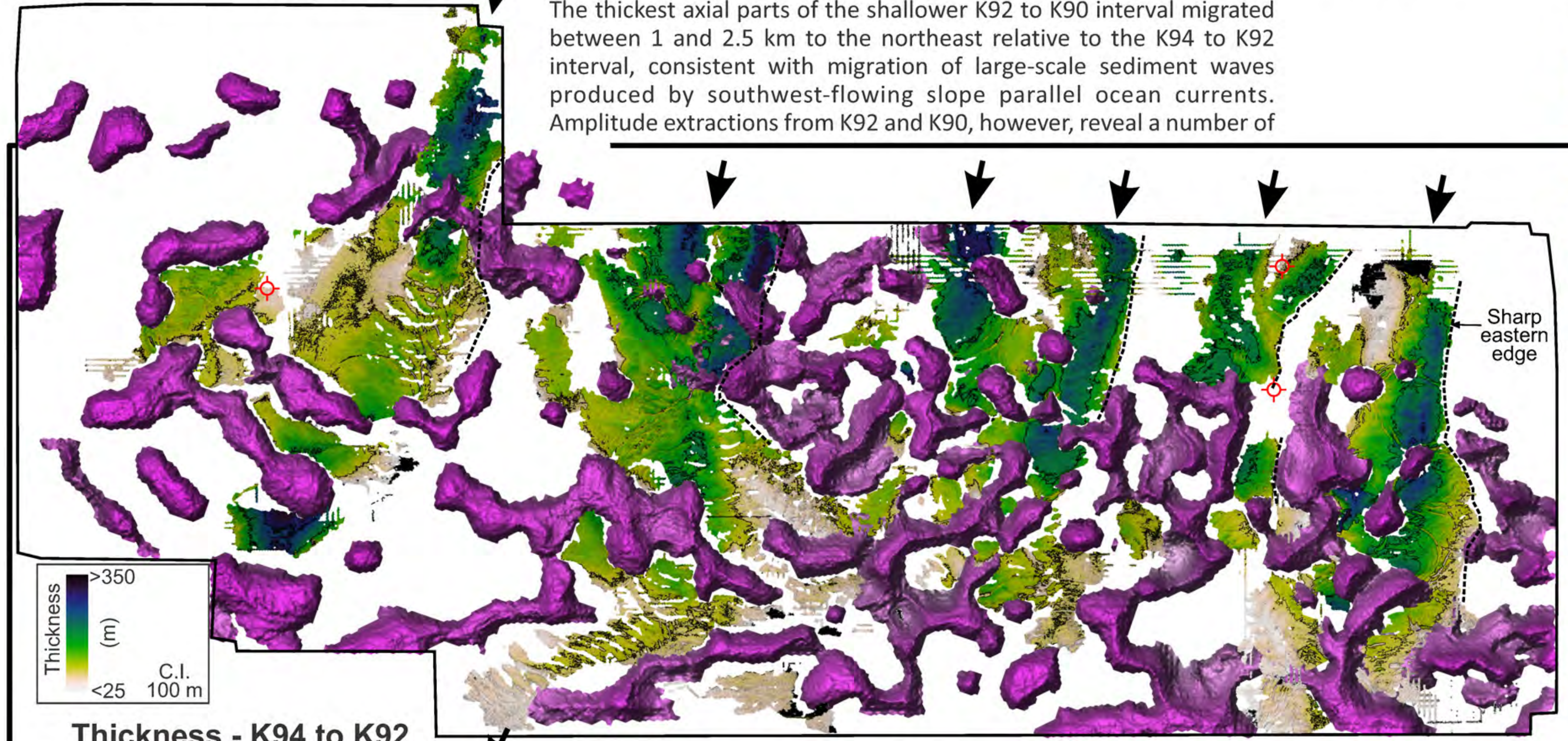
Five or six K94 to K78 slope corridors track through the Shelburne survey. Each contains thicker stacked intervals of mixed-amplitude sinusoidal reflections with an overall northeast migration direction on *strike-oriented* profiles (see Profile G - G'). Two markers - K92 and K90 - were correlated within the interval throughout the Shelburne survey. Both correspond to peaks (downward increase in impedance) that define individual horizons within the stacked series of long-wavelength sediment waves. The thickness between K94 and K92, and K92 and K90 is shown below. Both intervals are narrower and thicker up-slope, broadening and thinning downslope. Both also thin abruptly laterally along the corridor margins, particularly the eastern margin. The same markers are present in each corridor suggesting they share a common depositional history.

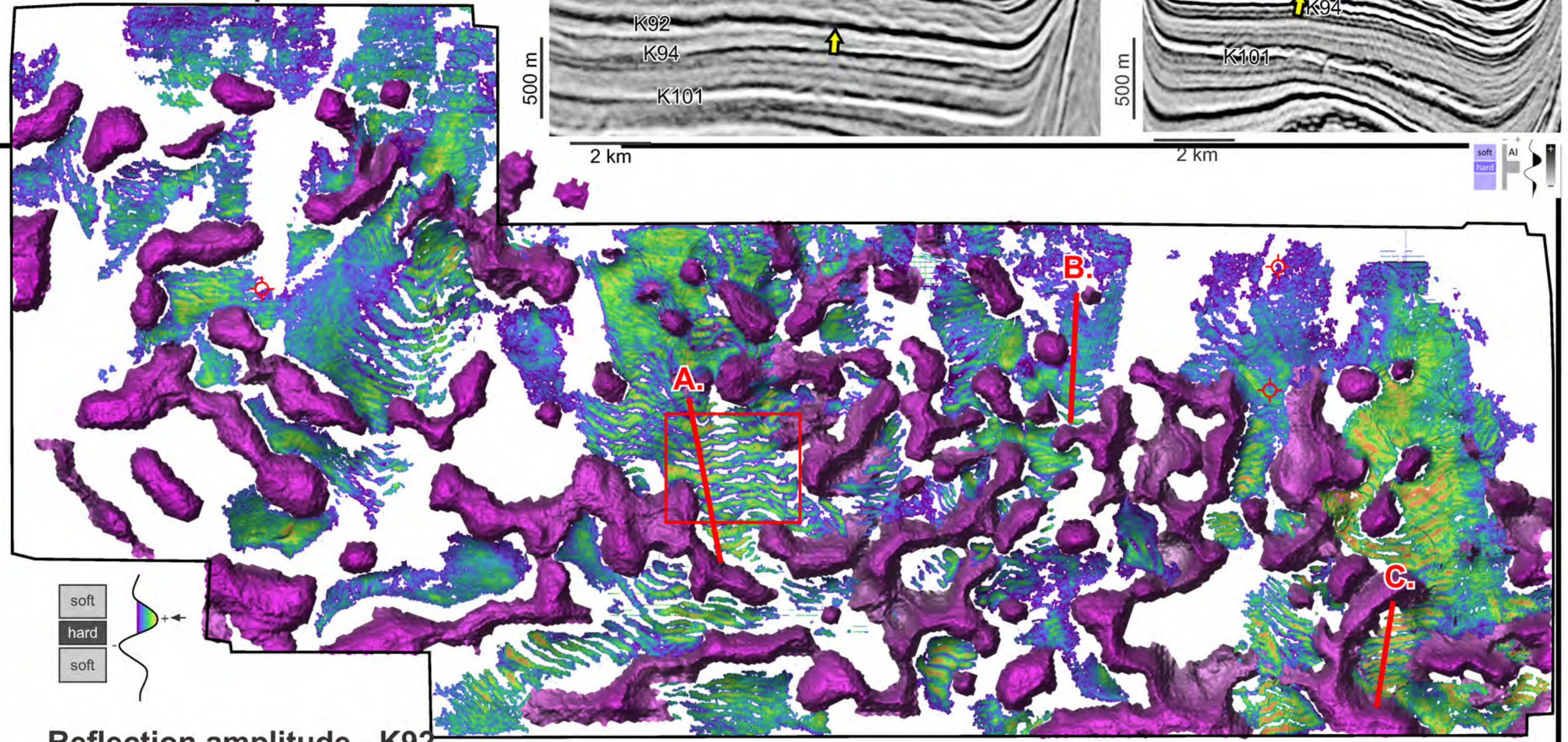
The thickest axial parts of the shallower K92 to K90 interval migrated between 1 and 2.5 km to the northeast relative to the K94 to K92 interval, consistent with migration of large-scale sediment waves produced by southwest-flowing slope parallel ocean currents. Amplitude extractions from K92 and K90, however, reveal a number of amplitude bands roughly normal to the axis of each corridor that produce a "tiger-stripe" pattern in planform, particularly in the seaward parts of the survey. The orientation of individual amplitude "stripes" bends along each corridor, between the confining corridor margins, in places flanked by salt structures. Seismic profiles show that the "tiger stripe" pattern is produced by both high, moderate and low amplitude reflections. The clearest examples are associated with the K92 marker characterized by strong amplitude variations along the marker, forming chains of isolated high amplitude "blips" (Profile A) or wavy reflections (Profile B) on *dip-oriented* profiles. The "tiger stripe" anomalies aggrade to form both low reflection amplitude (Profile B) and high reflection amplitude (Profile C) up-corridor migrating sediment waves, with 1 - 2 km wavelengths.



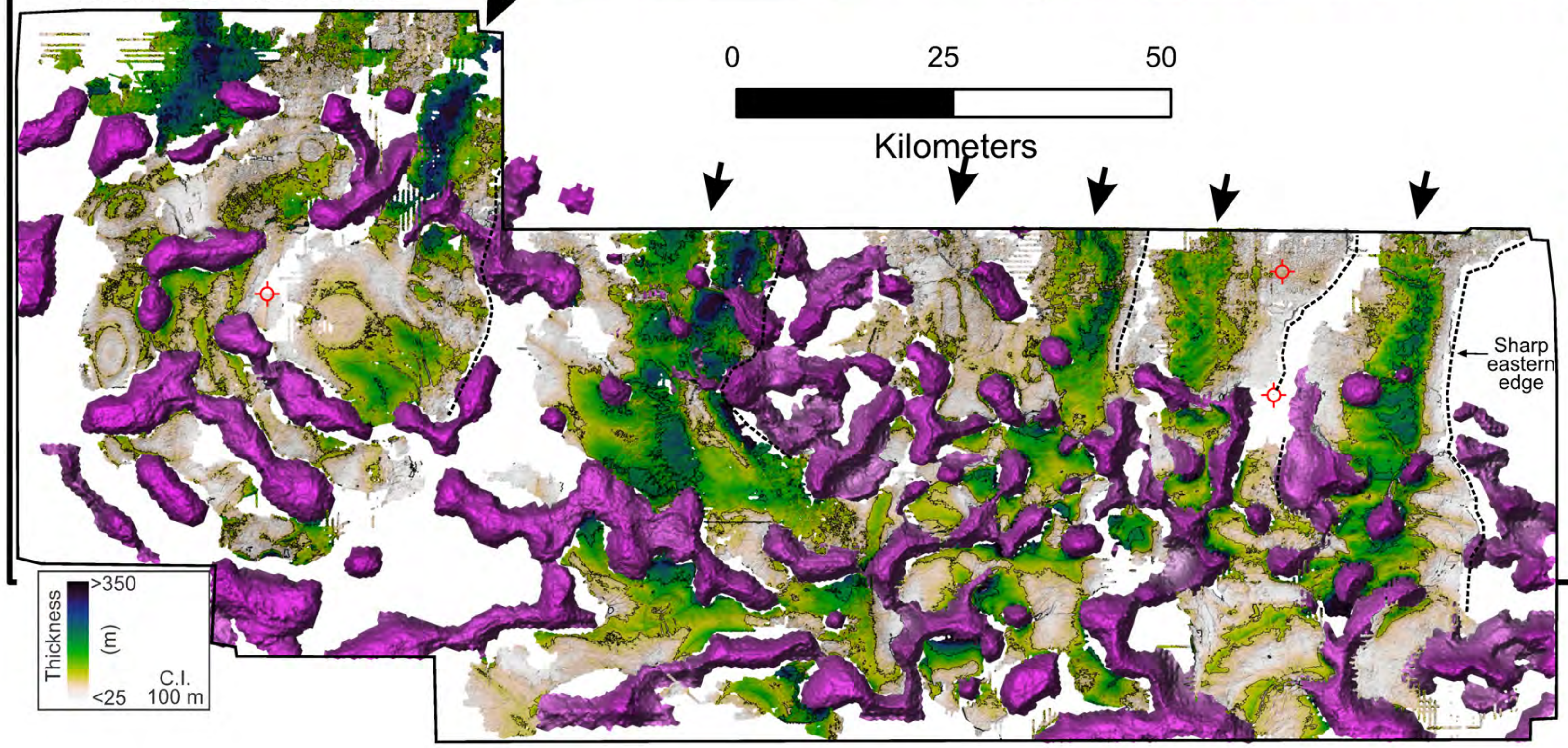
Thickness - K92 to K90



Reflection amplitude - K90

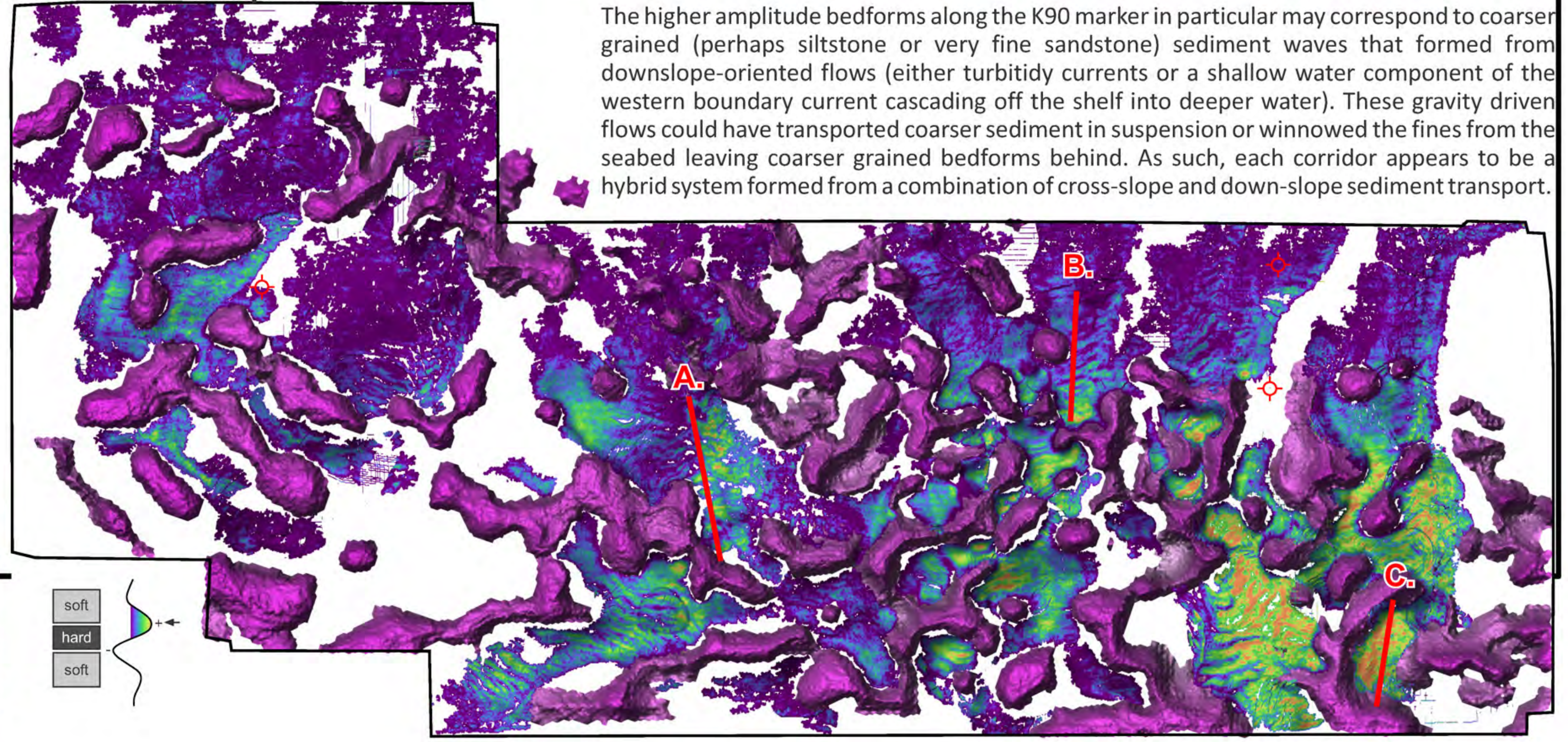


Thickness - K94 to K92



Reflection amplitude - K92

The higher amplitude bedforms along the K90 marker in particular may correspond to coarser grained (perhaps siltstone or very fine sandstone) sediment waves that formed from downslope-oriented flows (either turbitidy currents or a shallow water component of the western boundary current cascading off the shelf into deeper water). These gravity driven flows could have transported coarser sediment in suspension or winnowed the fines from the seabed leaving coarser grained bedforms behind. As such, each corridor appears to be a hybrid system formed from a combination of cross-slope and down-slope sediment transport.



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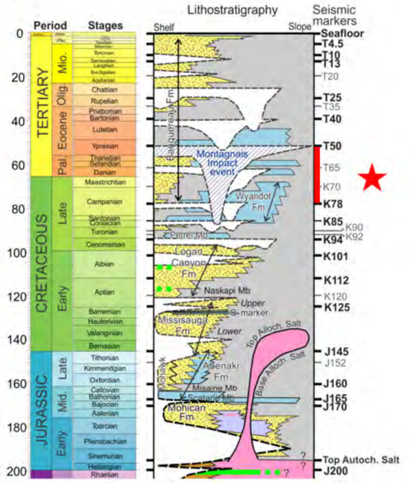


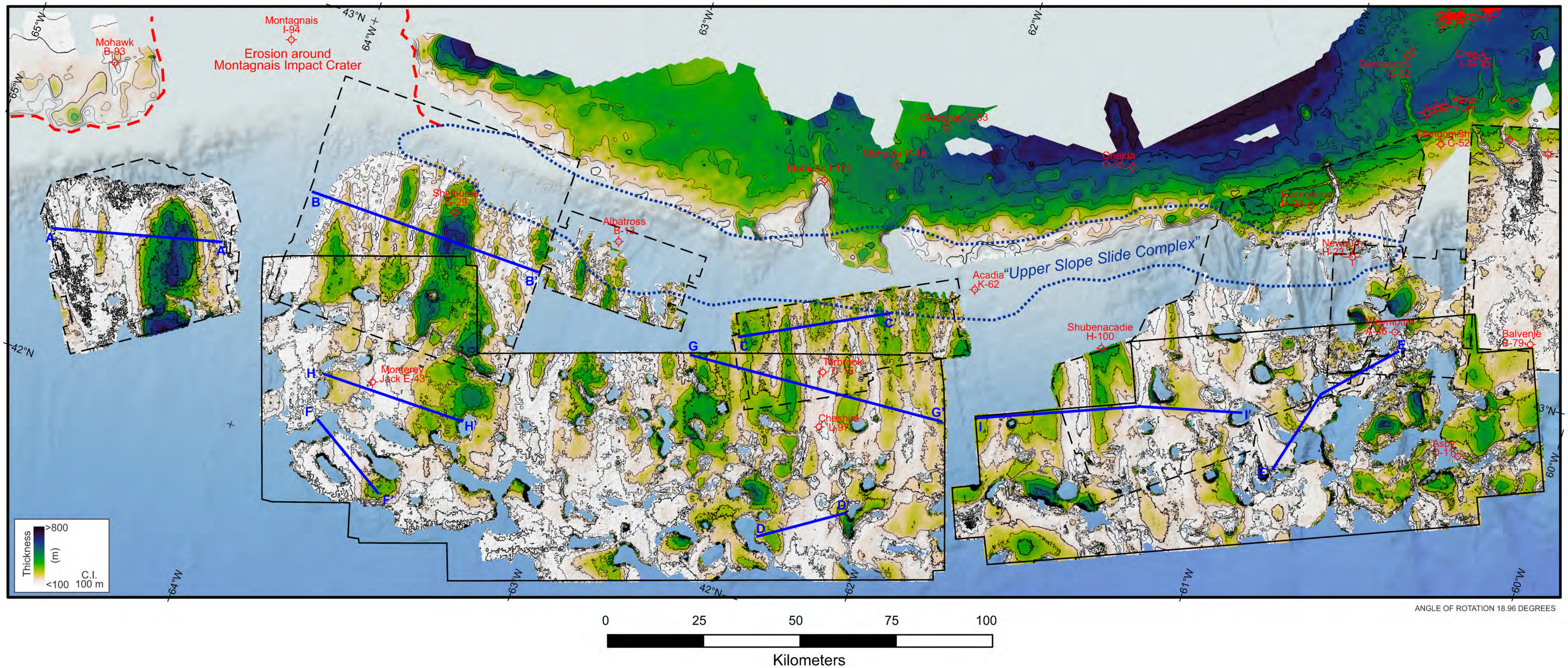
Thickness - K78 to T50 (latest Campanian to Early Eocene)

The final Cretaceous thickness map between the K78 and T50 markers includes a thin interval of Paleocene chalks on the slope that were widely eroded along the T50 surface and hence not suitable for generating regional maps. The distribution of K78 to T50 strata is similar to the underlying K94 to K78 succession, except that the amount of erosion along the upper surface is much greater, where a number of chute like canyons - some exceeding 15 km wide - removed large swathes of Upper Cretaceous and Paleocene strata (probably in response to the ~51 Ma Montagnais impact event; described in Chapter 5). K78 to T50 strata are preserved in a number of downslope-oriented erosional remnants ranging from 3 to 20 km wide and maximum thicknesses ranging from 400 to 740 m. Two of the thickest erosional remnants were penetrated at Shelburne G-29 and Shubenacadie H-100; both encountered a mix of Campanian to Paleocene chalks, marls, and calcareous shale (Fensome et al. 2008) that produce a distinctive reflection seismic response (see Profile I - I' that crosses the seaward part of the Shubenacadie remnant).

Markers within these remnants are generally reflective, and are commonly offset by small scale faults. In the best-preserved erosional remnants, there are three strong, heavily faulted but generally conformable peaks above the K78 marker, the shallowest of which is K70, which is the first Cretaceous marker removed by younger erosion (and its distribution is correspondingly limited). A fourth marker, (T65) defines the top of the Cretaceous succession (and base of the Paleocene chalks), but is separated by a clear erosional contact. As such, both T65 and T50 erode the Cretaceous chalk and marl series. The relatively conformable K78 to K70 succession shows wide variations in thickness reflecting pinching and swelling of the chalk/marl series and locally developed internal erosive surfaces. The complete series of markers can vary between > 460 m thick to less than 200 m thick over distances of <15 km, even without erosion along the T65 or T50 unconformities.

In the WG and Mamou surveys, internal markers within the erosional remnants are much more difficult to correlate. There is also a marked change in seismic facies approaching the region of salt canopies where the three distinct polygonally faulted peaks between K78 and K70 are no longer present immediately west of the salt canopies. This probably reflects an increase in erosion along the T65 surface, but it may also reflect increased canyoning within the K78 to K70 series here. The K78 to T50 interval thickens again within distal minibasins in the Shelburne survey and above the salt canopies in the eastern Tangier survey, where the reflective chalk/marl series shows convergent thinning onto salt highs.

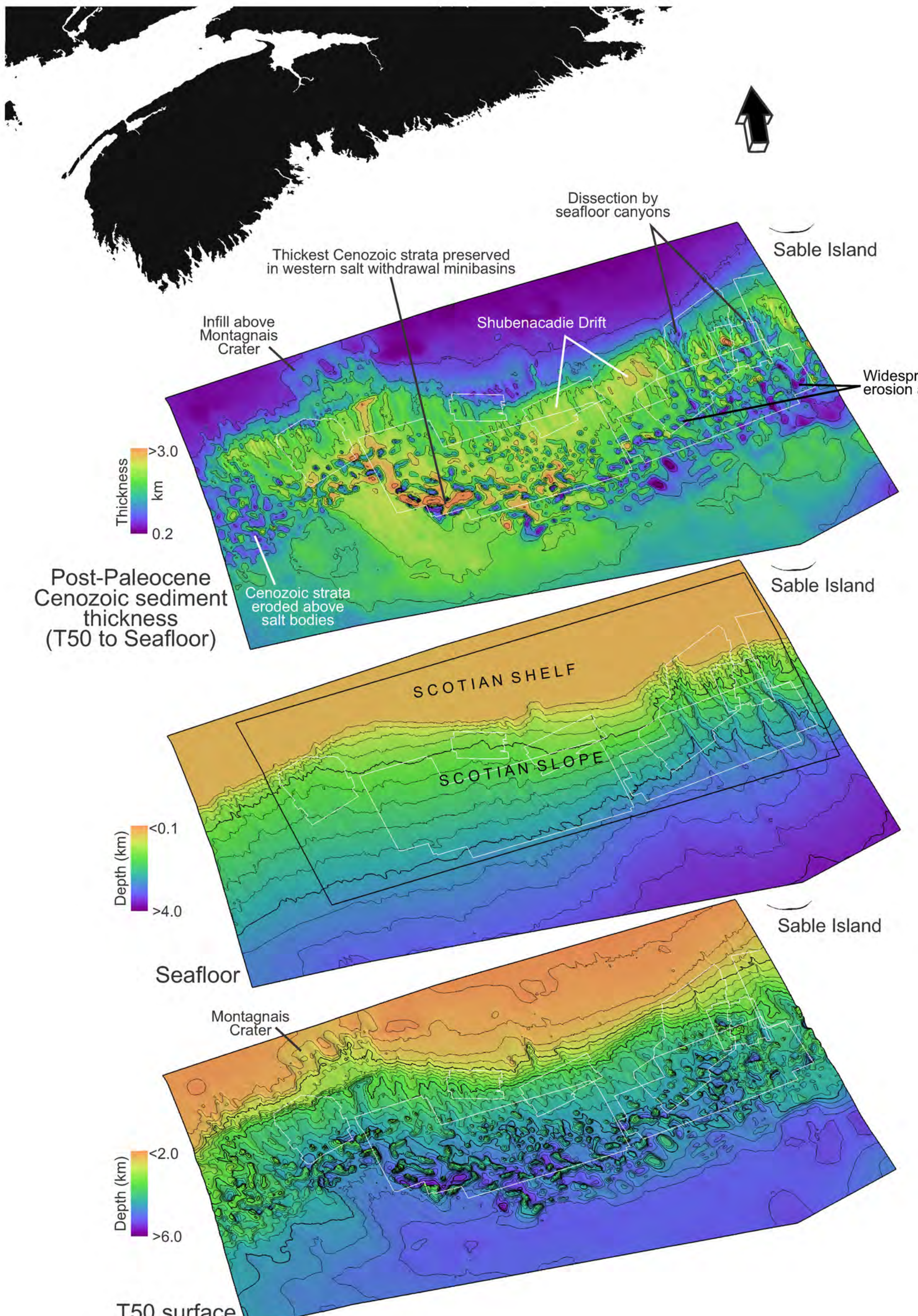
The equivalent succession on the shelf is more complete with a number of wells penetrating a 500 to 700 m thick Upper Cretaceous to Paleocene succession floored by Wyandot Formation chalks that pass sharply up-section into an upward-coarsening mudstone to sandstone succession of the Banquereau Formation (Wade and MacLean 1990; Weston et al. 2012). The succession is progradational, with low-angle foresets that built seaward, but is separated from the equivalent slope succession by a band of deformed and failed strata referred to by Deptuck and Campbell (2012) as the "upper slope slide complex". The slide complex is present in the landward parts of Thrumcap, Mamou, and WG surveys (discussed in more detail in Chapter 5). Two poorly cemented 2 m thick fine to medium grained Maastrichtian sands at Balvenie B-79 were probably sourced from Maastrictian deltas that are thickest on the shelf immediately landward of the well (Kidston et al. 2007).

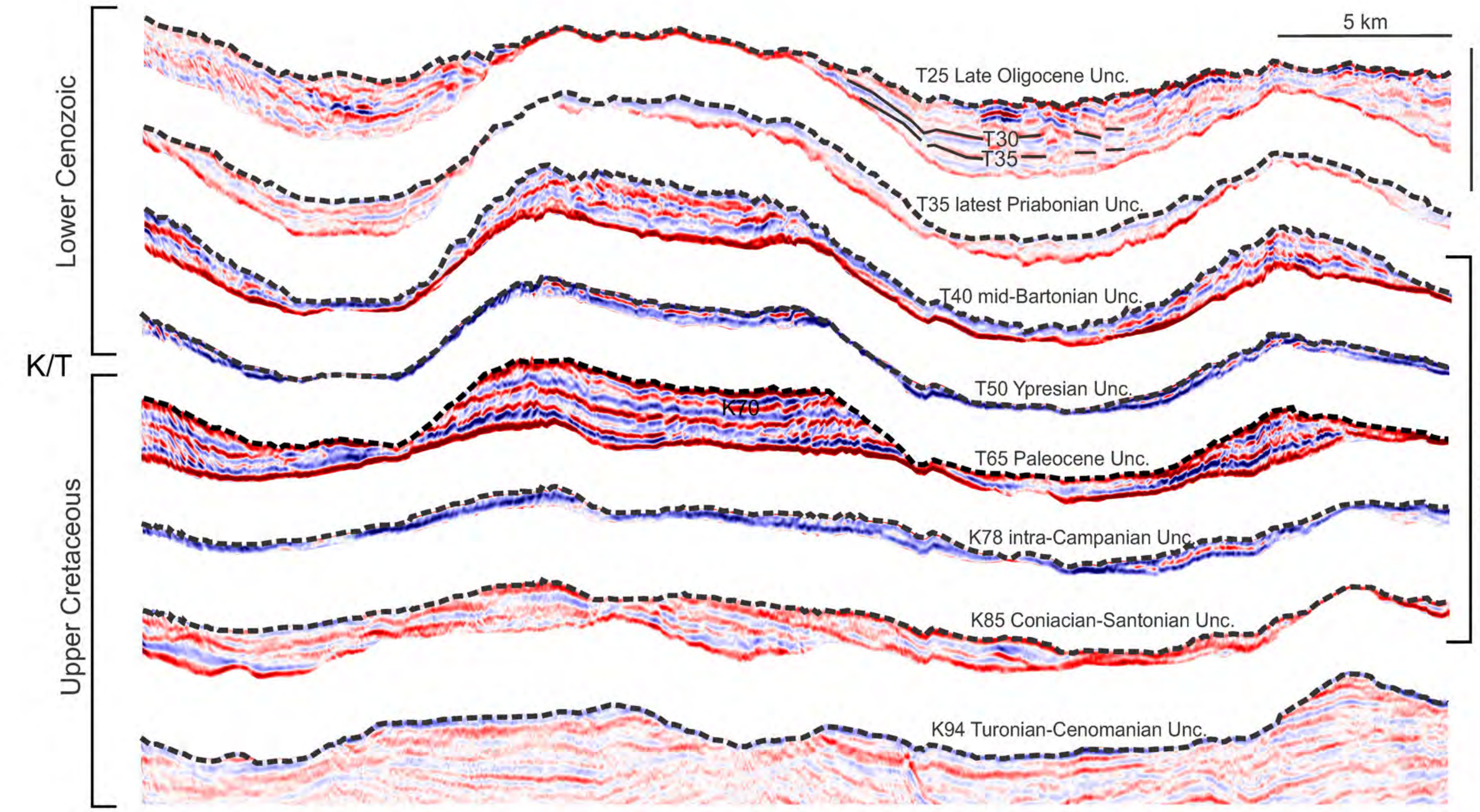


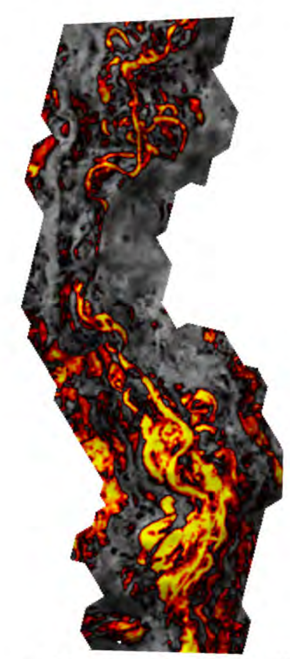
Atlas of 3D seismic surfaces and thickness maps, central and southwestern Scotian Slope

Chapter 5 – Cenozoic

Mark E. Deptuck and Kristopher L. Kendell






Sinuous channel belts along post-T25 turbidite corridors

Cenozoic Succession

The total Cenozoic sediment thickness (top left) between the Early Eocene T50 marker (lower left) and the seafloor (middle left) shows an abrupt westward shift in the thickest accumulations compared to the Cretaceous succession. The thickest intervals are found in salt withdrawal minibasins captured in the western and seaward parts of the Shelburne survey where they are up to 3.5 km thick. Unlike minibasins further landward, down-building persisted in this area until recently, with clear expressions of these salt structures (or at least the folds above them) on the modern seabed in the distal parts of the Shelburne and Tangier surveys. Thinning of the Cenozoic succession took place via widespread canyon erosion and Quaternary mass failure in the eastern study area, as well as on the slope furthest to the southwest, off Georges Bank.

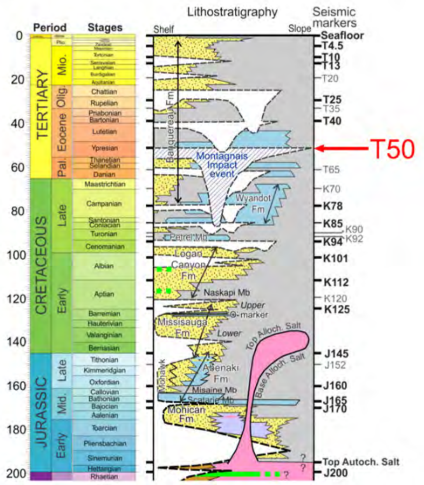
A sharp and widespread change in the erosional-depositional style is recorded between Middle and Upper Eocene strata in the study area. The transition from the T40 to the T25 markers ushers the end of the era of downslope-oriented laterally migrating 'thicks' that dominated sediment distribution in the Late Cretaceous through Early Paleogene, particularly along the western slope. The T25 marker shows little evidence of the wide and deep mid-Bartonian T40 canyons. The broad flat-floored canyons that formed as the marl and chalk series accumulated between the K85 and T40 markers, are sharply different from channel-belts and canyons that developed after the T25 marker. The former developed through repeated cycles of incision followed by drape of more chalks and marls, with little or no 'active' accumulation above canyon floors. Subsequent erosion simply re-occupied the same, or slightly shifted, corridor (depending on how active cross-slope currents were), repeating the cycle (stacked images above). In contrast, the latter contain clear coarse-grained lithologies along their axes associated with the migration of sinuous submarine channels (image to the left).

In addition to clear turbidite systems, the post-T25 era also records a sharp change in the style of contourite sedimentation and a marked increase in mass failures on the slope. Overall, the T25 to T13 succession records the contemporaneous north and west migration of the early Shubenacadie Drift (Campbell and Mosher 2015), with its associated up-slope migrating sediment waves, and southward accretion of an outer shelf and slope that steepened from the base to the top of the interval, periodically shedding mass failures that accumulated south and west of the developing contourite drift. Canyons incised along the T13 surface, and at least two other unconformities, interrupted but did not halt development of the Shubenacadie Drift, which continued to grow and migrate to the north and west throughout the Pliocene, where it ultimately reached its crescendo in the Torbrook survey and north of the Thrumcap survey, attaining a total thickness of more than 1.8 km. Canyon and channel development, mass failures, and contourite drift accretion and migration are all intimately related and dominate the latter part of the Cenozoic in the study area.

This chapter includes fourteen panels that summarize the Cenozoic mapping results from nine semi-contiguous 3D reflection seismic volumes on the central to western Scotian Slope. Starting with the T50 surface and associated Montagnais mass transport deposit, and ending with the seafloor marker.

Recommended citation:
Deptuck, M.E., and Kendell, K.L. 2020. SCOPE Project, Chapter 5 - Cenozoic, In: Atlas of 3D Seismic Surfaces and Thickness Maps, Central and Southwestern Scotian Slope, Canada-Nova Scotia Offshore Petroleum Board Geoscience Open File Report: 2020-006MF, 14 panels.

Mark E. Deptuck and Kristopher L. Kendell

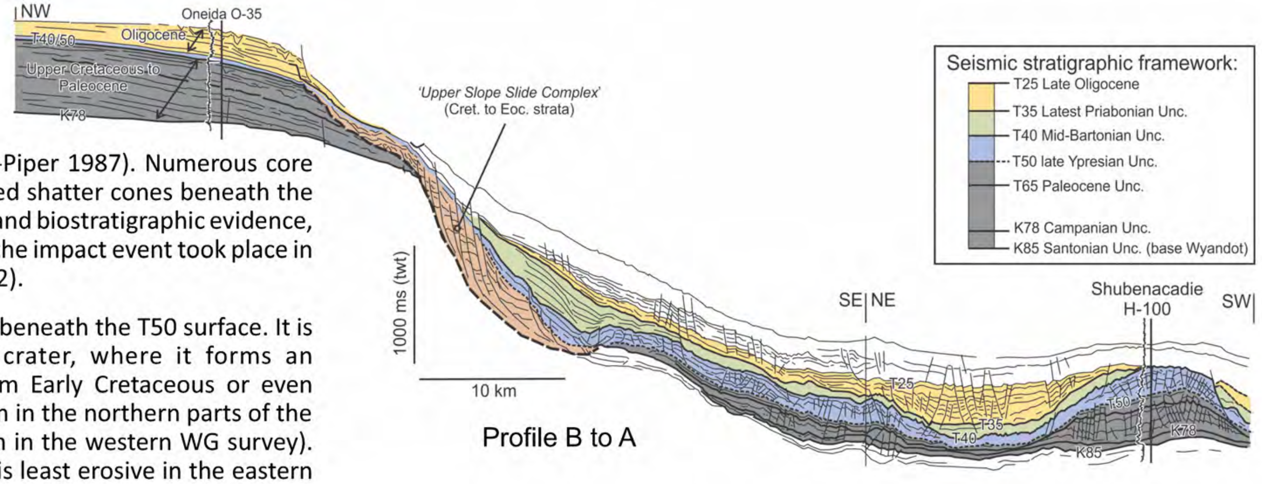


T50 - Ypresian Unconformity

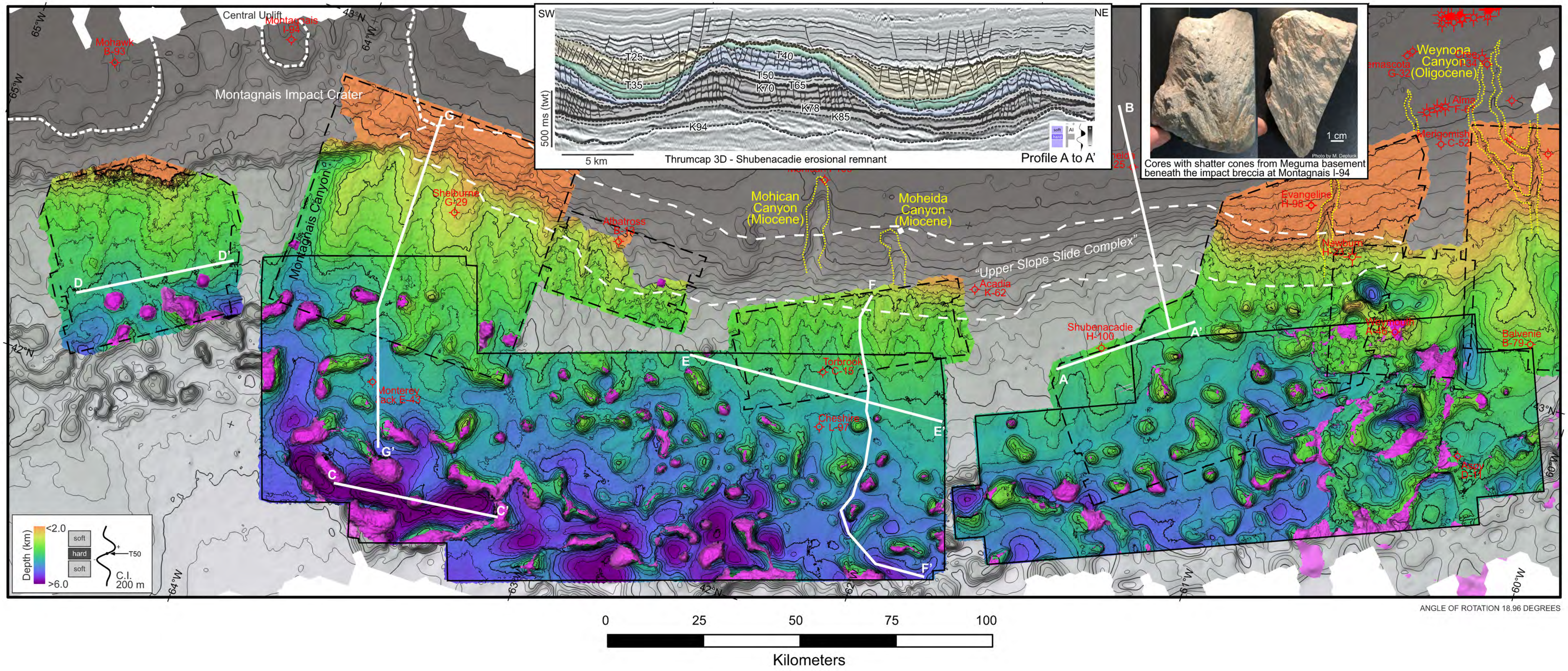
The T50 marker was picked as a zero-crossing below a high to moderate amplitude peak, and above a strong trough-peak pair generated by Paleocene chalks (where the underlying Upper Cretaceous-Paleocene chalk/marl series is well-preserved, for example at Shubenacadie H-100; see Profile A - A'). At Shubenacadie H-100 and Shelburne G-29, T50 coincides with an unconformity between late Ypresian and Paleocene strata (Weston et al. 2012). The T50 surface erodes Paleocene chalks and underlying Cretaceous strata, and was picked with a high degree of confidence in most areas. Coupled with erosion along the T65 marker (an unconformity below or just within a thin interval of Paleocene chalks), the two surfaces removed large swaths of underlying Late Cretaceous succession above K78.

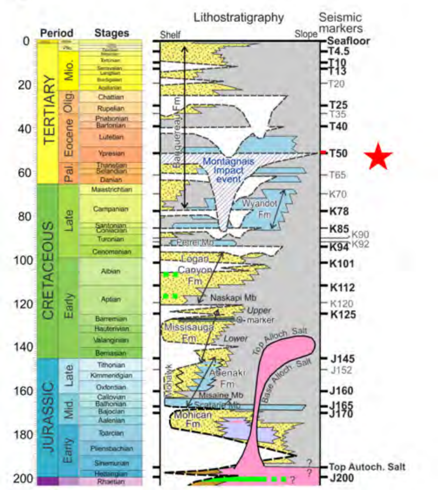
Both the T50 unconformity and a widespread mass transport deposit on the western Scotian Slope (Montagnais MTD, see next panel), have been linked to a bolide impact event that produced the 65 km wide Montagnais Impact Crater on the outer shelf in the western study area. The crater's central uplift, composed of raised basement rocks veneered by impact breccias, and intruded by melt rocks, was penetrated by Montagnais I-94 (Jansa and Pe-Piper 1987). Numerous core samples from basement rocks show nicely preserved shatter cones beneath the impact breccia (photo below). Seismic stratigraphic and biostratigraphic evidence, as well as radiometric dating of melt rocks, indicate the impact event took place in the late Ypresian (Jansa et al. 1989; Weston et al. 2012).

There are wide variations in the amount of erosion beneath the T50 surface. It is most deeply eroded approaching the impact crater, where it forms an unconformity separating Eocene strata above from Early Cretaceous or even Upper Jurassic strata below (e.g. above the platform in the northern parts of the Barrington survey, or along the Montagnais Canyon in the western WG survey). Canyons are widest and deepest here. The marker is least erosive in the eastern study area, in the Tangier, Thrumcap, Weymouth and Veritas surveys, where draping Paleocene strata separate T50 from Cretaceous strata everywhere except along the wide floors of T50 canyons (where Paleocene strata is < 40 m thick and locally absent). Thickness maps between T50 and T65 show that Paleocene strata are commonly more than 100 m thick in areas adjacent to canyons (above erosional remnants), reaching up to 180 m thick in some salt withdrawal minibasins in the southern and eastern Tangier survey. In the northern parts of the Thrumcap and Veritas surveys, T50 is largely conformable and was correlated landward, above a shelf clastic section where it merges with the overlying T40 marker. In some places on the shelf, the T50 marker was removed during the incision of a number of younger Oligocene to Miocene canyons (identified in yellow).



Profile B to A





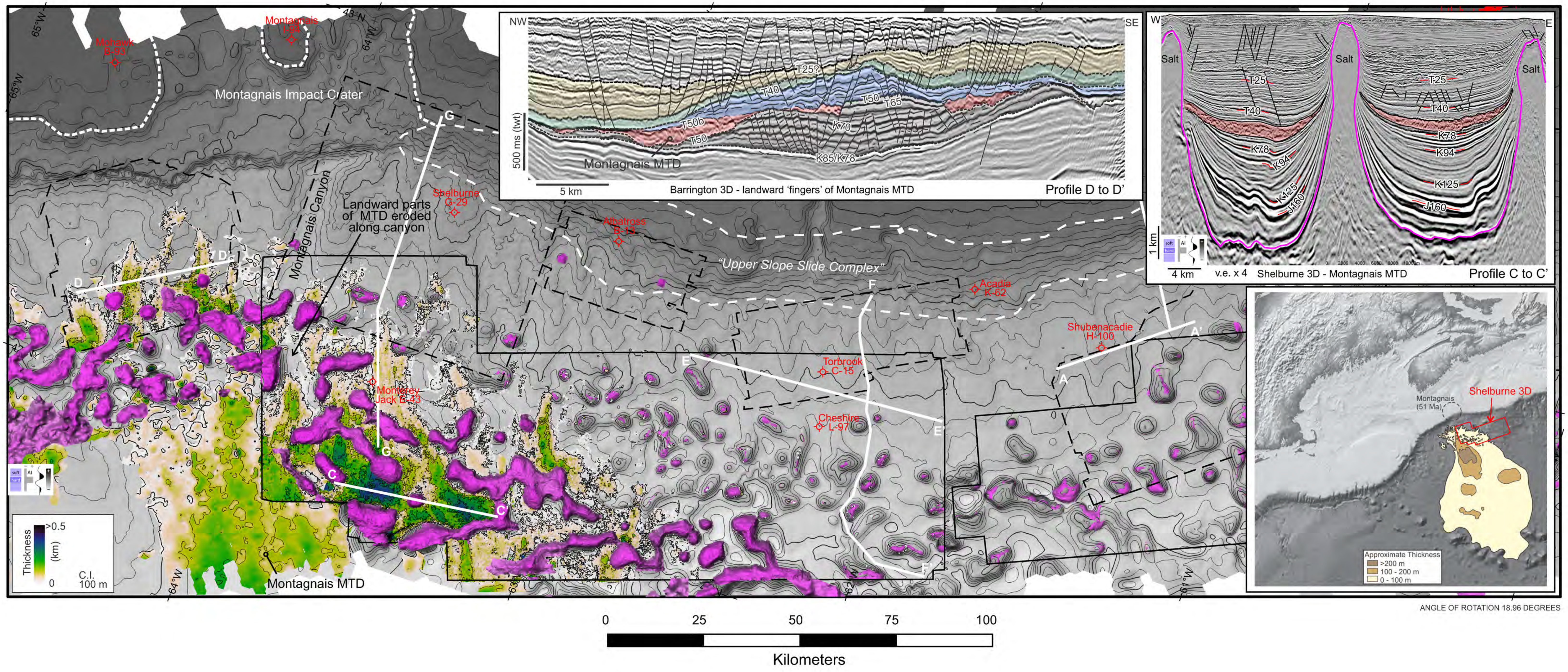
Thickness - T50 to T50b (Montagnais Mass Transport Deposit)

An interval of chaotic seismic facies corresponding to a large mass transport deposit (MTD) lies above the T50 surface in the Barrington and western Shelburne surveys. In addition to its base (T50), a second marker was correlated above it (T50b), with the resulting thickness of the deposit between the T50 and T50b markers shown below. It forms an excellent marker bed, corresponding to the oldest recognized large-scale MTD in the study area (several smaller scale MTDs were identified in Cretaceous strata, but these are volumetrically small in comparison). In the seaward parts of the western Shelburne survey it lies almost exactly mid-way through the post-salt stratigraphic column; its base is located 3220 m above the top salt marker and its top is located 3234 m below the seabed (Profile C - C').

The MTD has a strongly erosive base, along which a thin interval of Paleocene strata and varying amounts of underlying Cretaceous strata were eroded (Profile C - C'). Its landward parts form narrow fingers that point up-slope, towards the Montagnais impact crater. Deptuck and Campbell (2012) referred to this deposit as the Montagnais MTD, in part because of its inferred linkage to the impact event, but also because it lies downslope from Montagnais I-94. The top surface of the MTD is also eroded locally. This is the case, for example, along the path of the Montagnais Canyon, which is the most deeply incised canyon immediately seaward of the crater (its landward parts incise down to the J145 marker). Remnants of the MTD appear to be preserved above the intercanyon highs adjacent to it, demonstrating that some of the deepening of the Montagnais Canyon took place after the MTD was emplaced. Whether erosion was triggered as part of the impact event process itself (e.g. final catastrophic resurge of turbulent ocean water back into the crater cavity immediately after mass failure), or a younger unrelated period of canyon incision is not known.

On the continental shelf, the impact crater is notable in that there is no crater wall along its seaward side - only failure scarps across which more than a kilometer of Paleocene to Cretaceous strata were dislodged, and deep erosive furrows that divert around the central uplift. East of the crater, a complicated interval of deformed Upper Cretaceous to Eocene strata is found along a 12 to 22 km wide band that extends for 250 km away from the crater (see Profile B to A on previous panel). It is centered above the buried carbonate bank edge and contains a number of listric normal faults that sole into a detachment surface within Cretaceous strata (commonly coincident with the K94 marker). This feature, referred to as the "upper slope slide complex", may have been initiated at the same time as the impact event, though it is clear that it also experienced younger periods of deformation as well. Parts of the WG, Mamou, Torbrook, and Thumcap surveys cover this feature, which was also penetrated at Acadia K-62, Albatross B-13, and Newburn H-23. In the latter two wells, it contains an interval of mixed Ypresian, Paleocene, and Late Cretaceous nannofossils that was probably deposited during the impact event (Weston et al. 2012).

The Montagnais MTD thickens down the slope reaching a maximum thickness of 480 m in the southwestern most, and deepest, minibasins in the Shelburne survey (see Profile C - C'). In places, the deposit contains several large intact angular blocks, some with internal layering. Looking beyond the SCOPE study area, the Montagnais MTD is massive, covering 93 000 km², extending far out onto the abyssal plain where it onlaps the New England Seamounts more than 580 km from the impact site (Deptuck and Campbell 2012).



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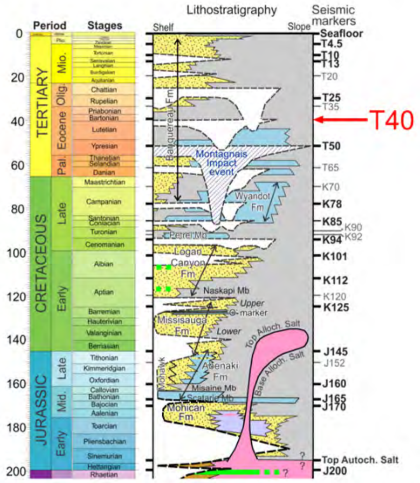


T40 - Mid-Bartonian Unconformity

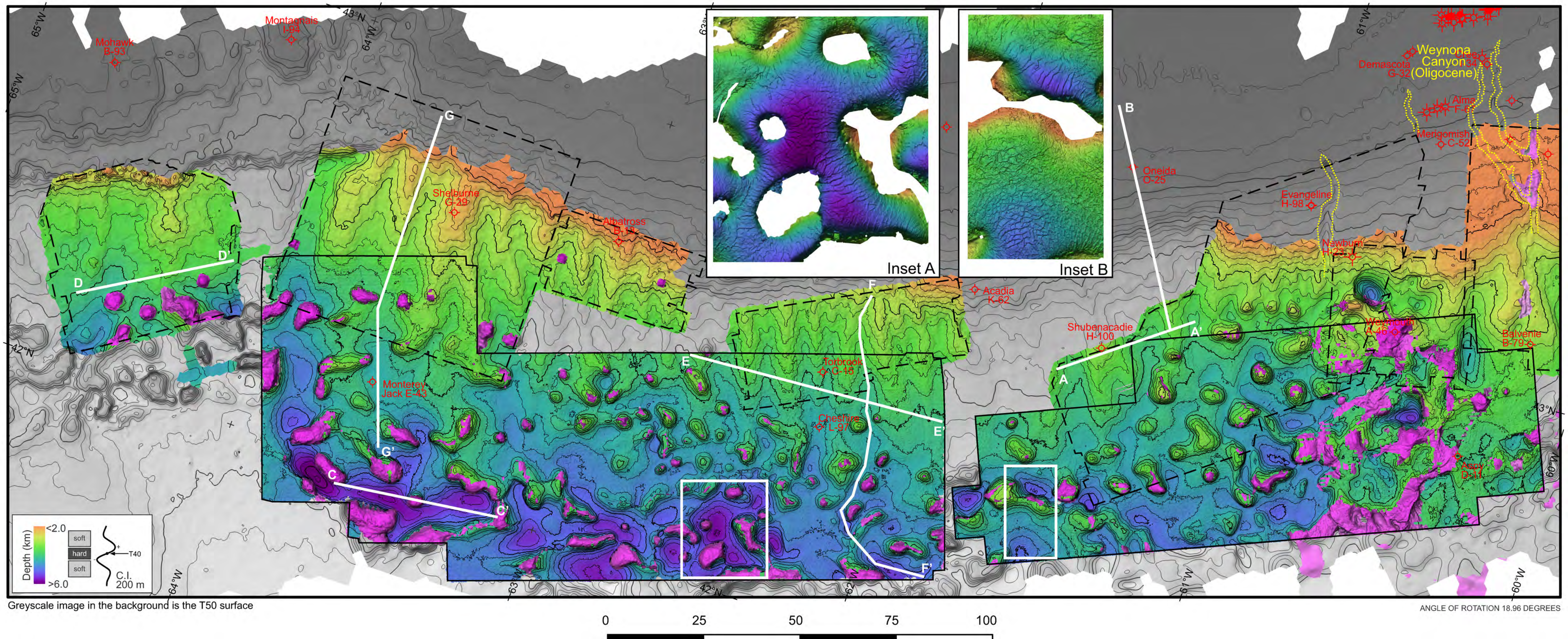
The T40 marker (Deptuck and Campbell 2012) corresponds to a zero-crossing beneath a sharp to diffuse moderate to low amplitude peak and above a broad high amplitude trough that caps an interval of heavily faulted elevated amplitude reflections (see Profile A - A'). T40 is a complex surface strongly fragmented by an intricate network of polygonal faults, as well as thin-skinned detachment faults above the margins of T50 canyons. The marker was correlated with a moderate to high degree of confidence everywhere except through the Barrington survey and the landward parts of the WG, Mamou, Torbrook and Thrumcap surveys where it is located within the "upper slope slide complex" (USSC) and is difficult to separate from the T50 marker (due to complex faulting in this deformed interval). T40 was correlated with a low to moderate degree of confidence in these areas.

The high density of small-scale faults, some with greater than 75 m of vertical displacement, requires a dense interpretation grid to successful autopick the T40 marker (see Insets A and B). Fault offsets continue into shallower intervals, commonly displacing the T30 and T35 markers, and in some cases much shallower intervals. Most of the small-scale faults do not offset the underlying T50 marker, producing sharply contrasting surface morphologies between these surfaces.

The T40 marker is also an unconformity, defining a period of widespread canyon erosion localized immediately above T50 canyons, where the surface is much smoother. Erosion along the T40 marker locally merges with the T50 marker above canyon axes, but an interval of Ypresian to Bartonian strata separates the two surfaces above intercanyon highs, and demonstrates there were at least two separate periods of Eocene canyon erosion (T40 and T50). A third period of erosion is also evident locally on seismic profiles between the T40 and T50 markers in the Barrington, WG, and western parts of the Shelburne surveys.

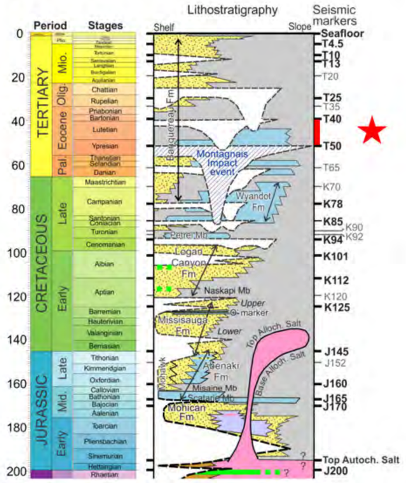
A number of wells calibrate the T40 marker, including Albatross B-13, Newburn H-23, Shelburne G-29, and Shubenacadie H-100 where T40 it is located within Bartonian marly claystones and/or shale (Weston et al. 2012). At Cheshire L-97 the T50 to T40 interval is very thin or absent due to amalgamation of erosive surfaces, and at Monterey Jack E-43, the marker lies above a 100 m thick mid to Late Eocene interval of claystone and marl.

The overall structure and morphology of the T40 marker closely resembles the T50 marker, with prominent canyons in the WG, Mamou, Torbrook and Thrumcap surveys that diminish in relief downslope. The location of T40 canyons is almost identical to T50 canyons, reflecting the mainly vertical aggradation that took place between the T50 and T40 surfaces, and the re-occupation of T50 canyons during T40 erosion (with focused erosion of the T50 to T40 interval along T40 canyon floors - see Profile A - A'). This is in contrast to older Cretaceous intervals where there is typically a lateral offset between the thickest parts of the underlying versus overlying intervals (commonly, but not exclusively, towards the northeast - see Profile E - E' on next panel). If such offsets are indeed driven by prevailing ocean currents, this could indicate a decrease in the intensity of the western boundary current starting in the Paleocene or a shift in current position away from the study area.



Greyscale image in the background is the T50 surface

ANGLE OF ROTATION 18.96 DEGREES

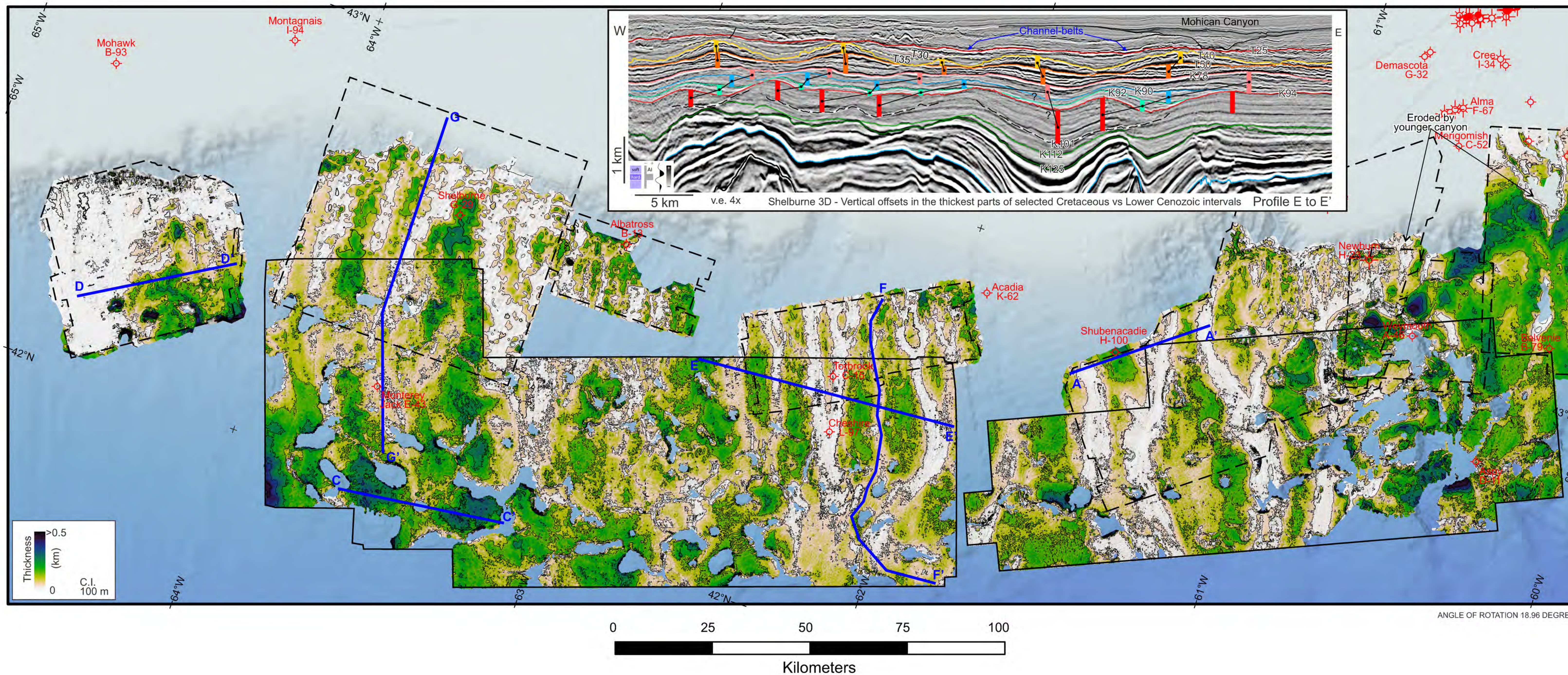


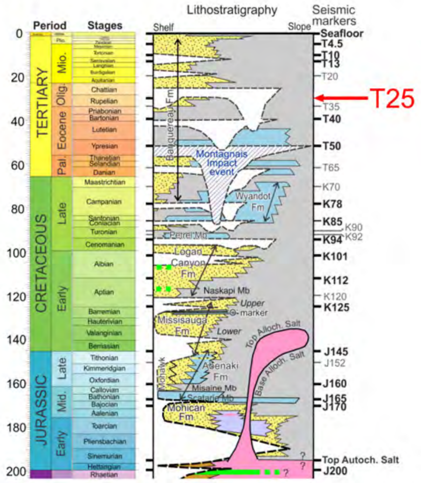
Thickness - T50b to T40 (latest Ypresian to Bartonian)

The T50b to T40 interval corresponds to Sub-unit 1b of Deptuck and Campbell (2012). It consists of a series of heavily faulted, but highly continuous moderate to high amplitude reflections that drape the underlying T50 unconformity or, where present, the Montagnais MTD. Moving seaward, the succession increasingly has a lower amplitude interval at its base, with higher amplitude markers above.

Like the K78 to T50 interval, the succession is best preserved along downslope-oriented thicks corresponding to erosional remnants between wide, flat-floored T40 canyons (some more than 10 km wide). The interval was removed by erosion at Cheshire L-97 and is < 100 m thick at Monterey Jack E-43, both locations where the T40 and T50 markers converge or merge along canyon axes. The succession has a fairly consistent "uneroded" thickness ranging from 200 to 300 m. At Shubenacadie H-100, for example, the T50 to T40 interval comprises 265 m of late Ypresian to Bartonian (Fensome et al. 2008; Weston et al. 2012) shale, marl, and chalk preserved within an erosional remnant in the Thrumcap survey (see Profile A - A' and B - A). The elevated reflection amplitude of this interval probably reflects impedance contrasts between pelagic carbonates and fine grained clastics (again similar to the underlying interval). Shelburne G-29 penetrated another erosional remnant in the WG survey containing 288 m of claystone that passes up-section into shale with thin siltstone and sandstone stringers. The erosional remnant here is less reflective, similar to the very wide erosional remnant in the Barrington survey (see Profile D - D'), and this may indicate that the T50 to T40 interval is less calcareous to the west.

The T50 to T40 interval also shows some local increases in thickness above salt withdrawal minibasins in the Weymouth and eastern Tangier surveys where it is more than 500 m thick. The interval has also been cut out along the Oligocene Wenonah Canyon that tracks through the Veritas survey.





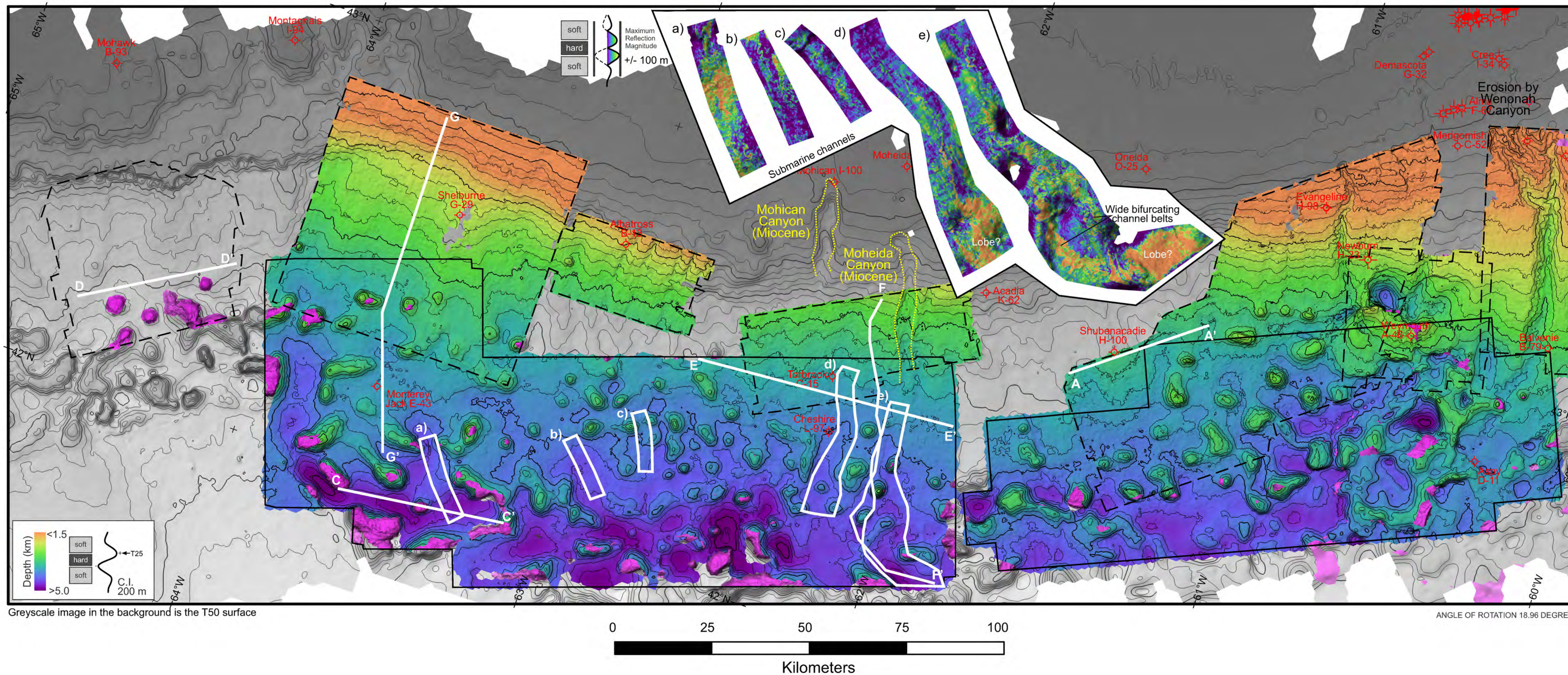
T25 - Late Oligocene Unconformity

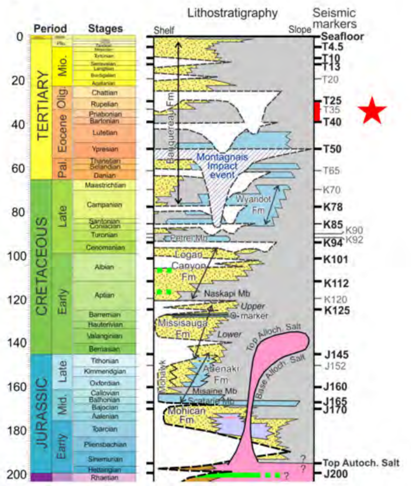
The T25 marker defines a stratigraphically complex period characterized by widespread erosion, mass wasting, sinuous turbidite channel development with terminal lobes, and onset of a new style of contourite sedimentation. The marker corresponds to a peak in most areas, but the surface is highly variable and aside from crustal markers, was one of the most challenging to correlate. It was carried both above an interval of MTDs (the first widespread period of mass wasting above the Montagnais MTD), and below a number of younger MTDs, some of which cut into the surface. For example, larger mass failures are present above T25 in the Thrumcap and Tangier surveys (MTD 5a of Christians 2015), and the Shelburne survey to the west. Where a MTD cuts into the T40 to T25 succession, the T25 marker was mapped along its erosive base. T25 also defines, or is cut by, a number of canyons, particularly in the Mamou survey and towards the eastern study area where canyon incision probably began around the T35 or T30 markers.

Most deepwater wells in the study area provide only loose constraints on the age of the T25 marker. At Shubenacadie H-100 and Shelburne G-29, T25 coincides with the T29 marker defined in The Play Fairway Study (OETR 2011), where Upper or Middle Miocene strata overlie Bartonian or Priabonian strata (Fensome et al. 2008; Weston et al. 2012). The large stratigraphic gap (Lower Miocene and entire Oligocene are unrepresented) reflects the evolution of the T40 to T25 succession as sedimentation was focused above the floors of wide and deep T40 canyons, with erosion or non-deposition focused above T40 intercanyon highs where both of these wells were drilled. The T40 to T25 thickness map on the next panel shows why these and other slope wells in the study area failed to identify Oligocene strata. With the exception of the recent Cheshire L-97 and Monterey Jack E-43 wells, all other slope wells in the study area penetrated the T40 to T25 succession where it has zero thickness.

The T25 marker at Cheshire L-97 is a latest Oligocene to earliest Miocene marker that caps a slightly coarser grained interval of well-sorted very fine to fine grained sandstone between 3945 and 3970 m (MD) above a 116 m Late Oligocene interval of dominantly siltstone down to 4086 m (MD) (reported on the mudlog; Cheshire L-97 End of Well Report). Our mid-Oligocene T30 marker ties just below this siltstone interval, above a claystone dominated Lower Oligocene to latest Eocene succession. At Monterey Jack E-43, T25 corresponds roughly to the Oligocene-Miocene boundary and caps a dominantly claytsone succession (Shell Canada Ltd., 2017). On seismic profiles, a thick MTD with an erosive base immediately underlies the marker at Monterey Jack. It accounts for roughly half the T40 to T25 interval penetrated at the well, and may have removed some in situ Late Oligocene strata.

The T25 marker shows little evidence of the wide and deep mid-Bartonian T40 canyons. Instead, the downslope-oriented thicks that dominated Cretaceous through mid-Eocene sediment distribution, especially in the western study area, were filled in and erased. Most salt bodies were buried by this stage, except for a few of the most distal diapirs in the Shelburne survey. **A number of canyons were excavated along the margin during the T35 to T25 interval, but it is difficult to precisely determine their timing because of closely spacing of markers.** In addition to canyons, at least eight sinuous submarine channel belts are recognized along the T25 surface in the Thrumcap, Tangier, and Shelburne surveys. The examples below are from 100 m windowed extractions above and below T25 from the Shelburne survey (Inset *a* through *e*). They are commonly located just above the T25 surface, and as such probably formed in the earliest Miocene.



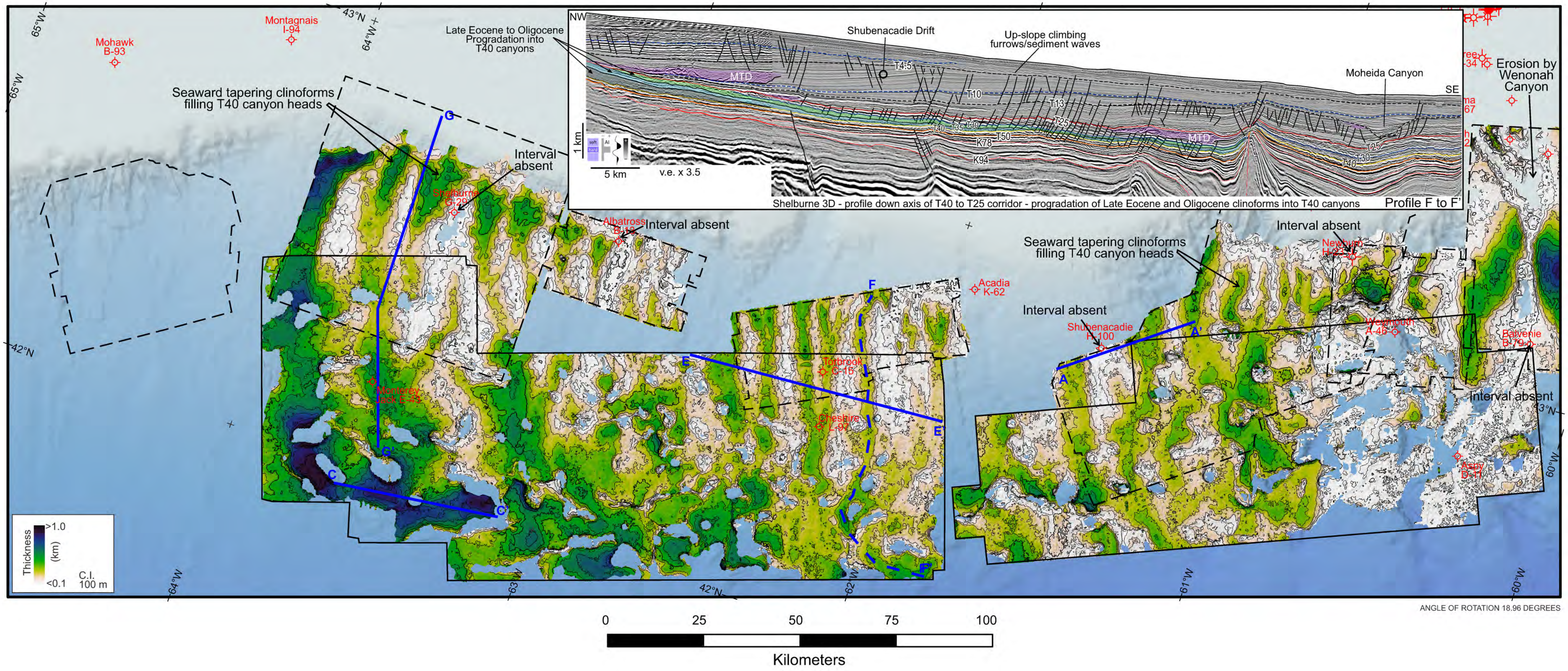


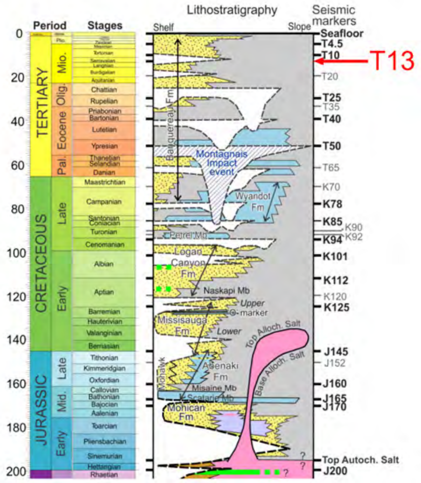
Thickness - T40 to T25 (Late Bartonian to Oligocene)

The transition from T40 to T25 marks a period of profound change on the central to western Scotian Slope. The thickness map below is essentially inverted from the underlying T50 to T40 succession. It is thick where the underlying interval is thin and is thin where the underlying interval is thick. **The T40 to T25 succession is thickest in the westernmost WG and Shelburne surveys, above the fill of the Montagnais Canyon and above actively subsiding minibasins south of Monterey Jack E-43 where the succession is up to 1100 m thick.** Along most other downslope elongated corridors it less than 600 m thick. The very wide T40 canyons were filled-in as strata prograded and aggraded between the T40 and T25 surfaces, with the T25 surface marking the end of the upper slope alternations between regularly spaced canyons and intercanyon highs that prevailed through much of the Cretaceous and into the early Paleogene (particularly in the western study area).

The shift from T40 (mid-Bartonian) to T35 (**moderate to strong peak above latest Priabonian strata**; Deptuck and Campbell 2012) to T30 (distinctive mid-Oligocene peak-trough pair calibrated at Cheshire L-97 and Monterey Jack E-43) and finally to T25 (latest Oligocene or earliest Miocene surface), tracks the gradual infill of the large T40 canyons and eventual resetting of the slope to a new sediment distribution regime. **The series is progradational in the heads of canyons, but more aggradational further seaward (see Profile F - F').** Unlike the T50 to T40 series, the T40 to T25 series is most complete along the axes of T40 canyons (as is largely absent above T40 intercanyon highs). Low amplitude seismic facies dominate the T40 to T30 succession in the heads of T40 canyons, where the interval is commonly folded or offset by faults in the Upper Slope Slide Complex. Latest Eocene to Oligocene strata are also commonly truncated by erosion along the T35 surface or from above where it was scoured by contour currents or T13 canyon erosion.

The T40 to T25 interval is more reflective in the seaward parts of the Shelburne and Tangier surveys where it is also more heavily offset by polygonal faults (profile F - F'). The interval is capped by a period of mass wasting that separates the T30 and T25 markers. Chaotic seismic facies are widespread in the western parts of the Shelburne survey, but are more localized in the Tangier and Thrumcap surveys where they form isolated "pod-like" accumulations of failed material between salt diapirs. They are equivalent to MTD 4a of Christians (2015), and record the first period of widespread mass failure in the study area since the Montagnais MTD in the Early Eocene. The T30 peak-trough pair was correlated with a high degree of confidence throughout the Shelburne and Tangier surveys, and along with the interval of chaotic MTDs above it, were needed to correlate the T25 surface. Above these mass transport deposits, reflection amplitude increases sporadically across the Shelburne and Tangier surveys, where widespread sinuous turbidite channels and associated terminal lobes formed along or just above the T25 surface. The latest Oligocene to earliest Miocene sandy interval just below the T25 marker at Cheshire L-97 is located immediately adjacent to the channel-belt captured in Inset "d" on the previous panel. T25 reflection amplitude is also very high in the eastern parts of the Tangier survey, where the marker is crisp and erosive. Numerous T35 to T25 canyons were incised across the eastern Tangier survey. We carried the T25 surface below the deeply incised Wenonah Canyon (Thomas 2005), but since the canyon fill is Oligocene, it is likely that initial incision took place earlier during T35 or T30, and had begun to fill by T25 (though this detail is not captured in the thickness map below).

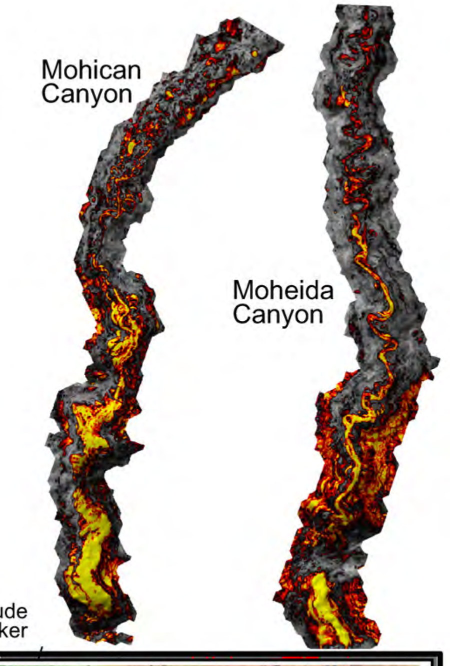




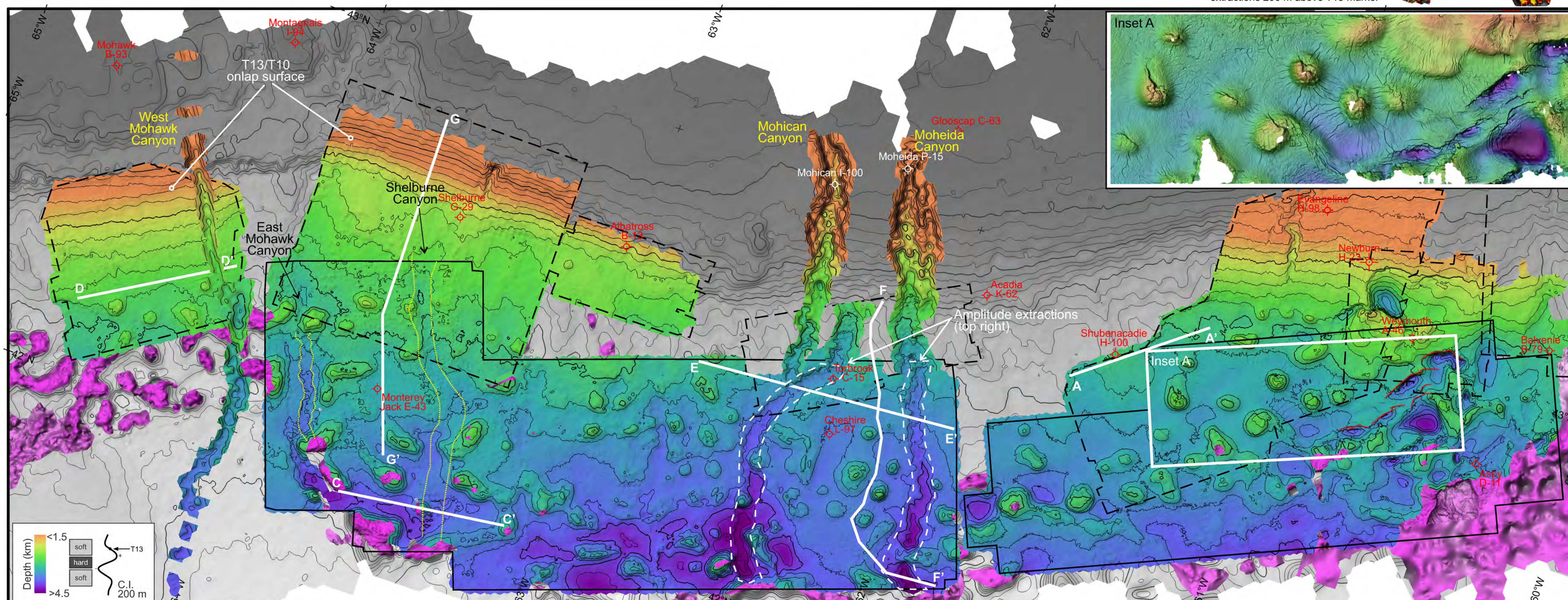
T13 - Mid to Late Miocene Unconformity

The T13 marker is an unconformity located in the lower parts of the Shubenacadie Drift (Campbell et al. 2015; Campbell and Mosher 2015) (Profile F - F'). It was correlated with a high degree of confidence through the eastern Shelburne, Tangier, Thrumcap and Weymouth surveys, where it forms a zero-crossing above a very strong, but laterally weakening peak, and below a moderate to very strong trough, along which there is erosion. The marker is widely offset across small-scale polygonal or radial faults (Inset A), especially in the seaward parts of the Shelburne and Tangier surveys. The marker is also offset across a series of NE-SW oriented listric faults that sole into allochthonous salt of the Sable Canopy. Merger between T13 and T10 makes it increasingly challenging to correlate it as a separate surface in the Veritas survey and landward parts of the Torbrook, Mamou, WG and Barrington surveys. Likewise, the marker is challenging to correlate through the western Shelburne survey where it is located within the upper parts of a succession of mass transport deposits (MTDs; Profile G - G'). Here, it was carried at the base of a higher continuity interval that separates chaotic MTDs below from a thin chaotic MTD above that defines the T10 marker in this area. T13 is widely eroded along younger unconformities in the seaward parts fo the Tangier survey and above a number of salt diapirs.

At Cheshire L-97, T13 is located near the base of the Upper Miocene section (in a succession dominated by mass transport deposits), whereas at Monterey Jack E-43 and Shubenacadie H-100 it is located in Upper Miocene strata (Fensome et al. 2008). In all three wells the marker is located within and interval of claystone or muddy siltstone. The T13 surface coincides with the onset of erosion along the West Mohawk, East Mohawk, Shelburne, Mohican, and Moheida canyons, most of which appear to have remained active until at least the T10 surface that either drapes above or merges with the canyon fill. **Landward incision of these canyons on the shelf is very deep - merging in places with the underlying K101 unconformity.** Their fill on the shelf and slope is complex and multi-phase, but generally with a lower interval of high amplitude reflections corresponding to sinuous channels (Inset B), and an upper interval of lower amplitude fill composed of sigmoidal reflections that migrate to the northeast, confined by the canyon margins (influenced by southwest-flowing contour currents; Campbell and Mosher 2015) (Profile F - F'). The T13 marker merges with the younger T10 marker in the landward parts of the Barrington, WG, Mamou, and Torbrook surveys, where the composite surface forms a steep slope that aggraded and prograded above the T25 marker. The steeper slope defines a prominent onlap surface for numerous post-T10 markers (Profile G - G').

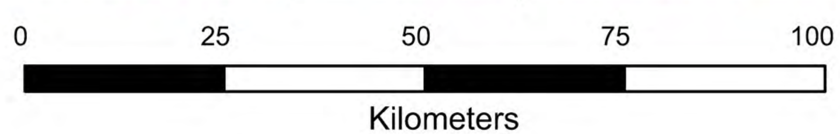


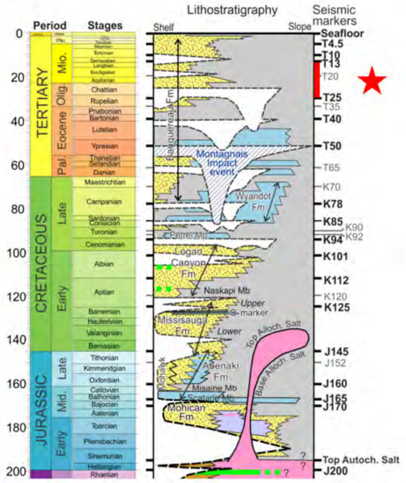
Shelburne 3D - Maximum Magnitude extractions 200 m above T13 marker



Greyscale image in the background is the T50 surface

ANGLE OF ROTATION 18.96 DEGREES





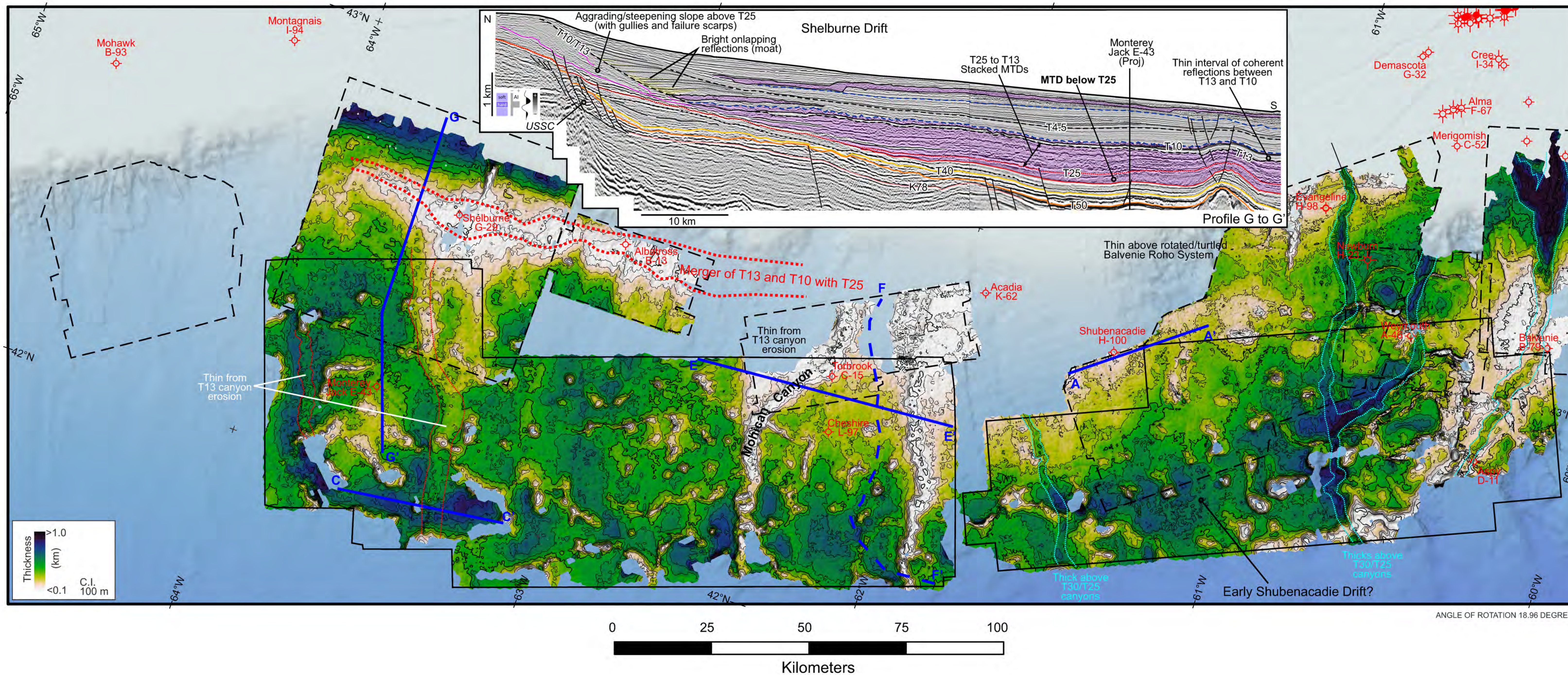
Thickness - T25 to T13 (Early to Middle Miocene)

Seismic facies between T25 to T13 can be broadly separated into two groups based on geographic area. East of the Mohican Canyon, the series comprises mainly continuous, though heavily polygonally faulted, seismic facies that are thickest in the seaward parts of the Tangier and eastern Shelburne surveys, thinning landward (see Profile F to F'). Amplitudes are variable, but generally high. In the seaward parts of the Tangier survey, successive sub-intervals in the T25 to T13 series migrated up-slope, towards the north and west, recording the early development of the Shubenacadie Drift (Campbell and Mosher 2015). Later migrating of the elongated drift brought its thickest parts into the northern Tangier, northeastern Shelburne, and eventually the Torbrook surveys by the Late Pliocene. The succession is dominantly claystone at Cheshire L-97.

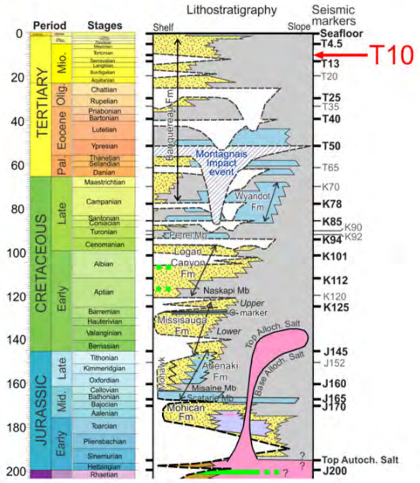
In contrast, west of the Mohican Canyon, seismic facies are dominantly chaotic, composed of stacked mass transport deposits (MTDs) with only thin preservation of higher continuity reflections between some events (for example separating the T13 and T10 markers) (see Profile G - G'). The succession here is up to 940 m thick in salt withdrawal minibasins in the southwestern Shelburne survey, where it may comprise 8 or 10 separate MTDs. The succession is claystone dominated at Monterey Jack E-43, which penetrated several stacked MTDs (Profile G - G').

There are a number of notable thickness variations within the T25 to T13 interval. It thins above most salt diapirs (see Christians 2015), as well as above rotated and turled blocks in the Balvenie Roho System. It also forms narrow elongated thins in locations where T13 canyons incise the interval from above (in particular along the Mohican and Moheida canyons), and likewise a number of thicker areas mainly along the paths of T30/T25 canyons located at the base of the interval (identified in light blue stippled). A thinner band also tracks west to east through the WG, Mamou and Torbrook surveys. On seismic profiles the T25, T13 and T11 surfaces amalgamate along this band into one erosive surface. At Shelburne G-29 it corresponds to an unconformity between Upper Miocene and mid-Eocene strata (Fensome et al. 2008). The thickest parts of the underlying T40-T25 interval (in the heads of T40 canyons) are also eroded in this area. In the Torbrook survey, for example, erosion planned off the top part of the Late Eocene to Oligocene clinoforms described earlier, generating an angular unconformity above the succession. Some of this erosion may be associated with scouring by southwest-flowing contour currents, where the Shelburne Drift onlaps the slope (Campbell and Mosher 2015).

Landward of this region, the T25 to T13 interval forms an east to west trending thick that parallels the thinner band immediately down slope. It is composed of aggradational to progradational clinoforms that progressively steepened the slope as it accreted towards the south. Internally it contains a number of failure scarps and heavily gullied surfaces, consistent with the plethora of MTDs located down the slope (Profile G - G').



Mark E. Deptuck and Kristopher L. Kendell

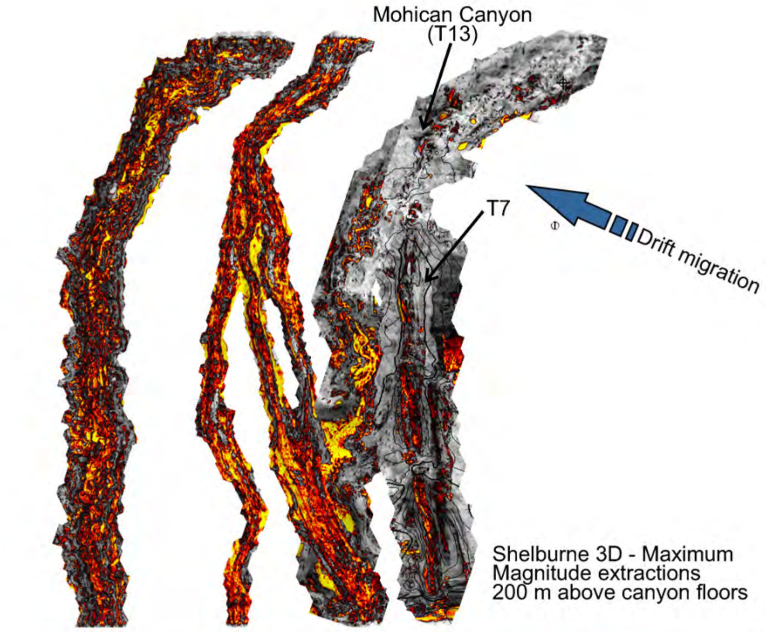


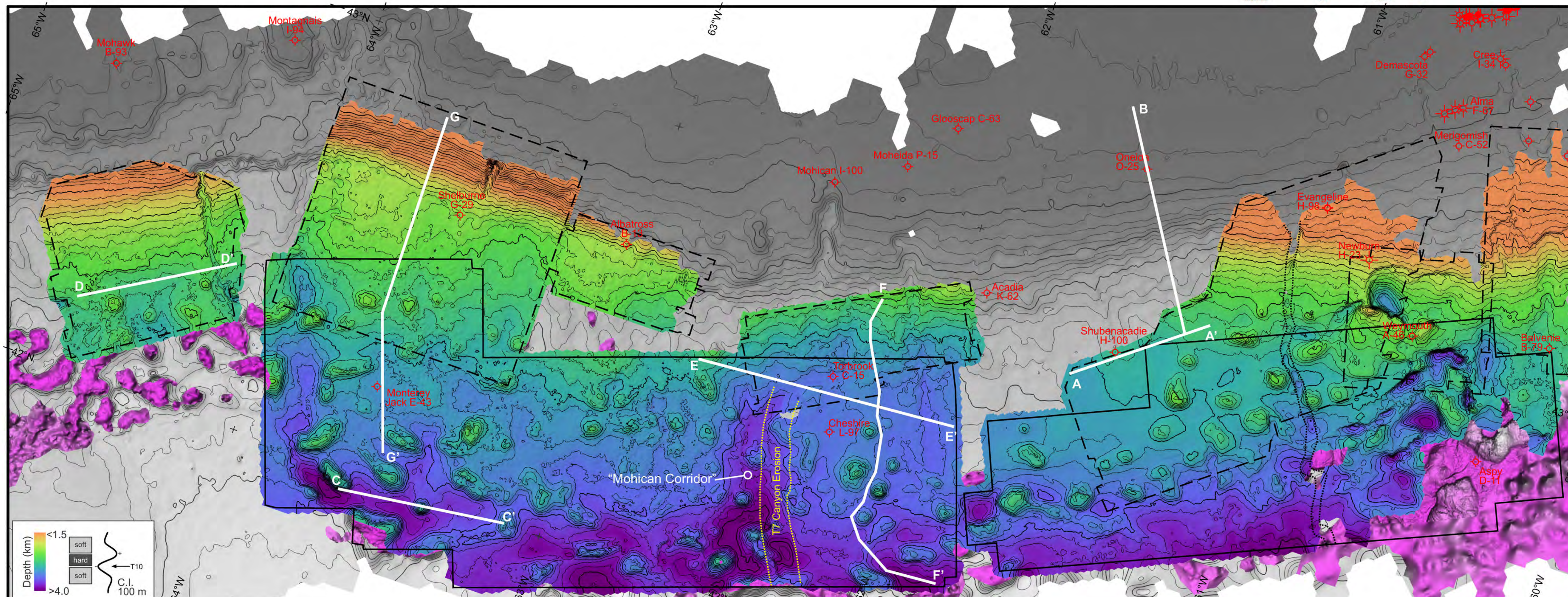
T10 - Late Miocene Unconformity

In the Tangier and eastern Shelburne 3D surveys, the T10 marker is a very strong continuous, but faulted, trough (downward decrease in impedance) located within a series of up to five higher amplitude generally layer-cake reflections. It overlies a similar but generally lower amplitude succession. At Cheshire L-97 and Monterey Jack E-43, T10 is a latest Miocene marker found in a claystone dominated interval. In the Torbrook, WG, Barrington, and western Shelburne surveys the marker is more heavily eroded and challenging to correlate. Here it was carried above a widespread and generally thin, blocky mass transport deposit. Its top surface forms a rugose but easily followed high amplitude trough that caps an interval of continuous reflections that separate it from T13. In the easternmost Tangier survey and the southern parts of the Veritas survey (above the salt canopies) the marker is also replaced by a slightly younger blocky MTD. T10 was carried above it here also.

T10 merges with T13 in the eastern parts of the Weymouth survey and landward parts of the Veritas survey, where the two surfaces are indistinguishable (corresponding to a very strong trough). Likewise, the two surface merge in the landward parts of the Barrington, WG, and Mamou surveys where the composite marker forms the prominent onlap surface for Pliocene markers in the younger parts of the Shubenacadie Drift.

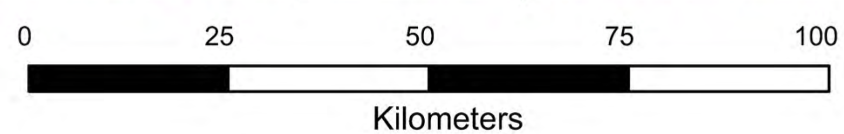
The T10 marker was carried above most of the T13 canyons, but the surface is still clearly erosional along some canyon axes. A clear negative-relief corridor is present above the Mohican Canyon, where the T10 surface is more erosive, cutting out parts of the T13 to T10 elongated drift. Another younger canyon (along the T7 marker, not described), incises the same corridor, merging with the T10 marker along its axis. Repeated downslope sediment transport through this "Mohican Corridor" continued through much of the remaining Cenozoic, generating complex interactions with the evolving Shubenacadie Drift. The inset on the right shows a number of these canyons, which all have the same bend on their landward reach where they were forced to divert around the impinging Shubenacadie Drift as it migrated to the north and west. Even the present day seafloor has a canyon along this same corridor (modern "Mohican Channel").

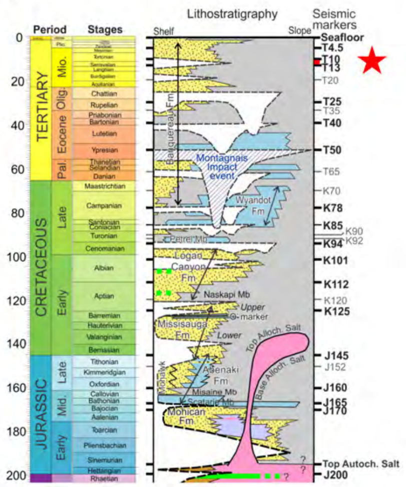




Greyscale image in the background is the T50 surface

ANGLE OF ROTATION 18.96 DEGREES



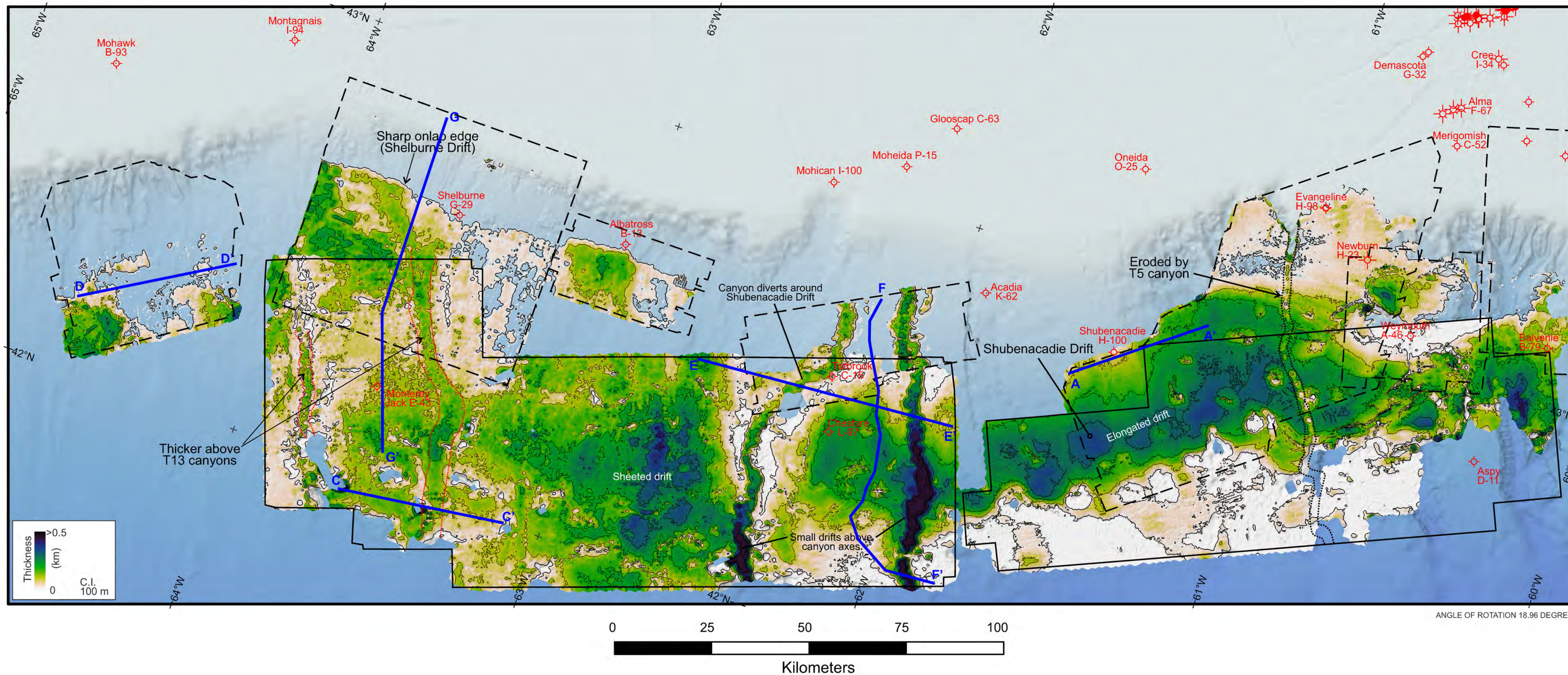


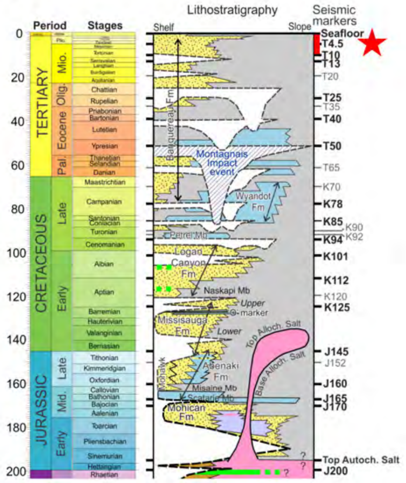
Thickness - T13 to T10 (Upper Miocene)

The T13 to T10 succession is composed of generally low-amplitude continuous reflections at its base, with higher-amplitude continuous reflections at its top. It forms a landward- and seaward-thinning lens in the eastern Shelburne and Tangier surveys, where its thickest parts (up to 400 m thick) are elongated to the southwest, defining the latest Miocene axis of the mud-prone Shubenacadie Drift (Campbell and Mosher 2015). Its thickest parts are offset roughly 20 km the north and west from that of the T25 to T13 interval. It is anomalously thick along the axis of the Moheida Canyon, and the distal axis of the Mohican Canyon where the elongated drift intersects the canyon, and small infill drifts with a convex-upward geometry occupy its upper fill (e.g. Profile F - F'). Two T13 canyons in the western Shelburne survey also cause the interval to thicken, but only minor drifts developed in their upper fill.

Between the T13 and T10 markers there are numerous small-scale "hook" scours that interrupt otherwise continuous reflections. Some of these are quite bright and could correspond to coarser lithologies. At Cheshire L-97, a thin sandstone interval was identified between T13 and T11 markers on the mudlog (at 3496 m MD), within a dominantly claystone succession.

The contourite drift continues west of the Mohican Canyon where its seismic stratigraphy is largely the same, except that its landward parts are locally thinned by erosion along the base of a MTD, and its thickness includes the thin blocky MTD that defines the T10 marker in the western Shelburne survey. It thickens slightly before tapering in the southwestern parts of the Shelburne survey (where it forms more of a sheeted drift rather than an elongated drift). Further west still, the T13 to T10 interval in the Barrington survey comprises a complex mix of contourite sediment waves, MTDs, erosional scarps, and turbidite channels (Campbell and Deptuck 2012), illustrating the complex feedback between down-slope and cross-slope processes, as well as salt tectonics that, in tandem, controlled sediment distribution along much of the margin.



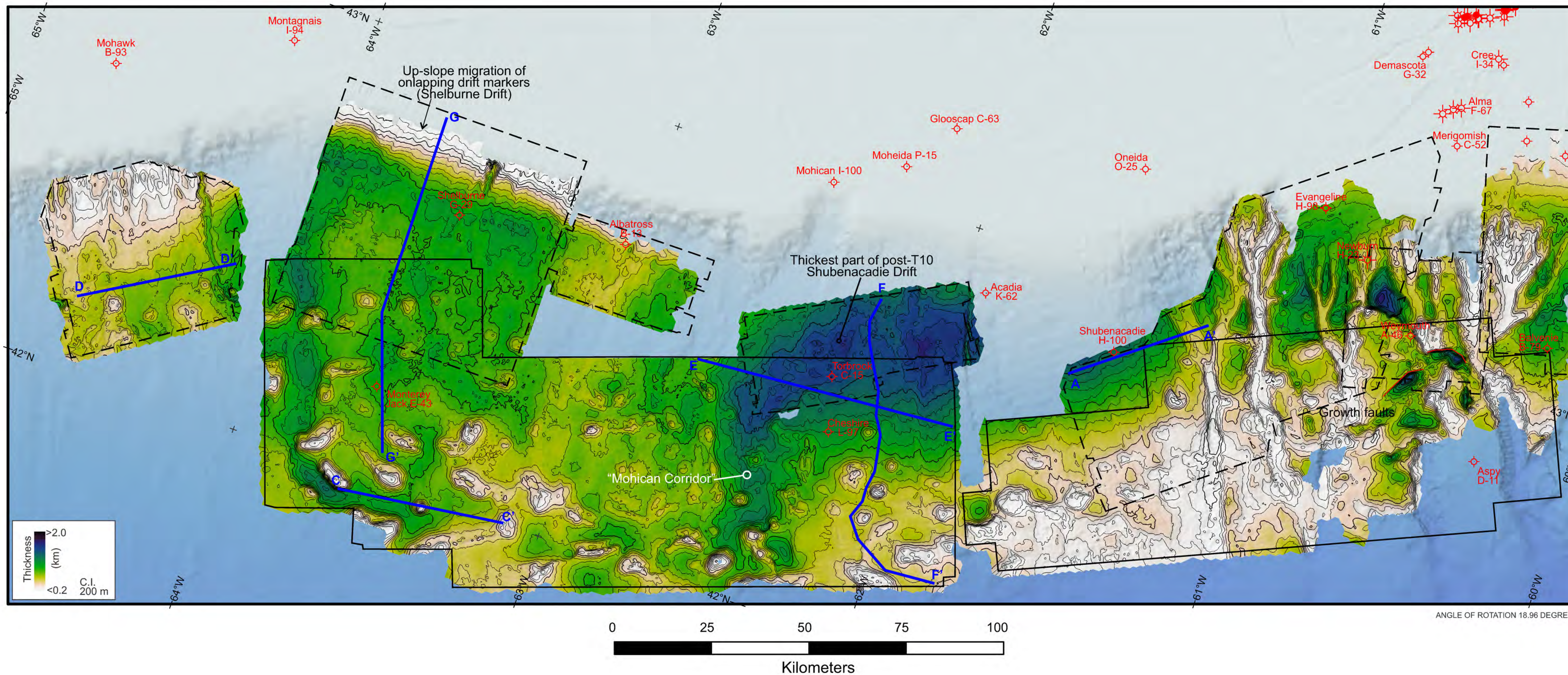


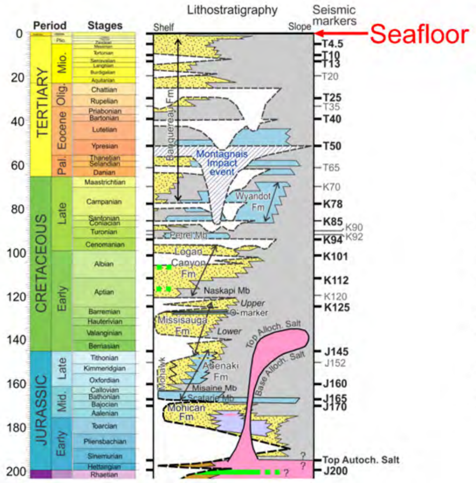
Thickness - T10 to Seafloor (Pliocene-Quaternary)

The remainder of the Cenozoic succession is grouped into the T10 to Seafloor thickness map. Overall the interval is thickest in the west and thin or absent in the east. It reaches a maximum thickness of more than 1.8 km in the Torbrook survey. The Pliocene growth of the Shubenacadie Drift accounts for most of the thickness here (Profile F - F'). Relative to the thickest parts of the Middle to Late Miocene drift (T13 to T10), the Shubenacadie drift migrated more than 40 km to the north and west through the Pliocene.

The Shelburne Drift (Campbell and Mosher 2015), located further west, sharply onlaps the T13/T10 slope, where it has a maximum thickness of 1.2 km (Profile G - G'). Onlapping markers in the drift, some with quite bright reflections along the moat, migrated roughly 20 km up the slope relative to the sharp onlap edge of the T13 to T10 interval. A few thin Late Miocene to Pliocene sands were encountered in the Shelburne Drift at Shelburne G-29 (Fensome et al. 2008; Kidston et al. 2007), and some of the brighter bands of reflections that onlap the slope could correspond to coarser grained lithologies within a dominantly shale to claystone contourite depositional system.

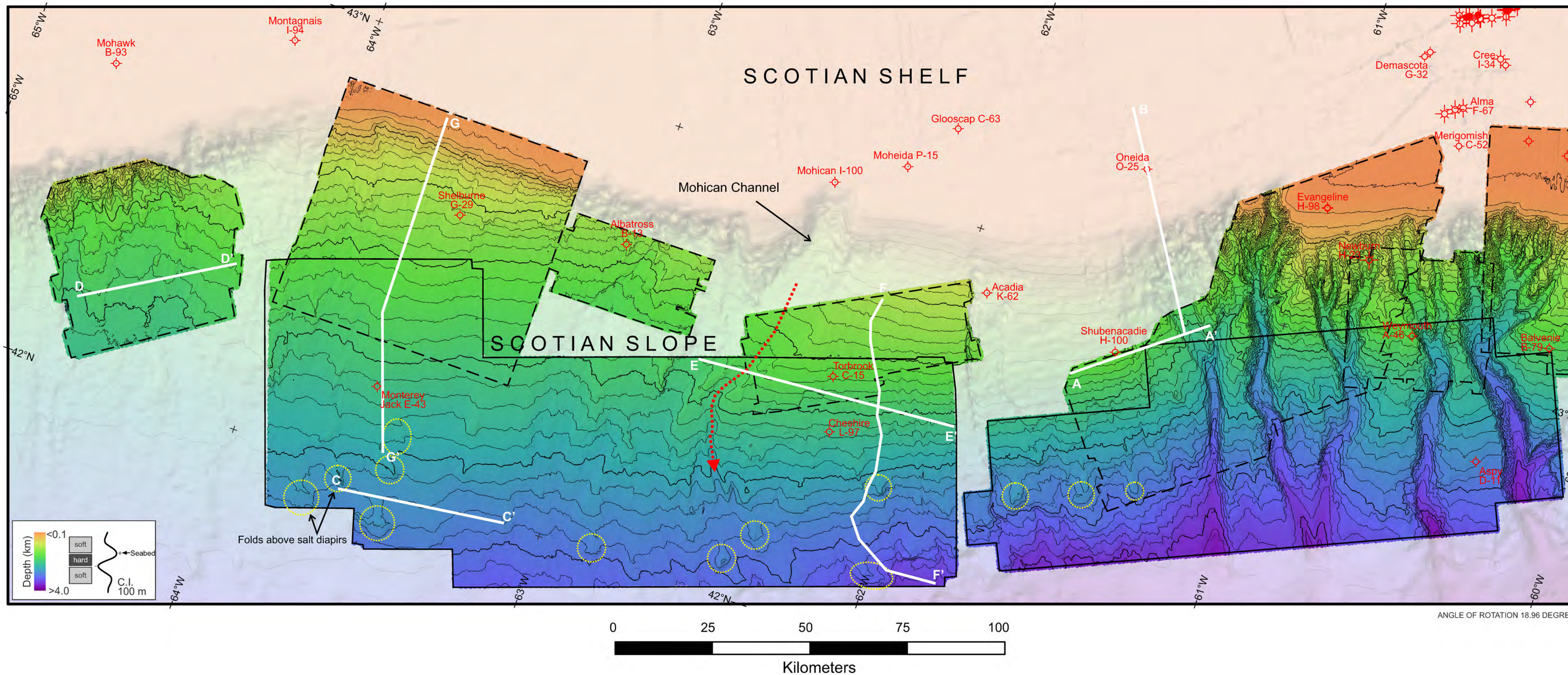
Widespread erosion of the Pliocene-Quaternary interval took place along modern canyons in the eastern study area, as well as a number of prominent Quaternary failure scarps (see Christians 2015). Three or four anomalous growth sections are also present in the Weymouth and eastern Tangier surveys. They form small basins with up to 1.8 km of strata accommodated along growth faults sole into the underlying salt canopy.

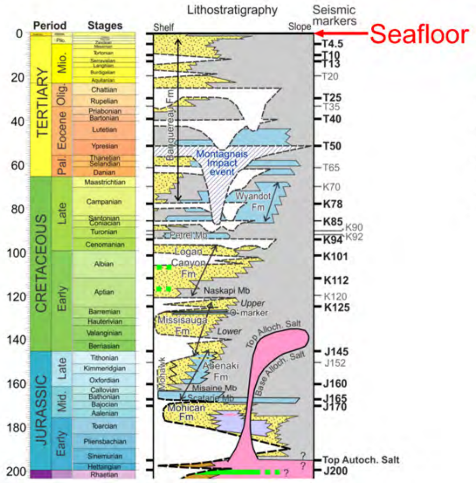




Seafloor

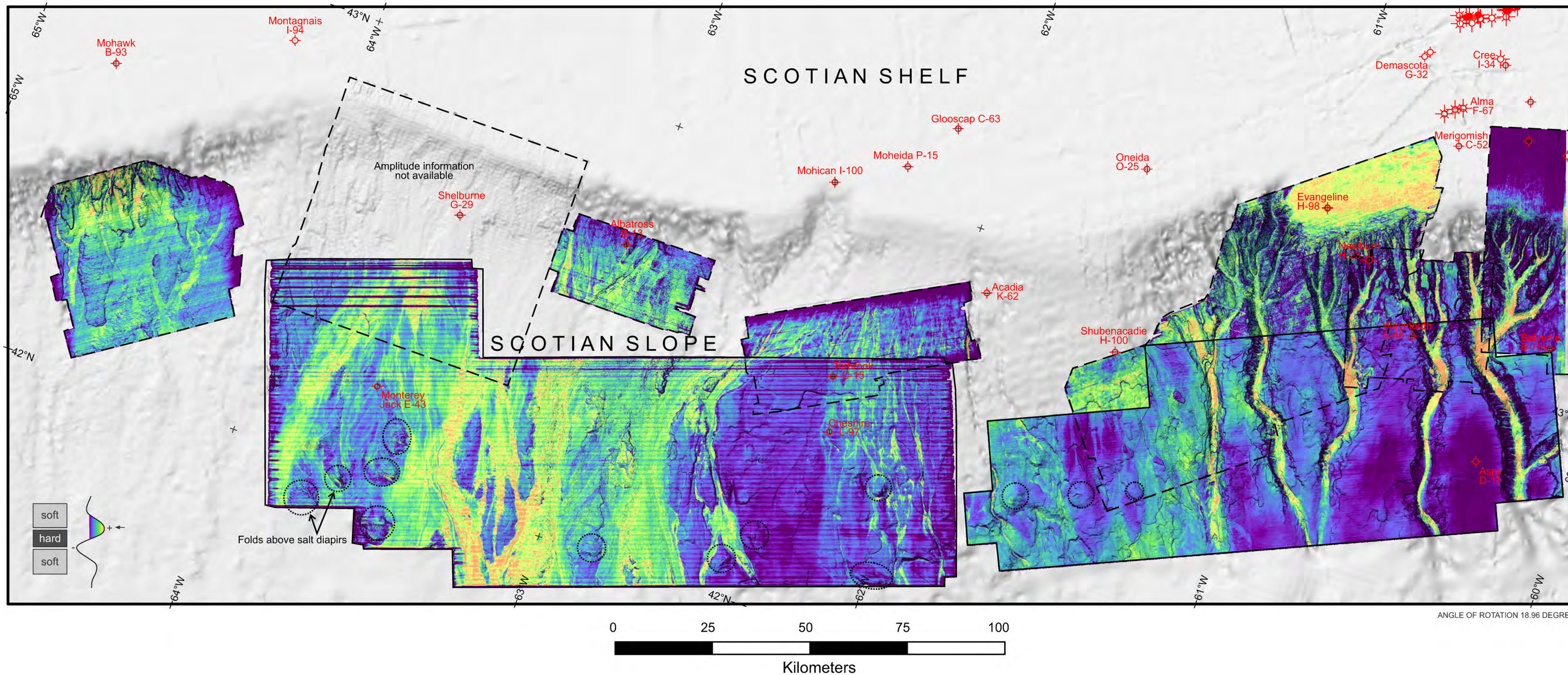
The seafloor marker was picked as a peak (downward increase in impedance), and except for the Thrumcap survey, where the seabed trace has been clipped, it forms a very consistent easy surface to snap to and autotrack, with some added care needed in regions where there are steeply dipping canyon margins. The surface is most heavily canyoned to the east in the Tangier, Thrumcap, Weymouth and Veritas surveys, and also in the west in the Barrington survey. Elsewhere the seabed is characterized by less prominent erosional channel systems and buried failure scarps. The red stippled line identifies the Mohican Channel, which also diverts around the Shubenacadie Drift. A number of seabed perturbations are present in the seaward parts of the Shelburne and Tangier surveys. These are areas where salt, or fold above salt, generate topography on the present day seafloor, and as seen in the next panel, redirect the trajectory of sediment transported down channels and through other corridors.





Seafloor - Reflection Amplitude

The amplitude response of the seabed is widely varying. Low reflectivity areas correspond to regions between downslope sediment transport corridors (between canyons in the east, and a variety of braided to curvilinear corridors in the west). Variation probably reflect average lithological changes in the shallow subsurface beneath the seafloor. Some artefacts are present, like the lineations in the northern Shelburne survey and the mismatched seabed amplitudes in the Thrumcap survey (where the seabed reflection was clipped).



References

BP Canada Energy Group ULC (2019) Subsurface Well History Report – Asp D-11/D-11A. Canada-Nova Scotia Offshore Petroleum Board File No. D406.

Campbell, D.C. and Deptuck, M.E. (2012) Alternating bottom current dominated and gravity flow dominated deposition in a lower slope and rise setting – insights from the seismic geomorphology of the western Scotian margin, Eastern Canada, In: B. Prather, M. Deptuck, D. Mohrig, B. van Hoorn, and R. Wynn (Eds), Application of the Principles of Seismic Geomorphology to Continental Slope and Base-of-slope Systems: Case Studies from Seafloor and Near-Seafloor Analogues, SEPM Special Publication 99, p. 329-346

Campbell, D.C., Shimeld, J., Deptuck, M.E., Mosher, D.C. (2015) Seismic stratigraphic framework and depositional history of a large Upper Cretaceous and Cenozoic depocenter off southwest Nova Scotia, Canada. Marine and Petroleum Geology, 65: 22–42

Campbell, D.C., and Mosher, D.C. (2015) Geophysical evidence for widespread Cenozoic bottom current activity from the continental margin of Nova Scotia, Canada, Marine Geology, 378: 237-260

Christians, A. (2015) Late Cretaceous to Cenozoic Reactivation of Central Scotian Slope Salt Bodies and the Impact on Slope Depositional Systems, Unpublished MSc Thesis, Dalhousie University, Halifax, Nova Scotia. 251 p.

Dehler, S.A., Keen, C.E., Funck, T., Jackson, H. R. & Louden, K.E. (2004) The limit of volcanic rifting: A structural model across the volcanic to non-volcanic transition off Nova Scotia. Eos Trans. AGU, 85(17), Jt. Assem. Suppl., Abstract T31D-04.

Deptuck, M.E. (2008) Subregional Geology, NS08-2 Call-for-Bids Package www.cnsopb.ns.ca

Deptuck, M.E., Kendell, K., and Smith, B. (2009) Complex deepwater fold-belts in the SW Sable Subbasin, offshore Nova Scotia. Extended Abstract, Canadian Society of Petroleum Geologists Annual Convention, Calgary, 4p

Deptuck, M.E. and Campbell, D.C. (2012) Widespread erosion and mass failure from the ~51 Ma Montagnais marine bolide impact off southwestern Nova Scotia, Canada, Canadian Journal of Earth Sciences, 49: 1567-1594

Deptuck, M.E. and Kendell, K.L. (2017) Chapter 13: A review of Mesozoic salt tectonics along the Scotian margin, eastern Canada, In: J. Soto, J. Flinch, and G. Tari, (Eds), Permo-Triassic Salt Provinces of Europe, North Africa and Central Atlantic: Tectonics and Hydrocarbon Potential, Elsevier, p. 287-312

Deptuck, M.E. and Altheim, B. (2018) Rift basins of the central LaHave Platform, offshore Nova Scotia. CNSOPB Geoscience Open File Report 2018-001MF, 54 p.

Deptuck, M.E. (2020) Nova Scotia's volcanic passive margin - exploration history, geology, and play concepts off southwestern Nova Scotia. Canada-Nova Scotia Offshore Petroleum Board, Geoscience Open File Report 2020-001MF, 32p.

Fensome, R.A., Crux, J.A., Gard, I.G., MacRae, R.A., Williams, G.L., Thomas, F.C., Fiorini, F., and Wach, G. (2008) The last 100 million years on the Scotian Margin, offshore eastern Canada: an event-stratigraphic scheme emphasizing biostratigraphic data. Atlantic Geology, 44: 93-126

Jansa, L.F., and Pe-Piper, G. (1987) Identification of an underwater extraterrestrial impact crater. Nature, 327: 612-614

Jansa, L.F., Pe-Piper, G., Robertson, P.B., and Freidenreich, O. (1989) Montagnais: A submarine impact structure on the Scotian Shelf, eastern Canada. GSA Bulletin, 101: 450-463

Keen, C.E., MacLean, B.C., and Kay, W.A. (1991) A deep seismic reflection profile across the Nova Scotia continental margin, offshore eastern Canada, Canadian Journal of Earth Sciences, v. 28, p. 1112- 1120

Kendell, K. (2012) Variations in salt expulsion style within the Sable Canopy Complex, central Scotian margin, Canadian Journal of Earth Sciences, v. 49, p. 1504-1522

Kidston, A.G., Smith, B.M., Brown, D.E., Makrides, C., and Altheim, B. (2007) Nova Scotia deepwater post-drill analysis, 1982-2004, Canada Nova Scotia Offshore Petroleum Board, Halifax, Nova Scotia, 181 p.

Miles, W. and Oneschuck, D. (2016) First Vertical Derivative of Magnetic Anomalies Map, Canada. Geological Survey of Canada, Open File 7878

OETR (2011) Play Fairway Analysis Atlas - Offshore Nova Scotia, Nova Scotia Department of Energy Report, NSDOE Records Storage File No. 88-11-0004-01, 347p. https://oera.ca/research/play-fairway-analysis-atlas

Pe-Piper, G. and Jansa, L.F. (1999) Pre-Mesozoic basement rocks offshore Nova Scotia, Canada: new constraints on the origin and Paleozoic accretionary history of the Meguma terrane, Bulletin of the Geological Society of America, 111: 1773-1791

RPS Energy, 2018. Biostratigraphic Analysis of Selected Intervals from the Cheshire L-97 and L-97A Wells, Offshore Nova Scotia,Canada. Prepared for the Nova Scotia Department of Energy.

Shell Canada Ltd., 2018. Cheshire L-97/L-97A End of Well Report. Canada-Nova Scotia Offshore Petroleum Board File No. D404.

Shell Canada Ltd., (2017) Monterey Jack E-43/E-43A End of Well Report. Canada-Nova Scotia Offshore Petroleum Board File No. D405.

Shell Canada Ltd., 2018. Cheshire L-97/L-97A End of Well Report. Canada-Nova Scotia Offshore Petroleum Board File No. D404.

Shimeld, J. (2004) A comparison of salt tectonic subprovinces beneath the Scotian Slope and Laurentian Fan. In: P.J. Post, D.L. Olsen, K.T. Lyons, S.L. Palmes, P.F. Harrison, and N.C. Rosen (Eds) Salt-Sediment Interactions and Hydrocarbon Prospectivity: Concepts, Applications, and Case Studies for the 21st Century, 24th Annual GCS-SEPM Foundation Bob F. Perkins Research Conference, Houston, p.502-532, CD-ROM

Thomas, F.C. (2005) Oligocene benthic foraminiferea from the Paleogene Wenonah Canyon, Scotian Shelf - normal versus canyon assemblages, Atlantic Geology, 41: 1-16.

Wade, J.A. and MacLean, B.C. (1990) The geology of the Southeastern Margin of Canada, Chapter 5, In M.J. Keen and G.L. Williams (Eds), Geology of the Continental Margin of Eastern Canada, Geological Survey of Canada, The Geology of Canada, p. 224-225

Welsink., H.J., Dwyer, J.D. and Knight, R.J. (1989) Tectono-stratigraphy of the passive margin off Nova Scotia, Chapter 14, In: A.J. Tankard and H.R. Balkwill (Eds) Extensional Tectonics and Stratigraphy of the North Atlantic Margins, AAPG Memoir 46: 215-231

Weston, J.F., MacRae, R.A., Ascoli, P., Cooper, M.K.E., Fensome, R.A., Shaw, D. and Williams, G.L. (2012) A revised biostratigraphic and well-log sequence stratigraphic framework for the Scotian Margin, offshore eastern Canada, Canadian Journal of Earth Sciences, 49: 1417-1462

Geophysical Reports for the 3D seismic surveys used in this study can be accessed here: https://cnsopbdigitaldata.ca/dmc-summary/