Call for Bids NS16-1 – Exploration history, geological setting and exploration potential of the central Scotian Slope

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1. Overview

The NS16-1 Call for Bids includes six parcels over the Sable Subbasin and central Scotian Slope. Parcels 1, 2, and 3, are located on the shelf, outboard of Sable Island. Parcels 4, 5 and 6 lie outboard the Sable Subbasin on the Scotian Slope (Figure 1.1). The water depths across these 3 parcels range from 150 - 4000 meters. There have been 2 wells drilled to date in these parcels, one of which encountered significant quantities of gas. The Annapolis G-24 well is within parcel 4 and was drilled by Marathon in 2001, this well encountered a total of 27 meters of net gas pay. The main exploration targets within these parcels are believed to be deep water turbidite deposits in the Cretaceous interval (Figure 1.2). Recent internal studies by the CNSOPB's resource assessment team have identified numerous shelf margin canyon systems throughout the Cretaceous that erode sand prone systems on the shelf and potentially delivered reservoir quality sands to this region. This implies that the risk of encountering reservoir quality sands is low to moderate within these parcels.

This document describes the exploration history, geological setting and exploration potential of Parcels 4, 5, and 6 (Section 3 of the CFB NS16-1 website). For information regarding Parcels 1-3 (Section 2 of the CFB NS16-1 website), refer to: **Call for Bids NS16-1 – Exploration History, geologic setting, and exploration potential: Sable Subbasin region.pdf**

3.1. Exploration History

The central Scotian Slope has very good 3D and 2D seismic coverage with the most recent and highest quality surveys collected during the late 1990s and early 2000s (Figure 3.1.1). The upper slope portions of NS-16-1 Parcels 4, 5 and 6 have contiguous coverage of good quality 3D data, and a regular spaced grid of various regional 2D seismic surveys is available along the entire mid-lower slope. The only seismic data available beyond 3000m water depth are 2D surveys.

Three wells have been drilled within the study area: Balvenie B-79, Annapolis G-24 and Crimson F-81 (Figure 3.1.1). Balvenie was drilled by Imperial in 2003, with a primary reservoir objective at the Albian level where several amplitude anomalies exhibiting modest AVO response were observed (Kidston et al., 2007). The Balvenie well reached total depth in the Albian target interval within which several thin, tight, gas-charged siltstones were encountered. These siltstones ranged from 1–8m thick and produced considerable mud-gas shows during drilling. The Balvenie B-79 well is within EL 2434 currently held by BP (Figure 3.1.1).

The Annapolis G-24 well in Parcel 4 was drilled by Marathon in 2001 to a TD of 6182m MD in the lower Missisauga Formation equivalent section (latest Valanginian) with a pre-drill target interval in early Aptian strata. The prospect's early Albian depth-structure map and dip seismic profiles are shown in Figures 3.1.2a and 3.1.2b respectively. Reservoir zones were not encountered in the Aptian target interval but three gas-bearing zones were discovered in Barremian strata from 4842–5528m MD. These zones were designated by the operator as the H, L and M Sand

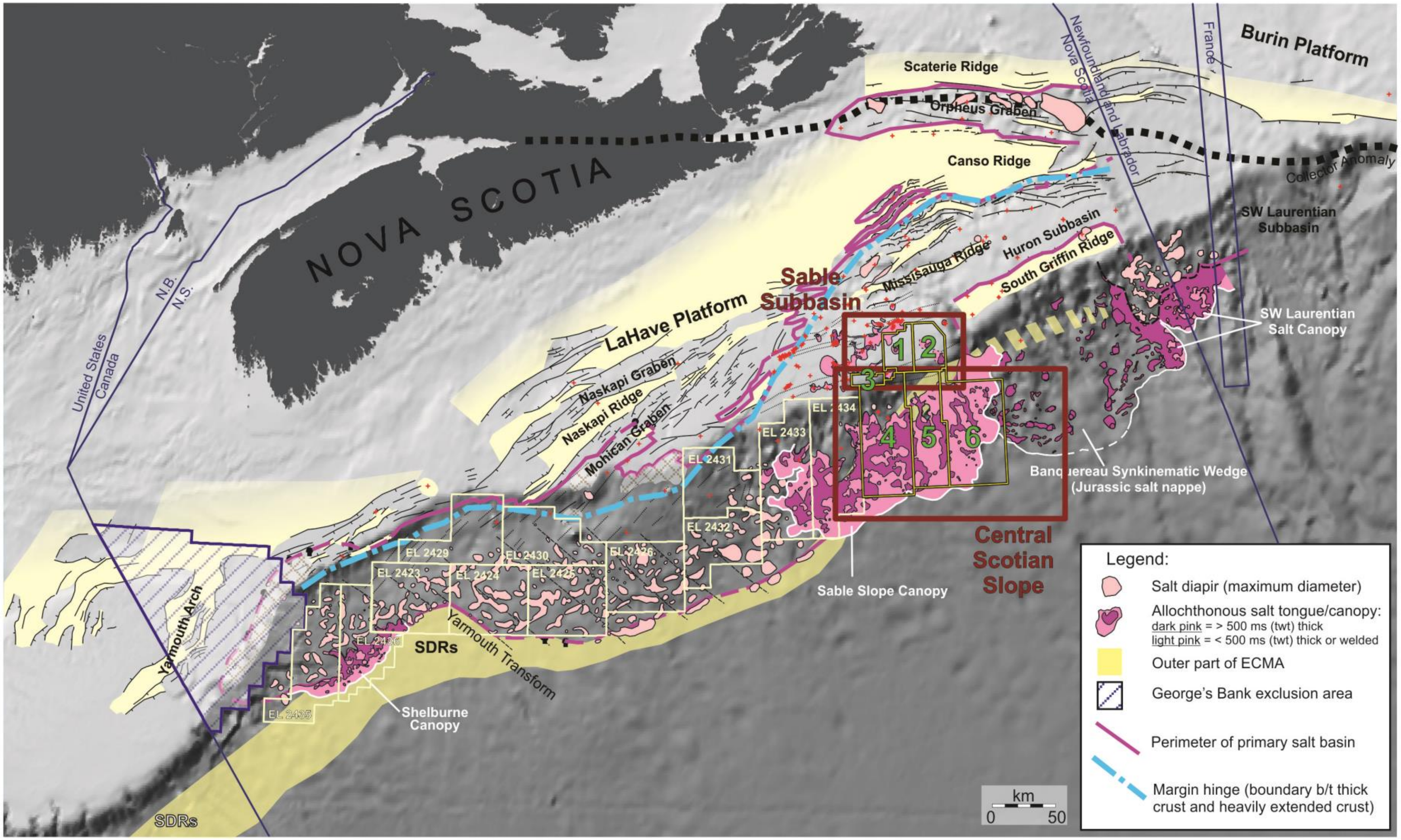


Figure 1.1 Basemap of the Scotian margin showing distribution of key structural elements. Some faults north of the Naskapi Ridge are from Wade and MacLean (1990). Most other elements are from Deptuck and Kendell (in prep).

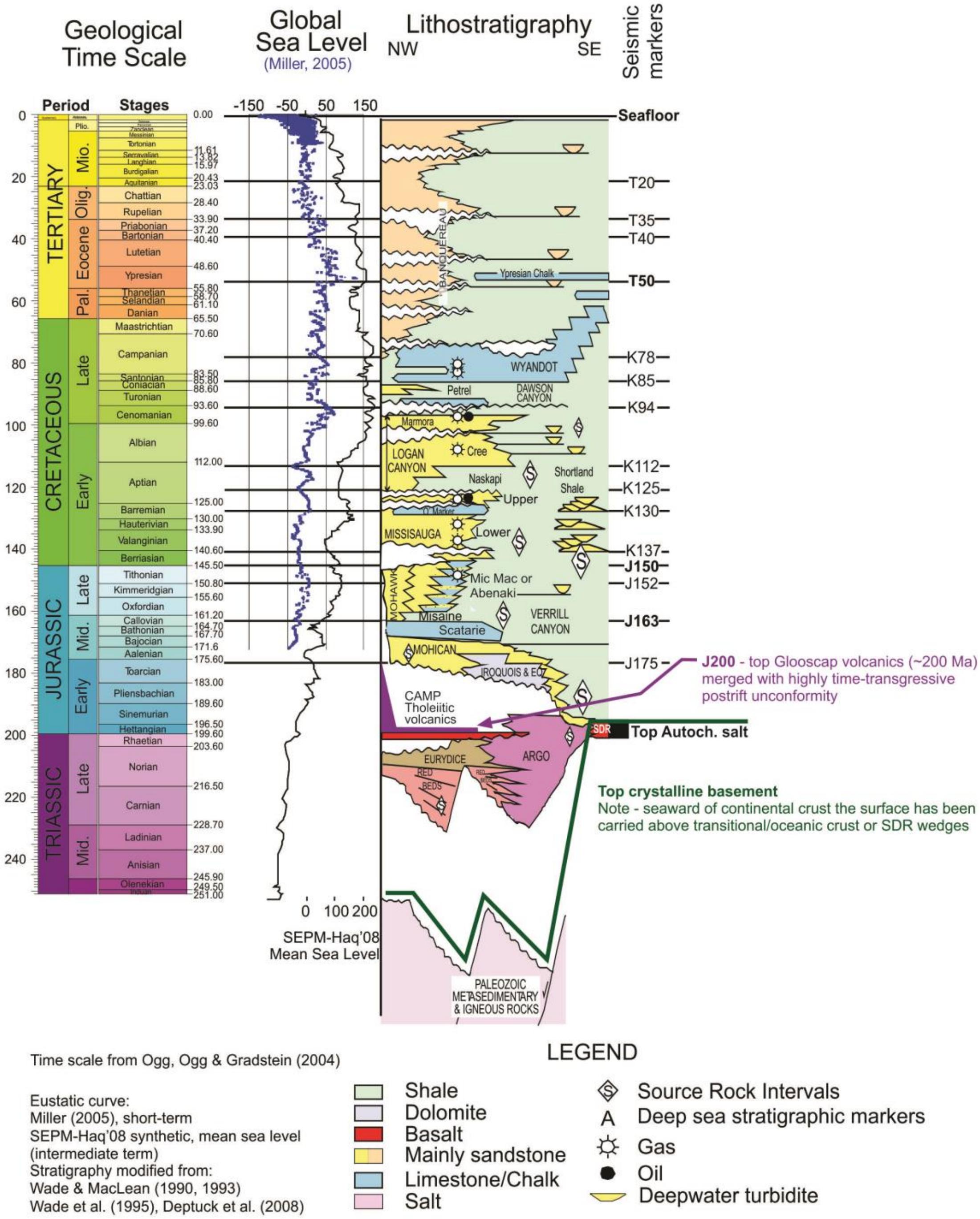


Figure 1.2 Stratigraphic column adpated from OETR (2011), with key seismic markers.

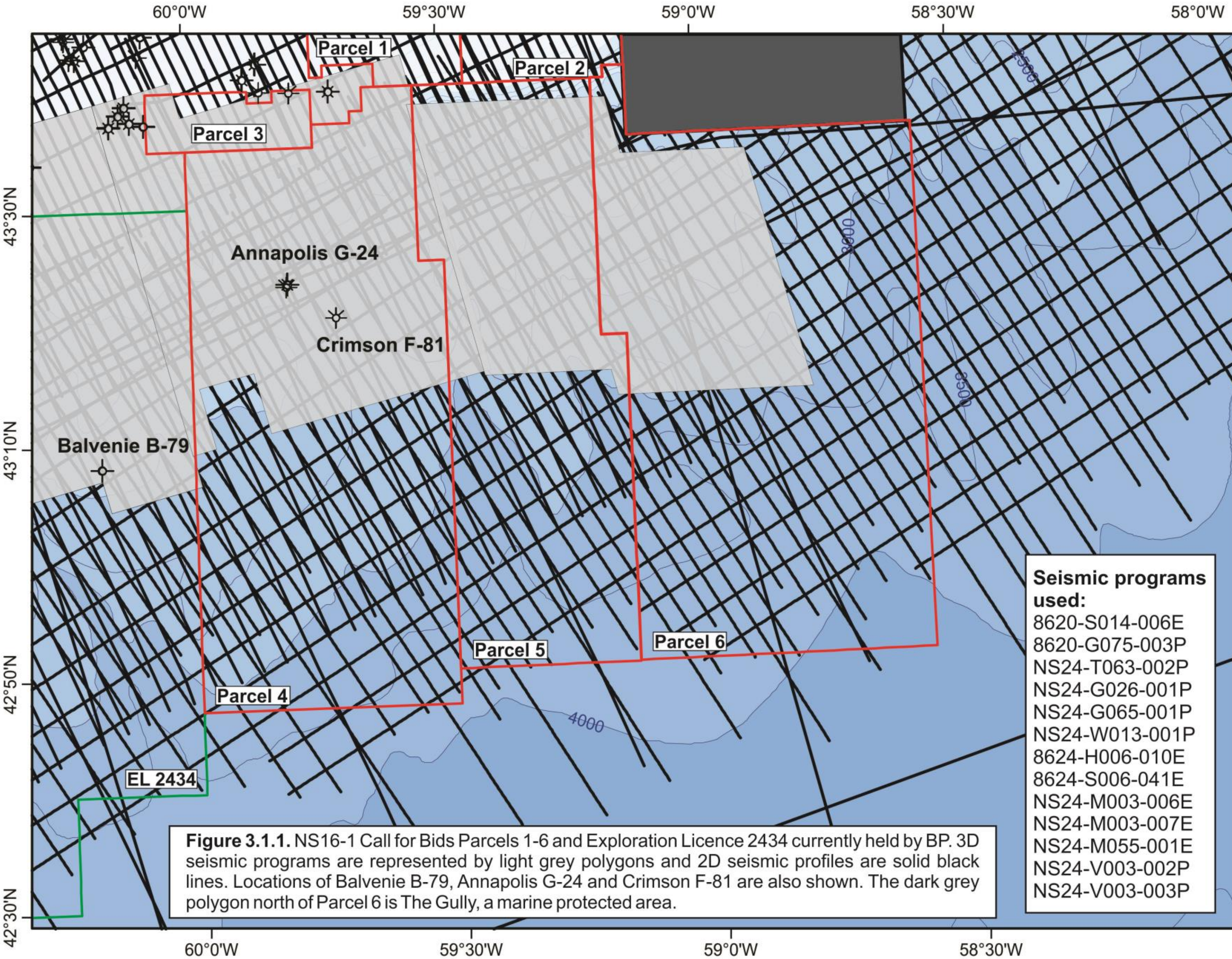


Figure 3.1.1. NS16-1 Call for Bids Parcels 1-6 and Exploration Licence 2434 currently held by BP. 3D seismic programs are represented by light grey polygons and 2D seismic profiles are solid black lines. Locations of Balvenie B-79, Annapolis G-24 and Crimson F-81 are also shown. The dark grey polygon north of Parcel 6 is The Gully, a marine protected area.

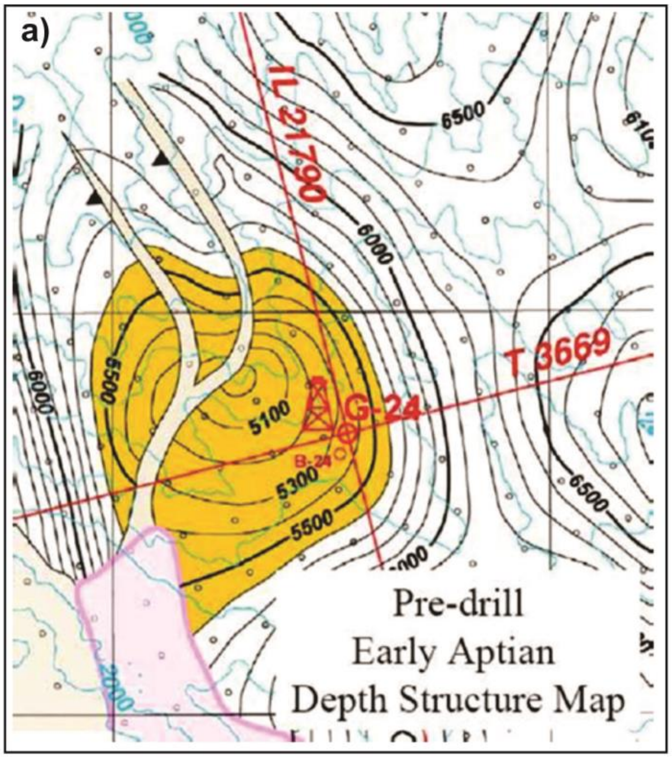
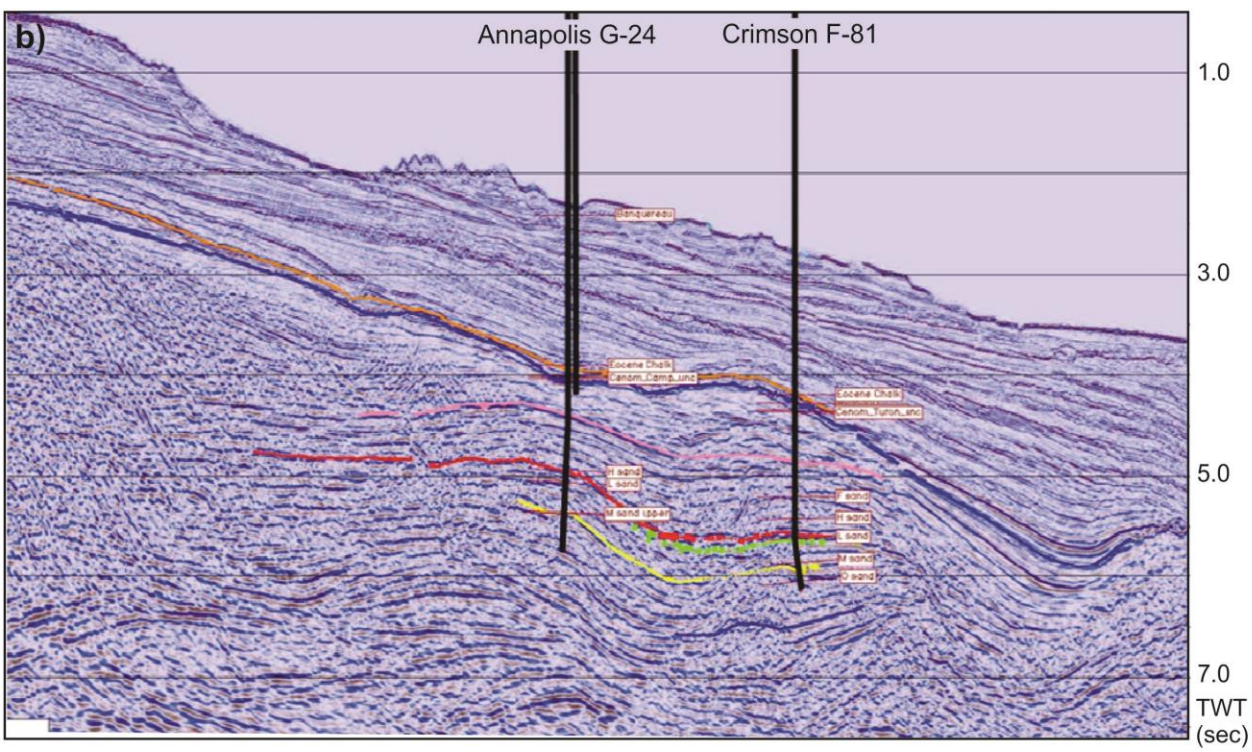


Figure 3.1.2. a) Pre-drill depth structure map of Annapolis G-24. as mapped by Marathon. Note that this map is of the early Aptian, the pay sands at this location were found in an older Hauterivian-Barremian interval. **b)** Seismic profile intersecting both the Annapolis and Crimson wells. (both images modifed after Kidston et al., 2007)



(Marathon 2002) though the H and L “sands” are not individual sands per se but gross intervals of interbedded sands, siltstones and shales (Kidston et al., 2007).

The H Sand extends from 4842–4866m MD and is Mid-Barremian age (upper Missisauga equivalent) (Marathon, 2002). It consists mostly of interbedded shales, silts and minor sands. There is a cumulative total of 3.8m net pay across the entire interval summed from a number of very thin sands less than 1m thick.

The L Sand is found over the 5040.5–5097.8m MD interval and is also Mid-Barremian age (Marathon, 2002). It is lithologically similar to the H Sand except the sand/silt ratio is higher. The zone has a total of 5.3m of net pay over a 57.3m gross interval. Reservoir quality is also better with an average net pay porosity of 17% compared to 14.8% for the H Sand (Kidston et al., 2007).

The Late Hauterivian M Sand is the main reservoir zone within the Missisauga Formation equivalent (Marathon, 2002). It consists of two sands with fair to very good porosity and a total of 18.2m of net gas pay. These sands have a porosity range of 12–25% and fair to very good permeability (Kidston et al., 2007).

Marathon’s Crimson F-81 well was a follow-up to Annapolis G-24 gas discovery and located about nine kilometers to the southeast of G-24 (Figure 3.1.1). It was spudded in 2004 and drilled in 2091.5m of water. The pre-drill structure map and corresponding seismic line are shown in Figures 3.1.3a and 3.1.3b with the target described as a faulted anticlinal feature developed during the Late Cretaceous as a result of salt withdrawal (Kidston et al., 2007). The Crimson reservoir objectives were Early Cretaceous deep water sands deposited seaward of the sand-rich Sable paleodelta, where a thicker, more sand-prone reservoir was anticipated down-slope from the Annapolis well and associated turbidite fan system.

Crimson F-81 was drilled to a TD of 6676m MD within the Missisauga equivalent section of Early Hauterivian to latest Valanginian age. No significant hydrocarbon-bearing zones were encountered. Reservoir quality was generally much poorer than Annapolis consisting of several thin, tight, very fine to fine-grained sandstones and siltstones in a shale-dominated succession (Kidston et al., 2007). One reservoir quality sand was discovered at 6414m MD in the Late Hauterivian upper Missisauga equivalent. The O Sand is 13m thick and composed of fine-grained calcareous sandstone with an average porosity of 13% (maximum porosity 15%).

Balvenie, Annapolis, and Crimson are located directly downslope from a Late Jurassic to Early Cretaceous sand-prone deltaic system, and reservoir-quality, gas-bearing coarse siliciclastics are proven in the Annapolis well. Recent seismic mapping near Annapolis and Crimson indicates that while this region is in a prime location for turbidite deposits, rapidly evolving paleo-bathymetry related to salt tectonics prevented thick turbidite reservoirs from accumulating at these well locations.

For example, Figure 3.1.4a is a depth-structure map near the top of the M Sand interval (Late Hauterivian). The gas-charged Annapolis structure is the prominent simple closure on the western edge of the diagram, whereas the Crimson structure, located southeast of Annapolis, is a three-way closure against a younger minibasin and associated secondary salt weld. An isopach map between the top M Sand (K132) and top Jurassic (J152) horizons indicates the lower Missisauga equivalent section in places is more than 1 km thick (Figure 3.1.4b). Neither well fully penetrated this interval and neither well targeted the thickest part of the isopach. The interval thins to less than 300 m thick in two regions: northwest of Annapolis, above the salt-cored high that forms the main Annapolis structure, and south of Crimson where the interval onlaps a salt body. The thickest lower Missisauga deposits appear to divert around the Annapolis structure, continuing towards gaps in salt feeders to the east of Crimson and/or southwest of Annapolis. The best developed turbidite reservoirs in Annapolis (18.2m of net gas pay in the M sands) and Crimson (13m thick O sand) were encountered in this interval, and additional reservoir

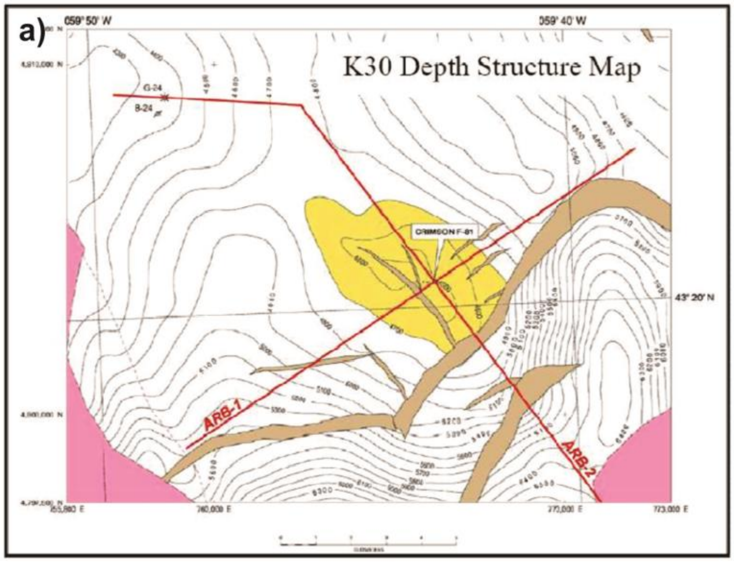
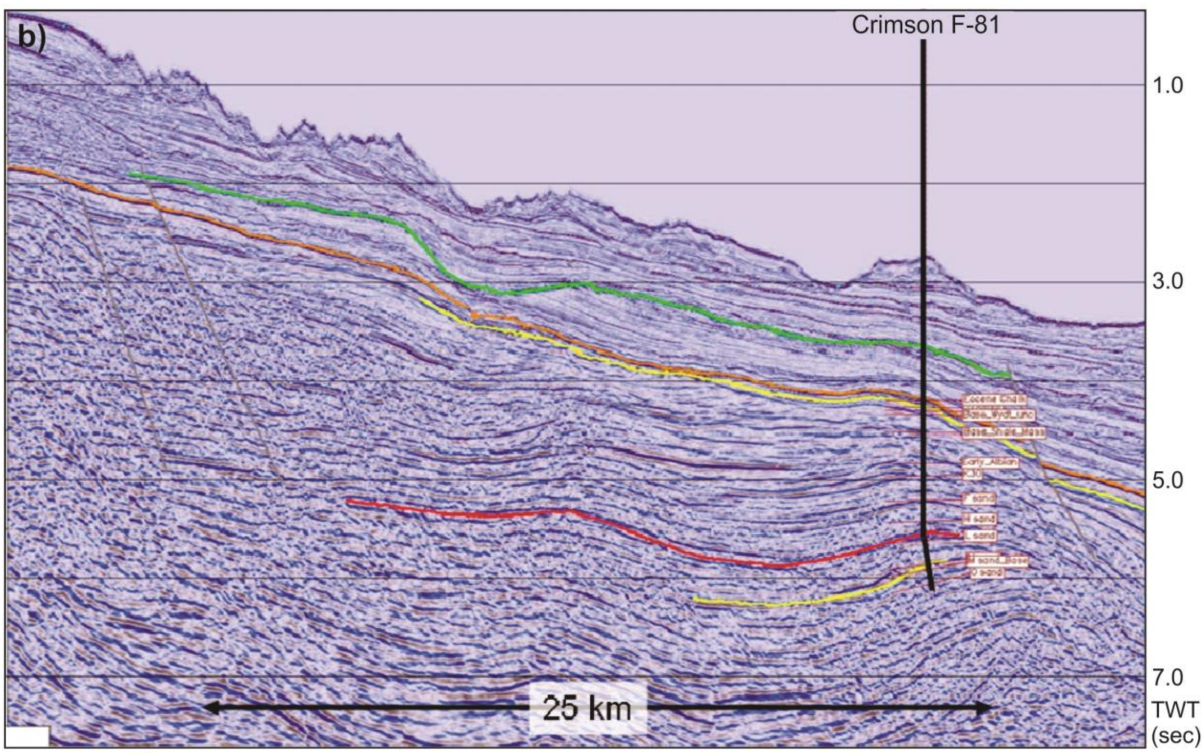


Figure 3.1.3 a) Pre-drill depth-structure map of Marathon's Early Aptian K30 seismic horizon at the Crimson F-81 well location. **b)** Seismic profile intersecting the Crimson F-81 well. (Both images modifed after Kidston et al., 2007)



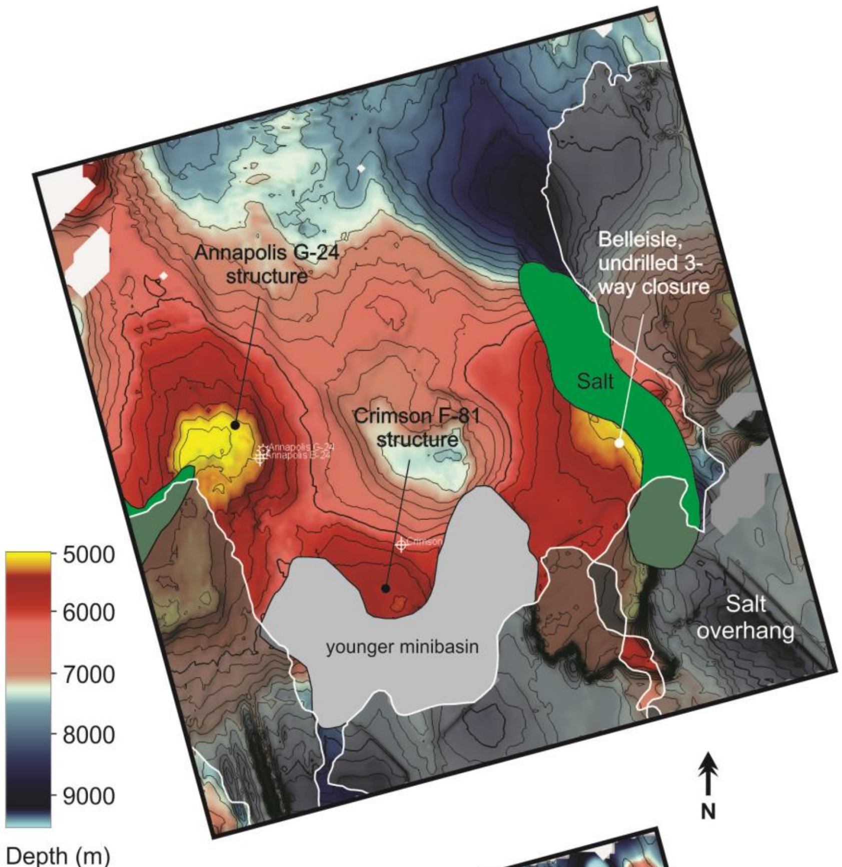


Figure 3.1.4 a) Depth-structure map generated on a seismic horizon near the top of the `M` sand (~K132, late Hauterivian) intersected at the Annapolis G-24 well. Green polygons represent salt bodies, transparent black polygons are areas with salt overhang and the grey polygon is a region where the surface comes into contact with a younger minibasin (a salt body during the Hauterivian)

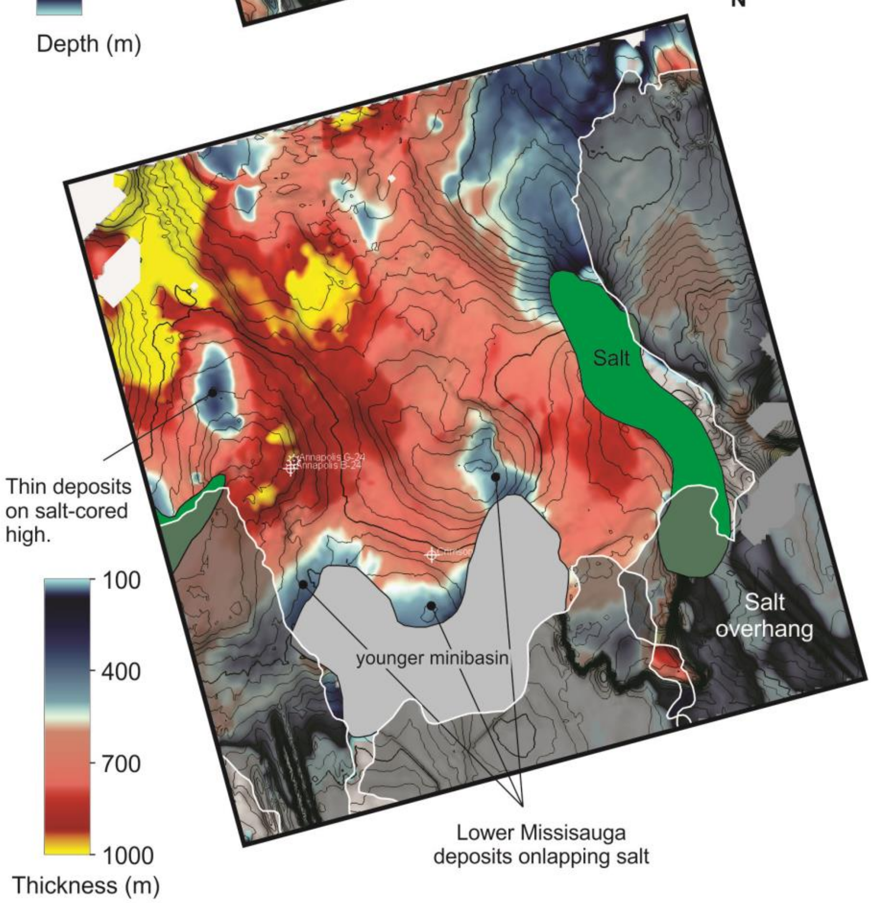


Figure 3.1.4 b) Thickness map between late Hauterivian (above) and top Jurassic seismic horizons, representing the thickness of the lower Missisauga (~K132 to J150). Depth-structure contours from the K132 map in 3.1.4a. Green polygons represent salt bodies, transparent black polygons are areas with salt overhang and the grey polygon is a region where the interval comes into contact with a younger minibasin (a salt body during the early Cretaceous)

may be present in the deeper unpenetrated parts of this isopach.

The depth-structure map at the top of Annapolis' Mid-Barremian L Sand interval displays a very similar trend of structural highs as revealed in the Late Hauterivian M Sand map. This is expected as these intervals are only separated by about 550m of strata (Figure 3.1.5a). The thickness map of the interval between these sands however, is drastically different with a prominent thin trending north-south through the Annapolis and Crimson wells (Figure 3.1.5b). The thickest parts of this Barremian interval lie to the northeast where thicknesses reach 1.5km, whereas Annapolis and Crimson penetrate it where it is only about 400m thick. Annapolis' L Sand is found within this thinner section with 5.3m of net pay over a 57.3m gross interval. That reservoirs and gas-pay were encountered in this thinner interval is encouraging, and together with the thicker gas-bearing M Sands within the K132 to J152 interval suggest that targeting expanded depositional sections should improve the possibility of encountering thicker reservoir quality turbidites.

3.2 Geological Setting

3.2.1 Basement Architecture

Seismic imaging of the basement beneath the central Scotian Slope is generally poor due to the presence of complex allochthonous salt bodies and a very thick (>14km) post-rift stratigraphic succession. In addition, the J200 seismic horizon (approximate base Jurassic and top basement) is not easily mapped in 3D seismic surveys (where imaging is better) due to the short seismic record length that is often clipped at 8-9 seconds (twt). Nonetheless, using previously published magnetics data (Oakey and Dehler, 2004) and recent observations from other studies (e.g. Deptuck et al., 2014), combined with careful mapping from available 2D seismic surveys, a top basement seismic horizon was interpreted with a moderate degree of confidence even beneath the extensive allochthonous salt canopies in the study area.

On the southwestern Scotian Slope the East Coast Magnetic Anomaly (ECMA) is interpreted to approximate the continental–oceanic boundary and its location is coincident with seaward dipping reflections observed on seismic profiles (Klitgord and Schouten, 1986; Keen et al., 1990; Dehler, 2010; Labails et al., 2010). The ECMA is also present along the central Scotian Slope but its trajectory shifts northward just west of the NS16-1 region as it crosses Parcels 4, 5 and 6. Seaward of the ECMA, the J200 marker was correlated along the top of highly rotated blocks interpreted to correspond to oceanic crust (Figure 3.2.1). This rugose basement continues along the eastern Scotian Slope, and in areas of improved seismic imaging (particularly where overlying allochthonous salt is thin or absent) there is an obvious linear NE-SW trend to the basement fabric that appears to be related to the development of brittle rotated crustal blocks (Figure 13 in Deptuck et al., 2014). In the study area, velocity effects from the overlying Sable Slope Canopy disrupt this basement fabric. A 3D velocity model generated for this study attempts to remove velocity artefacts associated with the overlying salt canopy and subsequent depth conversions of the J200 marker suggest that the NE-SW linear trend in the basement fabric continues underneath the Sable Slope Canopy (Figures 3.2.1 and 3.2.2). The sharp pointed crests of these rotated basement blocks show a high degree of alignment (red dots in inset; Figure 3.2.2; see also Deptuck et al., 2014), and the grey polygons attempt to show the distribution of the rotated fault blocks that were mapped with a higher degree of confidence.

The NE-SW trend generated by these rotated blocks does not appear to extend along or landward of the ECMA, and salt feeders commonly root down into a primary salt basin along or landward of the ECMA. This suggests that, as in the southwest (Deptuck, 2011; Deptuck et al. 2015) and northeast (Deptuck et al., 2014) portions of the Scotian margin, the ECMA

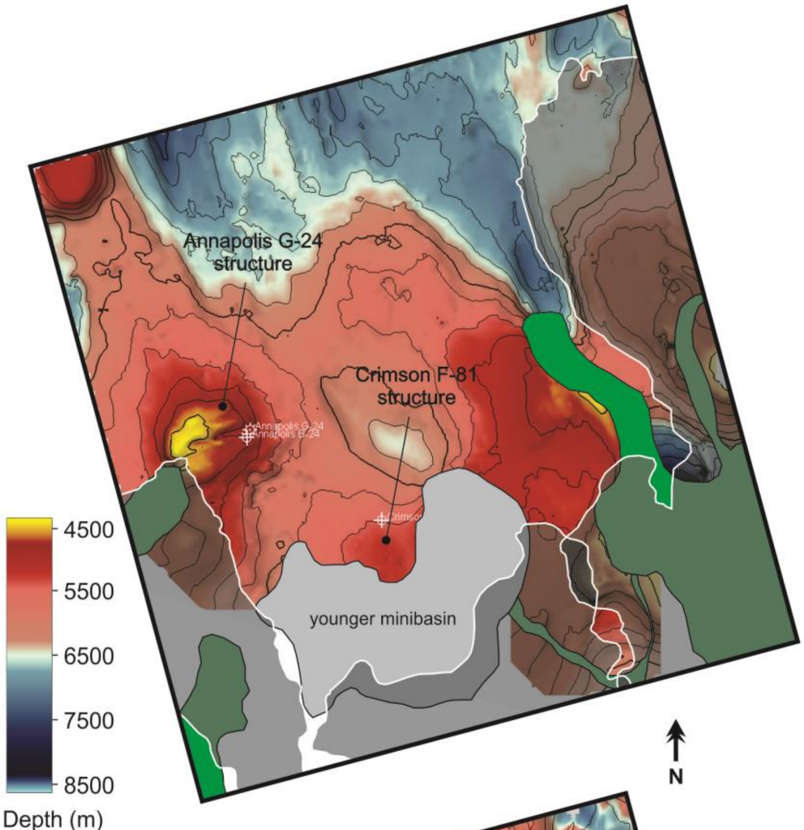


Figure 3.1.5 a) Depth-structure map generated on a seismic horizon near the top of the `L` sand interval (K130, mid Barremian) intersected at the Annapolis G-24 well. Green polygons represent salt bodies, transparent black polygons are areas with salt overhang and the grey polygon is a region where the surface comes into contact with a younger minibasin (a salt body during the Barremian)

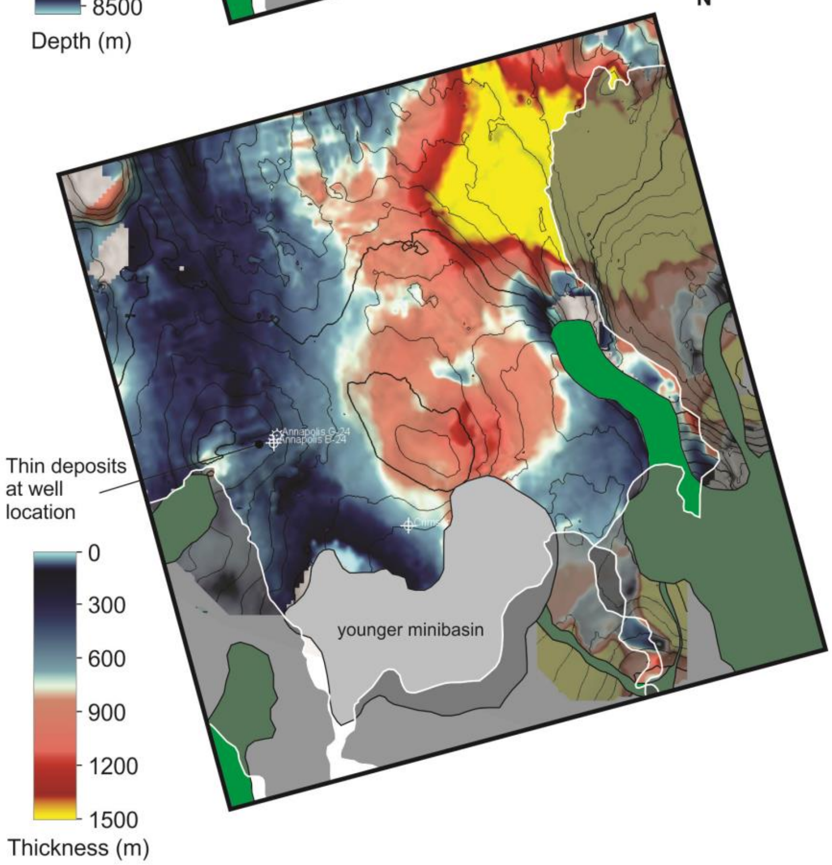


Figure 3.1.5 b) Thickness map between the K130 and K132 seismic horizons (Hauterivian). Depth-structure contours from the above figure. Green polygons represent salt bodies, transparent black polygons are areas with salt overhang and the grey polygon is a region where the surface comes into contact with a younger minibasin (a salt body during the Barremian)

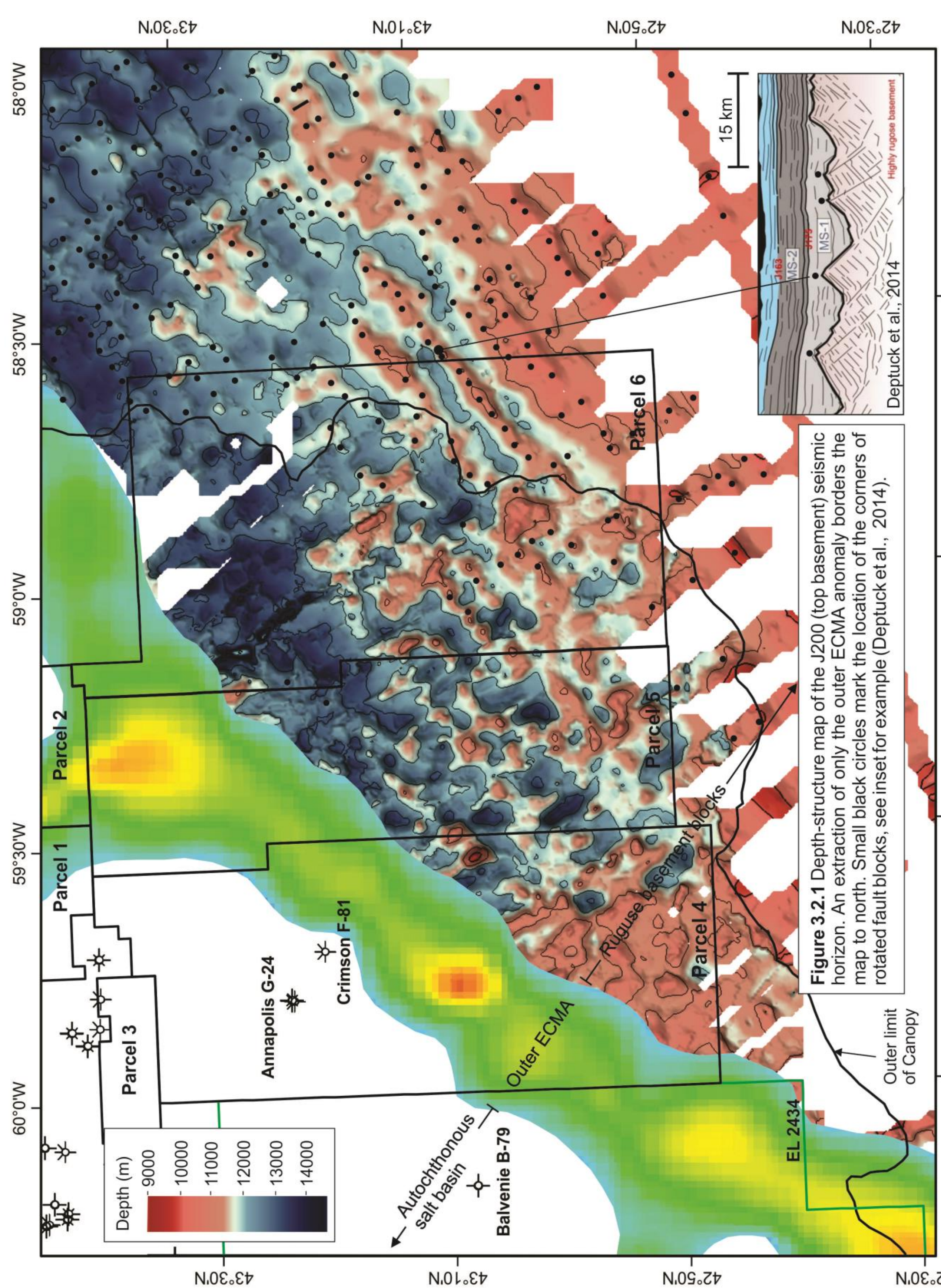


Figure 3.2.1 Depth-structure map of the J200 (top basement) seismic horizon. An extraction of only the outer ECMA anomaly borders the map to north. Small black circles mark the location of the corners of rotated fault blocks, see inset for example (Deptuck et al., 2014).

Kendell et al. 2016

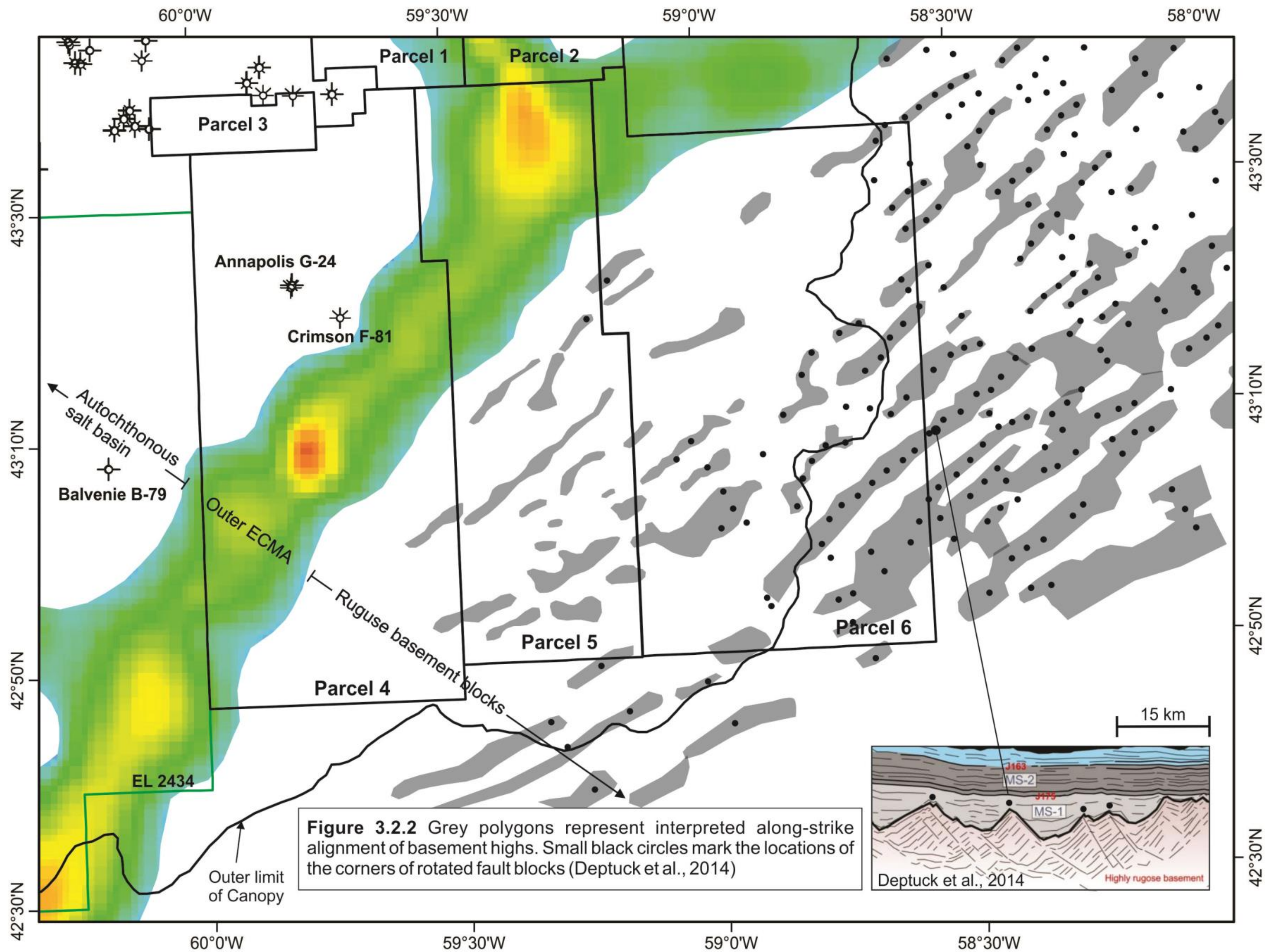


Figure 3.2.2 Grey polygons represent interpreted along-strike alignment of basement highs. Small black circles mark the locations of the corners of rotated fault blocks (Deptuck et al., 2014)

coincides with an important structural boundary, and closely approximates the seaward boundary of the autochthonous salt basin. This observation is reinforced by the lack of salt feeders in the region of rotated basement blocks seaward of the ECMA. All mapped salt feeder systems that supplied salt to the Sable Slope Canopy are interpreted to originate from salt deposited above continental crust north of the ECMA.

3.2.2 Salt tectonics

There are two canopy systems within the central Scotian Margin; the Sable Shelf Canopy ("Shelf Canopy") and the Sable Slope Canopy ("Slope Canopy") (Kendell, 2012). Although they are approximately 50 kilometers apart, they are linked in multiple locations by welded detachment systems. Extensional systems detaching in the Shelf Canopy expelled salt downdip supplying varying amounts of salt to the Slope Canopy (Kendell, 2012). Unravelling the complex salt tectonic history responsible for forming these canopy systems is crucial for generating accurate structure and thickness maps and is critical when considering the local petroleum systems. Figure 3.2.3 shows the location of the NS16-1 parcels relative to these canopy systems. Parcels 1 and 2 are located above the Shelf Canopy. Parcels 4, 5 and 6 are located principally above the Slope Canopy, and are bounded to the west and east by two very distinct, salt-related detachment systems. West of Parcel 4 is the Balvenie Roho System (BRS) (Deptuck et al., 2009). Named after the well drilled on a related structural high, this large salt-based detachment system was sourced by underlying salt feeders near the end of the Jurassic, with its detachment surface in Lower Cretaceous strata. BP's Exploration Licence 2434 overlies this detachment system. East of Parcel 6 is an older salt-based detachment system, the Banquereau Synkinematic Wedge (BSW) (Ings et al., 2006). The BSW differs from the BRS in that a) it is an older detachment system (Middle to Late Jurassic), and b) there are no underlying feeders. Instead, the system formed above one large allochthonous tongue or nappe expelled from the shelf region, rather than above an amalgamated salt stock canopy supplied by numerous feeders on the slope (Deptuck et al. 2014). Mapping efforts in this study are generally limited to the area between these two regional-scale features.

Parcels 4, 5 and 6 are located across the Sable Slope Canopy (Figure 3.2.4). This large canopy system covers approximately 12 700km^2 with regions where the allochthonous salt is as thick as 3500m. Kendell (2012) described a variety of salt expulsion systems in the landward parts of these parcels, ranging from amalgamated salt stocks, counter-regional systems, rohos and hybrid features (Figure 3.2.3). The northern parts of Parcels 4, 5, and 6 overlie the autochthonous salt basin where salt is largely welded out. A time-structure map above the salt indicates the top of salt here is stratigraphically deeper than anywhere else in the study area (Figures 3.2.4 and 3.2.6). A number of primary feeders (salt stocks) supplied salt to the early canopy system, and later reactivation of these feeders took place as younger deep minibasins were deposited, expelling salt from the primary stocks (identified with dashed outlines in Figures 3.2.5 and 3.2.6). These minibasins are only found within Parcels 4 and 5 (Figure 3.2.6) where the salt stocks are rooted to the autochthonous basin (Figure 3.2.7). Similar basins may exist landward of Parcel 6. Most of these salt stock-loading basins are located either above or north of the ECMA. In map view, some basins are located slightly seaward of the ECMA but this is because they loaded seaward leaning salt feeders extending from the primary salt basin.

One of the most complex regions of salt-related deformation is found in the northern part of Parcel 5, above the autochthonous salt basin where a potential branch of the outer ECMA turns sharply to the north (Figures 3.2.4, 3.2.5). Here, a salt-stock canopy has been identified where it is unclear whether salt stocks are rooted to a Lower Jurassic allochthonous system or to the primary salt layer (Figures 3.2.4, inset). Differentiating between the regional allochthonous welded systems in this area and the true autochthonous

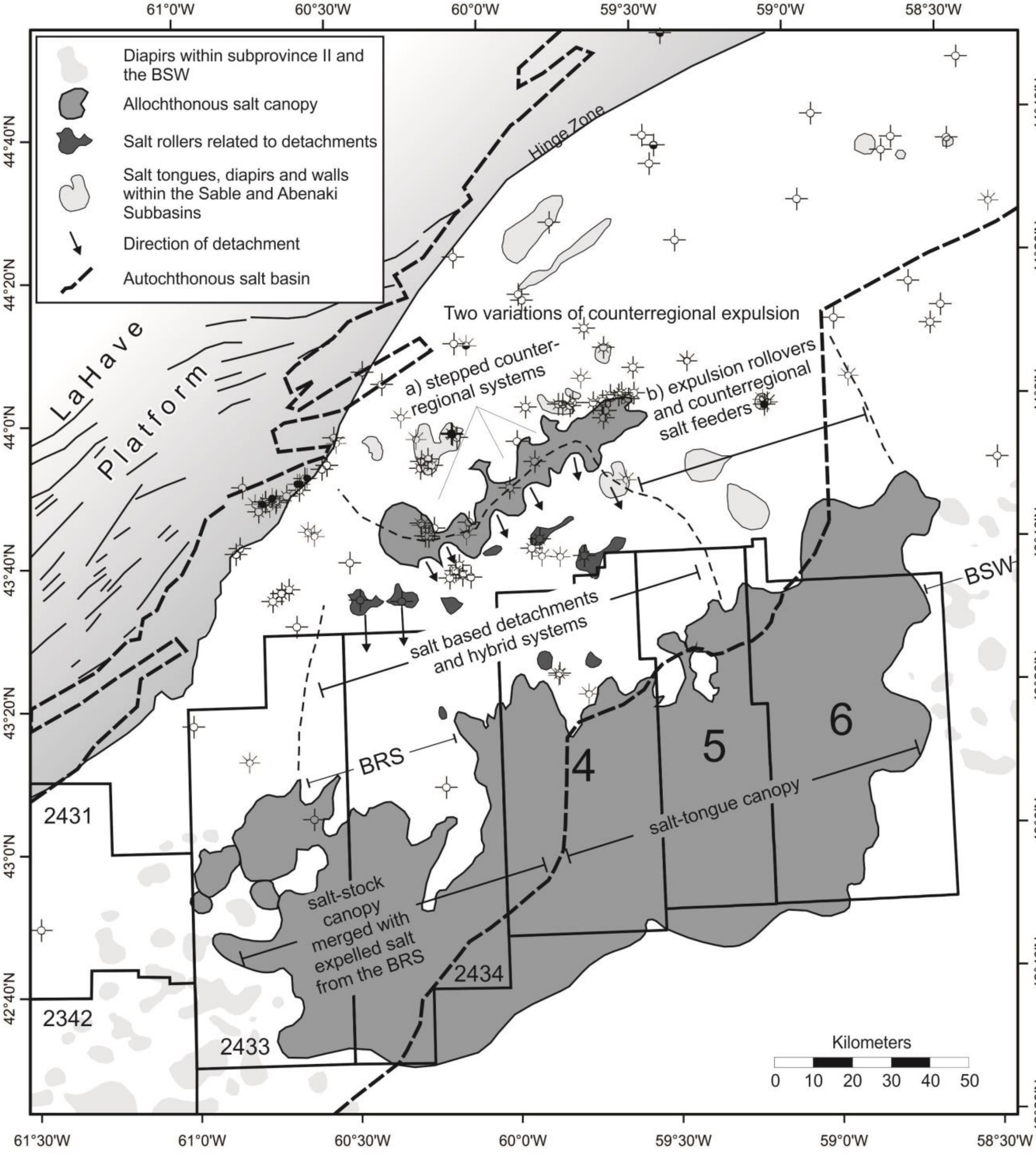


Figure 3.2.3 Expulsion styles found inboard the Sable Slope Canopy as identified by Kendell (2012). Call for Bids Parcels 4, 5 and 6 are identified along with the current deep water Exploration Licences. The dashed lines identify the limits of the autochthonous salt basin. BRS - Balvenie Roho System, BSW - Banquereau Synkinematic Wedge (Figure modified from Kendell 2012).

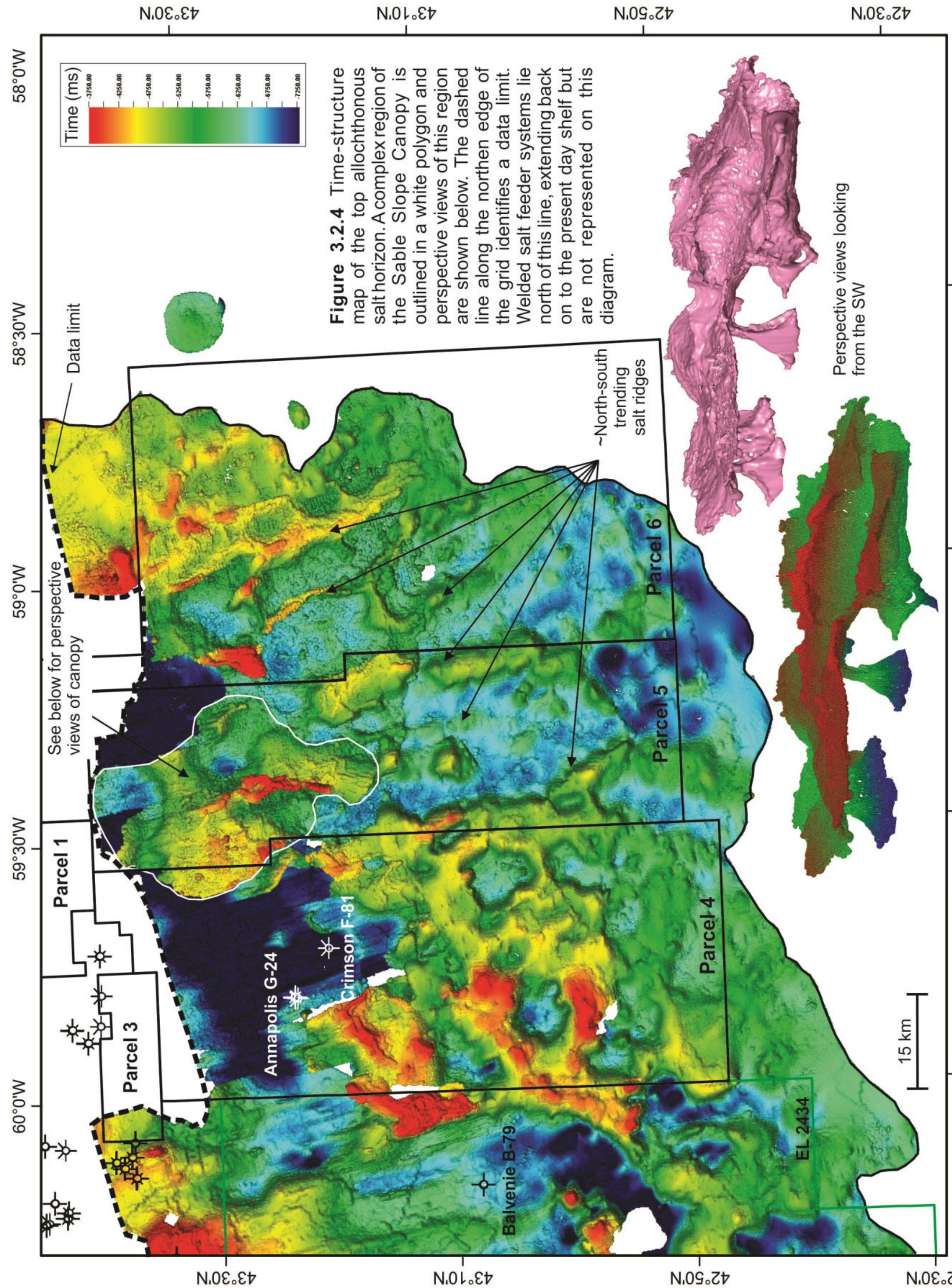


Figure 3.2.4 Time-structure map of the top allochthonous salt horizon. A complex region of the Sable Slope Canopy is outlined in a white polygon and perspective views of this region are shown below. The dashed line along the northen edge of the grid identifies a data limit. Welded salt feeder systems lie north of this line, extending back on to the present day shelf but are not represented on this diagram.

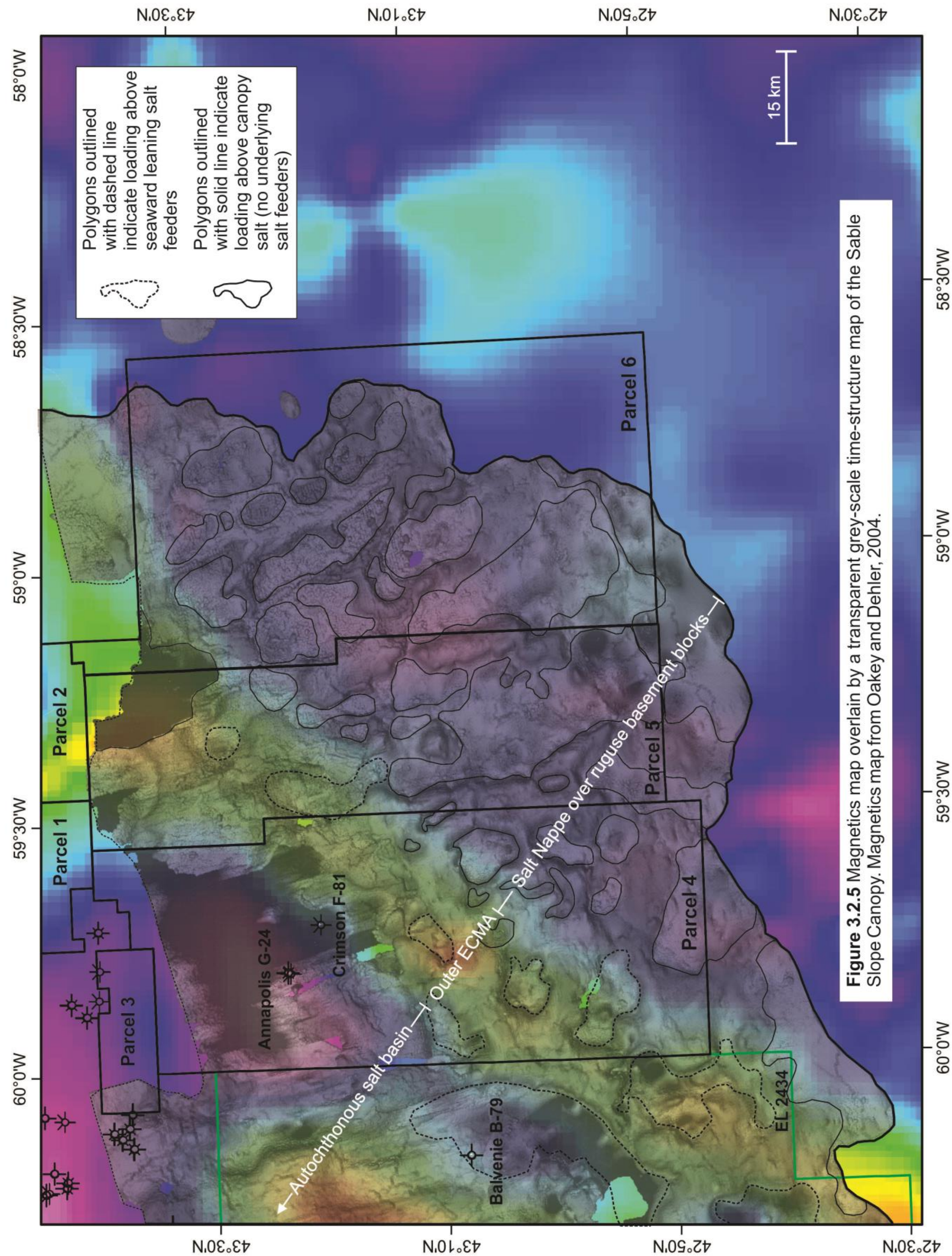


Figure 3.2.5 Magnetics map overlain by a transparent grey-scale time-structure map of the Sable Slope Canopy. Magnetics map from Oakey and Dehler, 2004.

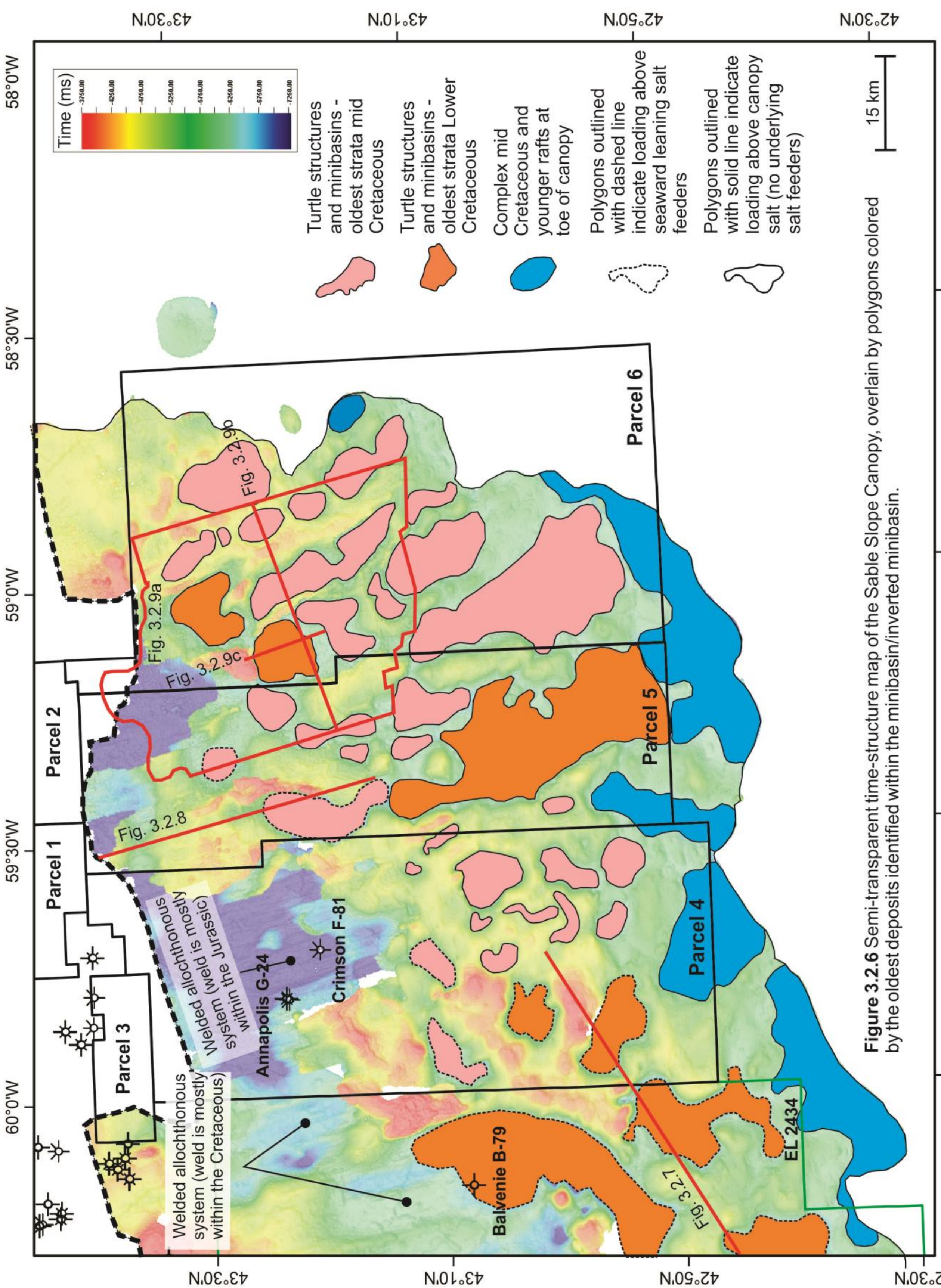


Figure 3.2.6 Semi-transparent time-structure map of the Sable Slope Canopy, overlain by polygons colored by the oldest deposits identified within the minibasin/inverted minibasin.

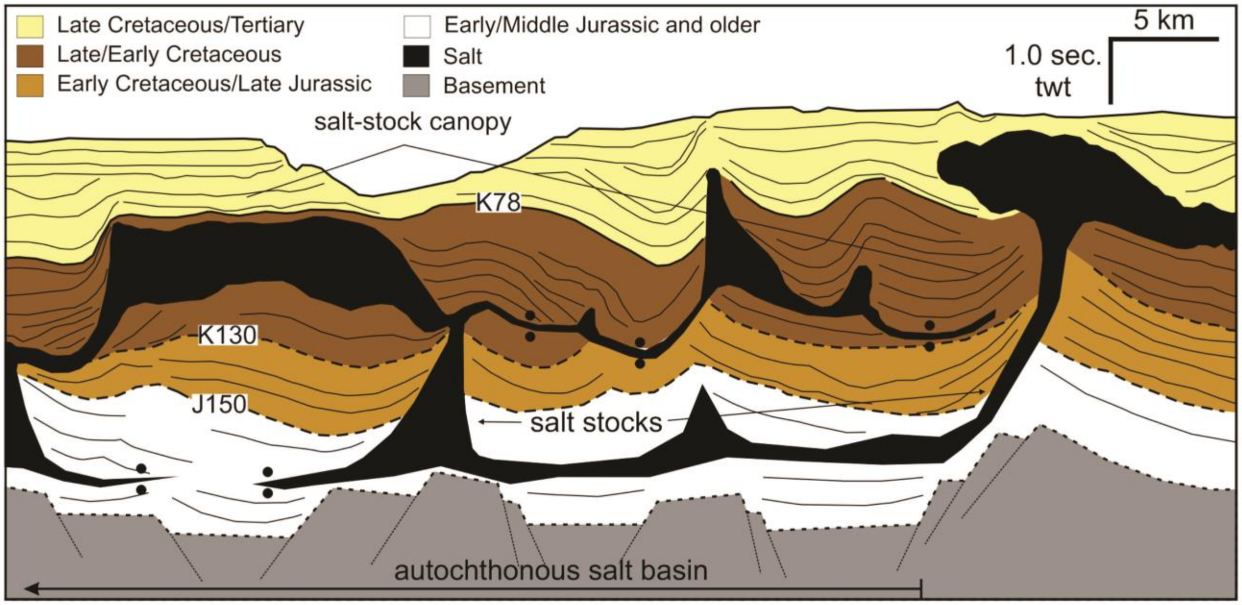


Figure 3.2.7 Seismic based line drawing through a salt-stock portion of the canopy within Parcel 4. Pairs of black circles indicate locations of thin to welded salt. (modified from Kendell, 2012)

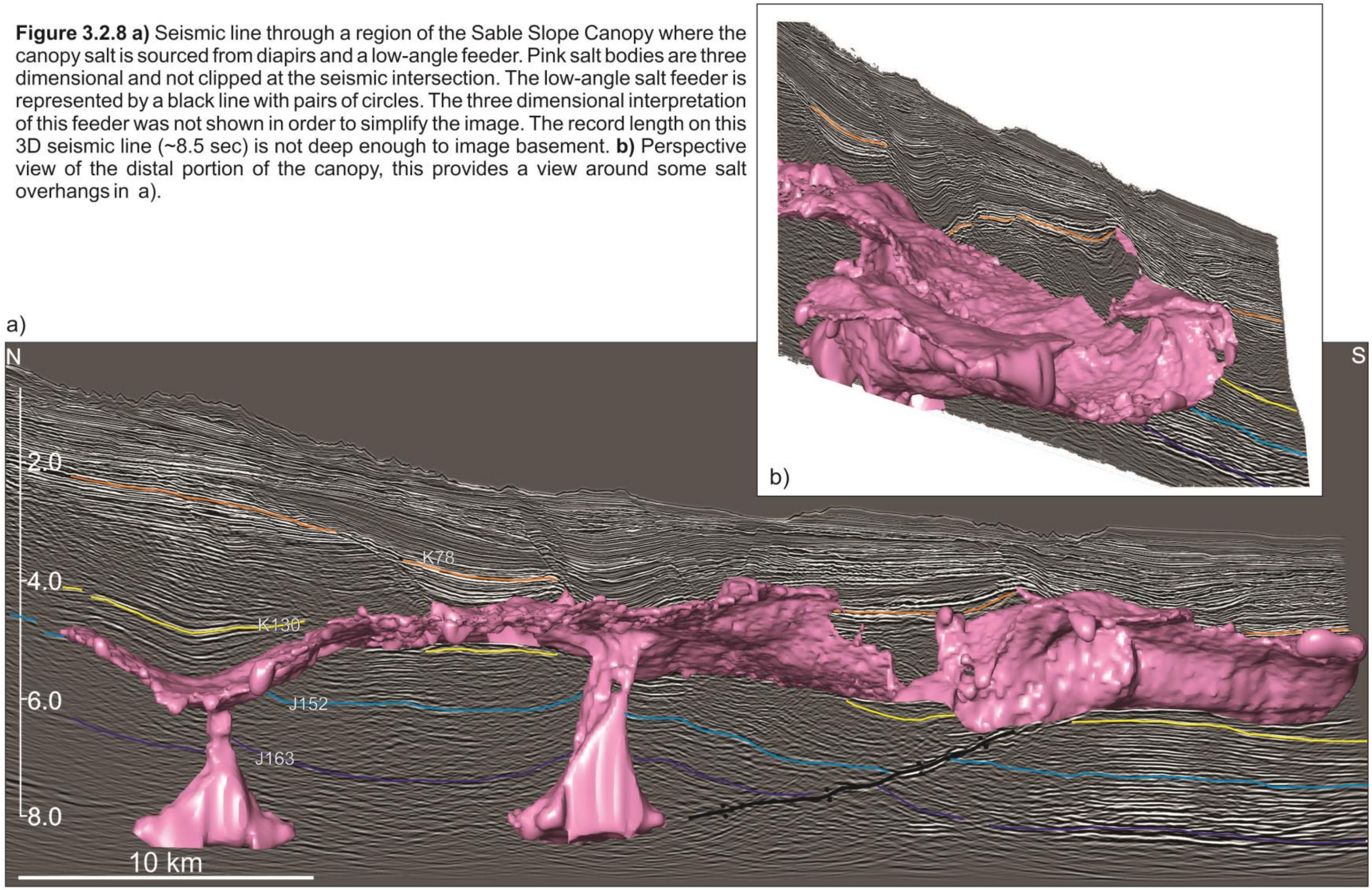
level is further complicated by poor imaging at depth and shallow record lengths of 3D seismic volumes. Nevertheless, several salt stocks appear to have amalgamated in this region, and as such it is analogous to the amalgamated Balvenie salt-stock canopy further west (Figure 3.2.8).

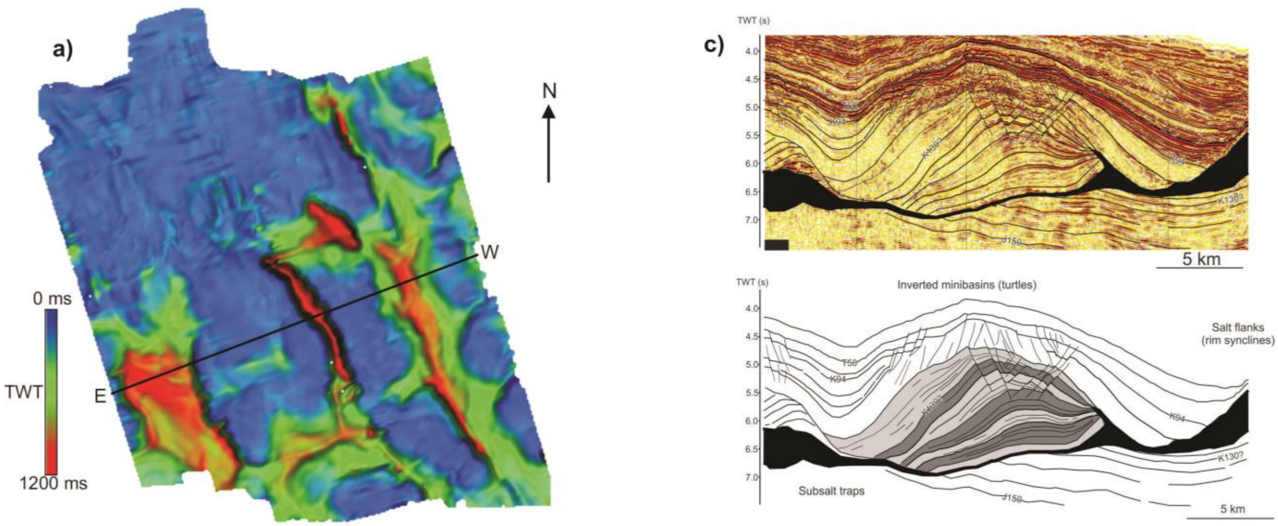
In contrast, most of the Slope Canopy is located outboard the autochthonous salt basin south of the ECMA, above interpreted oceanic crust. The Slope Canopy lies within much younger stratigraphic intervals, ranging from Cretaceous to Tertiary (Figure 3.2.5). Salt tectonism associated with the canopy system is relatively simple and better imaged compared to the inboard systems. Salt withdrawal minibasins, extensional turtle structures and rafts are commonly identified throughout the canopy. Basins loading canopy salt (with no underlying salt stocks) are abundant throughout Parcels 4, 5 and 6 (colour coded in Figure 3.2.6 according to the age of the oldest strata within them), with the majority located in what are considered to be extensional or detachment corridors. These corridors are most evident on the top salt time-structure map in Parcels 5 and 6 where they are flanked by adjacent salt highs (Figure 3.2.4). The salt highs appear to have formed during sediment loading above canopy salt, in some cases as the basins were translated downdip and locally inverted into turtles or half turtles. Figure 3.2.9(c) illustrates an example of an inverted basin interpreted to contain Lower Missisauga equivalent strata displaced along a corridor in Parcel 6. The seaward toe of the Slope Canopy system also appears to be veneered by a complex arrangement of rafts and rotated blocks containing mid-Cretaceous strata, where the canopy salt also tends to be thinner (Figure 3.2.6).

3.2.3 Postrift Structure and Stratigraphy

A velocity model was built to depth convert mapped seismic markers to produce isopachs and to correct a number of artifacts that impede accurate seismic interpretation and assessment of structure maps in the

Figure 3.2.8 a) Seismic line through a region of the Sable Slope Canopy where the canopy salt is sourced from diapirs and a low-angle feeder. Pink salt bodies are three dimensional and not clipped at the seismic intersection. The low-angle salt feeder is represented by a black line with pairs of circles. The three dimensional interpretation of this feeder was not shown in order to simplify the image. The record length on this 3D seismic line (~8.5 sec) is not deep enough to image basement. **b)** Perspective view of the distal portion of the canopy, this provides a view around some salt overhangs in a).





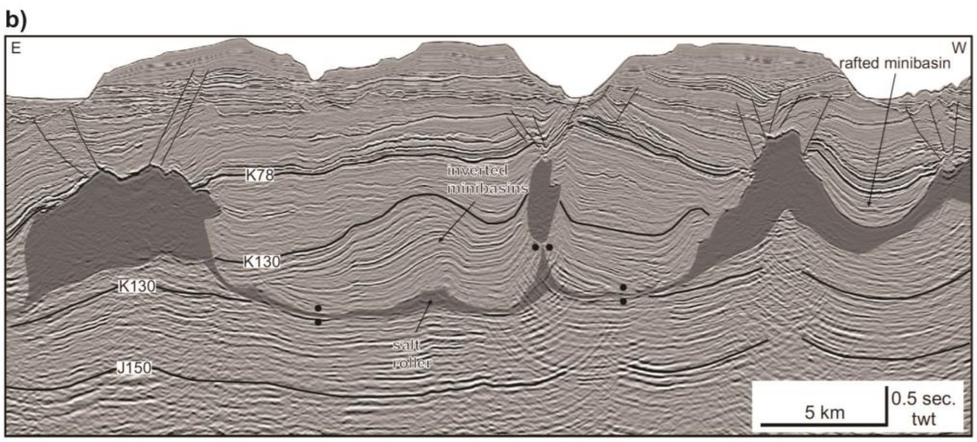


Figure 3.2.9. a) Time-thickness of a portion of the Sable Slope Canopy and location of intersecting seismic line (E-W). **b)** Strike seismic line through the Sable Slope Canopy. Pairs of black circles mark the locations of salt welds. (Images modified from Kendell, 2012) **c)** Interpreted seismic profile and line drawing of a dip line through the inverted minibasin labeled in (b).

study area. The heavily incised post-Pleistocene seafloor (particularly along the upper slope; see Figure 3.2.10) and highly variable water depths create velocity artifacts within time-migrated seismic datasets. Likewise, mapped Cretaceous and Jurassic seismic markers commonly underlie the Sable Slope Canopy, with abrupt changes is salt thickness associated with canopy loading. Velocity "pull up" effects on horizons beneath thicker remnants of canopy salt are particularly problematic. The velocity model generated for this study has helped correct many of these artifacts, increasing interpretation confidence, though several artefacts still remain. Balvenie B-79, Annapolis G-24 and Crimson F-81 were used to generate the time-depth relationships for the model. These wells provide time-depth curves for the Cretaceous and shallower intervals (deepest penetration is to the top Valanginian at Annapolis) with constant velocities used for the Jurassic section below well penetrations. Based on analysis of salt penetrations on the Scotian Margin by Shimeld (2004), a salt velocity of 4400 m/sec was also used.

The J200 seismic marker, as described earlier, is difficult to interpret north of the ECMA where it deepens beneath the autochthonous salt basin; as such there is a zone with no data in the northern part of Parcels 4 and 5 (Figure 3.2.1). The mid-Jurassic J163 (Callovian) depth-

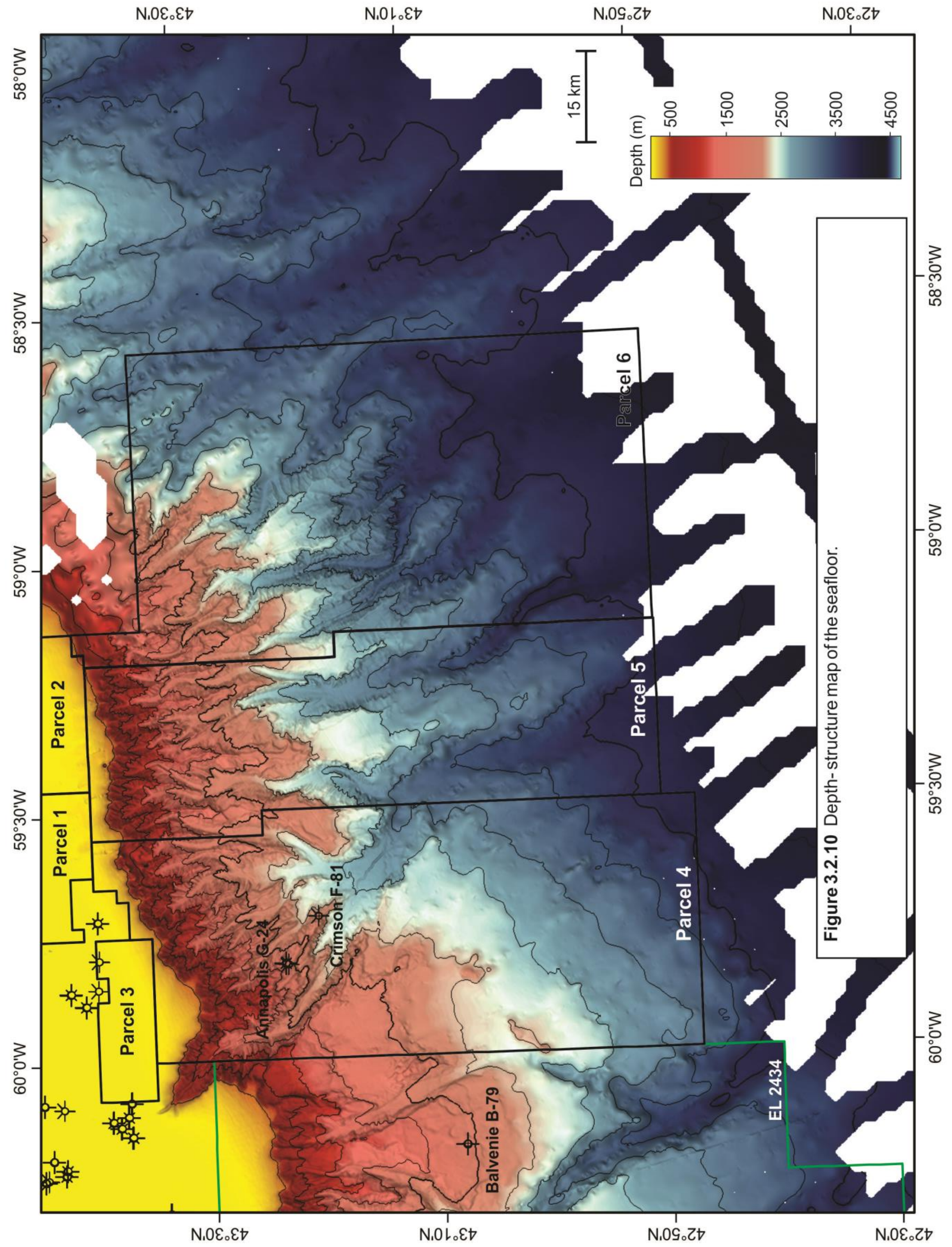


Figure 3.2.10 Depth-structure map of the seafloor.

structure map indicates the Lower to Middle Jurassic section is generally between 9 and 10 km below sea level across most of the study area, shallowing slightly in Parcel 4 (Figure 3.2.12). Multiple salt contacts define the location of mid Jurassic feeders in the northern parts of the parcels, when salt was still within the autochthonous salt basin north of the ECMA.

The Late Jurassic J152 (Tithonian) depth-structure map has numerous structural highs along the northern half of the parcels and also northeast of Parcel 6 where the J152 marker drapes over detached Jurassic strata and inverted successions within the BSW (Figure 3.2.13). The structural highs passing through Annapolis and Crimson are related to salt withdrawal/loading (and subsequent inversion) of the advancing salt front, as the Mic Mac Formation prograded across the shelf and slope. Any potential closures on this map are below the base of the wells drilled in this region. As shown by the salt contacts, a widespread NE trending salt wall extending roughly 100 km was expelled along the seaward margin of the primary salt basin in the Late Jurassic.

Widespread salt canopies began to form in the Early Cretaceous. Salt tongues and amalgamated tongues migrated up and out of the primary salt basin in numerous areas, climbing across the Early Cretaceous underpinned by oceanic crust (Figure 3.2.14). Similar to the J152 map, a trend of structural highs landward of the advancing salt is evident on the K130 (Hauterivian) depth structure map, and two of these structures were tested by the Annapolis and Crimson wells. There are multiple locations above the canopy where high-displacement extensional corridors are noted. Basins and turtle structures within these corridors are rafted downslope towards the SSE and are shown in Figure 3.2.14. The Sable Slope Canopy was fully formed by the Late Cretaceous (Figure 3.2.15), when it reached its maximum downslope extent, with salt displaced up to 85 km from the seaward edge of the primary salt basin. Numerous deep proximal basins (in the northern half of Parcels 4-6) formed at this time as the landward parts of the salt canopy were reactivated. Some of these basins are more than 5km deep. The locations of these basins coincide with the continent-ocean crustal boundary (i.e. the ECMA) and are the result of loading the east-west trend of early salt feeders along the southern edge of the autochthonous salt basin.

Isopach maps

Total postrift thickness within Parcels 4-6 is greater than 14km (Figure 3.2.11). The Early (Pleinsbachian) to Middle (Bajocian) Jurassic Mohican Formation defines the initial postrift fill in the Scotian Basin and consists of texturally immature fluvial to shallow marine sandstones, siltstones, and red-brown and green shales (Given, 1977) with the thickness of its deep water equivalent shown in Figure 3.2.16. The SSW-NNE trend of sediment thicks represents infilling of the troughs between rotated basement blocks (see Figure 3.2.1). This J200-J163 succession also thickens in the northern edge of the parcels where it probably first began to load the salt basins in this area.

Deposition of the Mohican Formation or its equivalents in the Middle Jurassic was followed by an influx of siliciclastics of the Mic Mac and coeveal carbonates of the Abenaki formations (Wade and Maclean, 1990). An expanded section of these Late Jurassic sediments is present northeast of Parcel 6 within the BSW (Figure 3.2.17). It extends into the deep water portions of Parcels 5 and 6 but tapers to less than 1 km within Parcel 4. Inboard of the salt, multiple depositional corridors developed where a focusing of Late Jurassic deposits occurred and is particularly notable near the Annapolis and Crimson wells. The thickness map defines an undrilled interval, and while its facies are unknown they are expected to be deep water equivalents to the Mic Mac and Abenaki (i.e. siliciclastics and re-worked carbonate sediments deposited as calciclastic fan complexes?)

The Missisauga Formation was deposited in the Early Cretaceous (Berriasian to Barremian). This sand-rich sequence of fluvial, deltaic and shallow marine clastic sediments is divided into Upper and Lower members

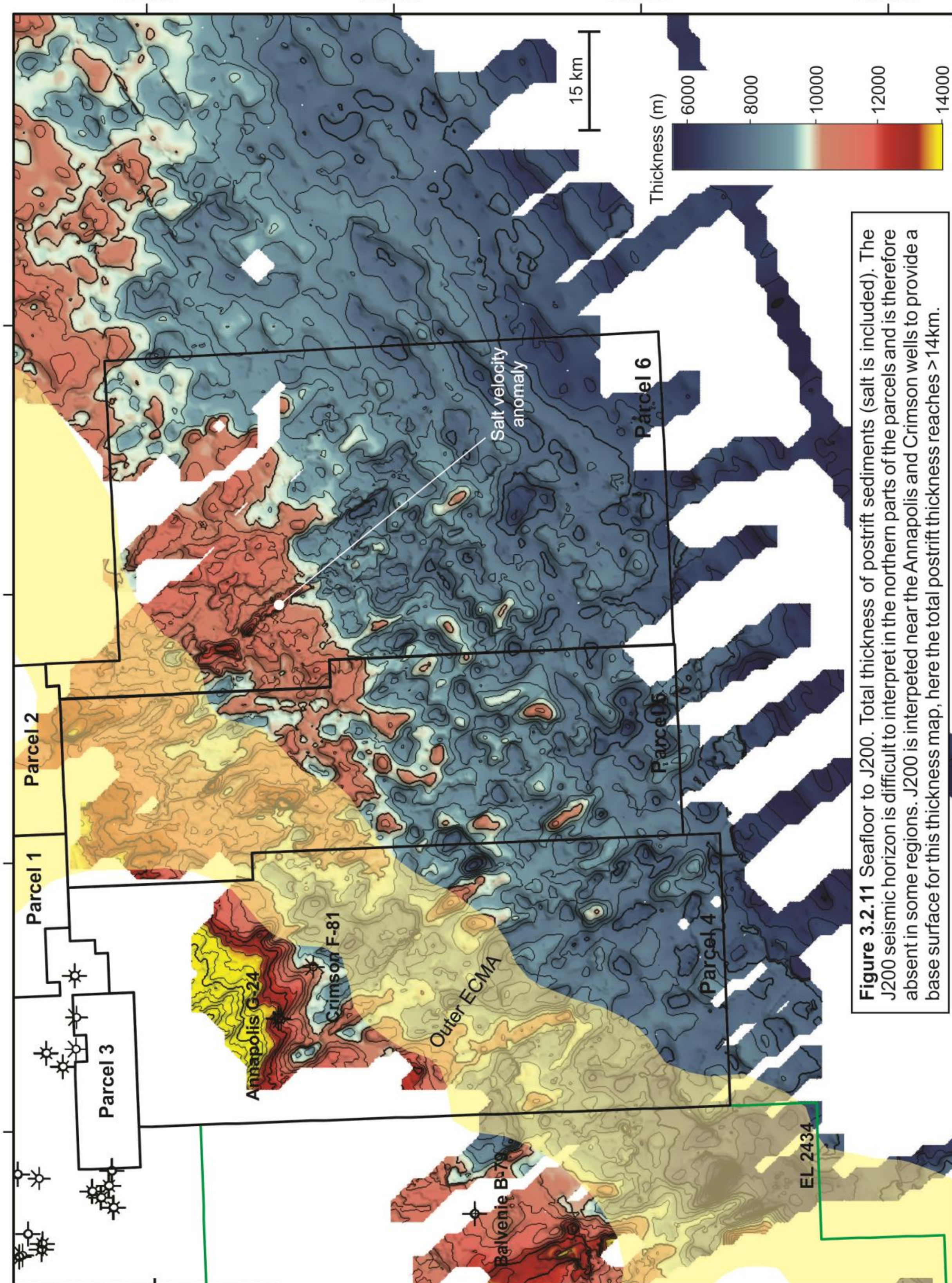


Figure 3.2.11 Seafloor to J200. Total thickness of postrift sediments (salt is included). The J200 seismic horizon is difficult to interpret in the northern parts of the parcels and is therefore absent in some regions. J200 is interpeted near the Annapolis and Crimson wells to provide a base surface for this thickness map, here the total postrift thickness reaches >14km.

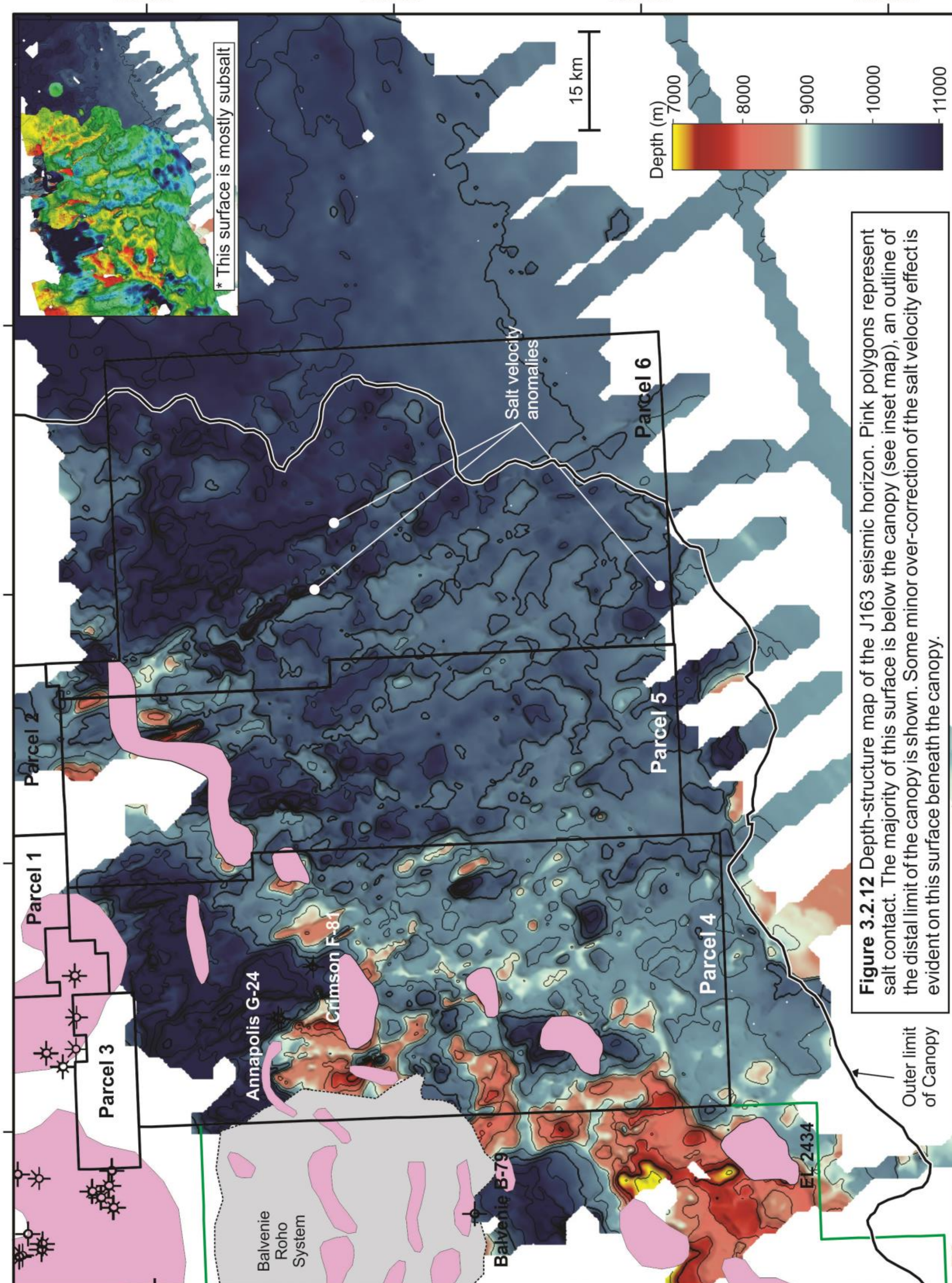


Figure 3.2.12 Depth-structure map of the J163 seismic horizon. Pink polygons represent salt contact. The majority of this surface is below the canopy (see inset map), an outline of the distal limit of the canopy is shown. Some minor over-correction of the salt velocity effect is evident on this surface beneath the canopy.

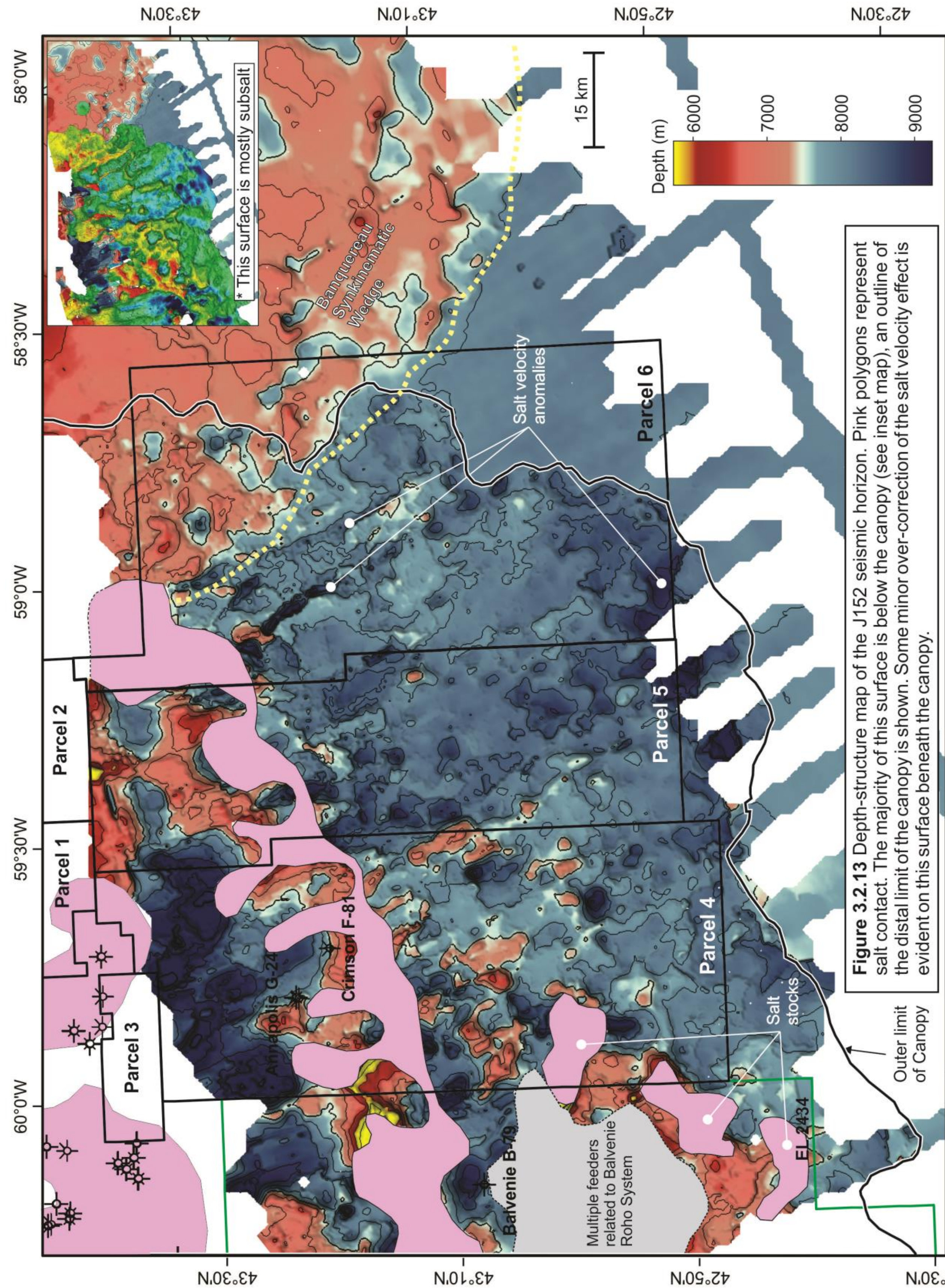


Figure 3.2.13 Depth-structure map of the J152 seismic horizon. Pink polygons represent salt contact. The majority of this surface is below the canopy (see inset map), an outline of the distal limit of the canopy is shown. Some minor over-correction of the salt velocity effect is evident on this surface beneath the canopy.

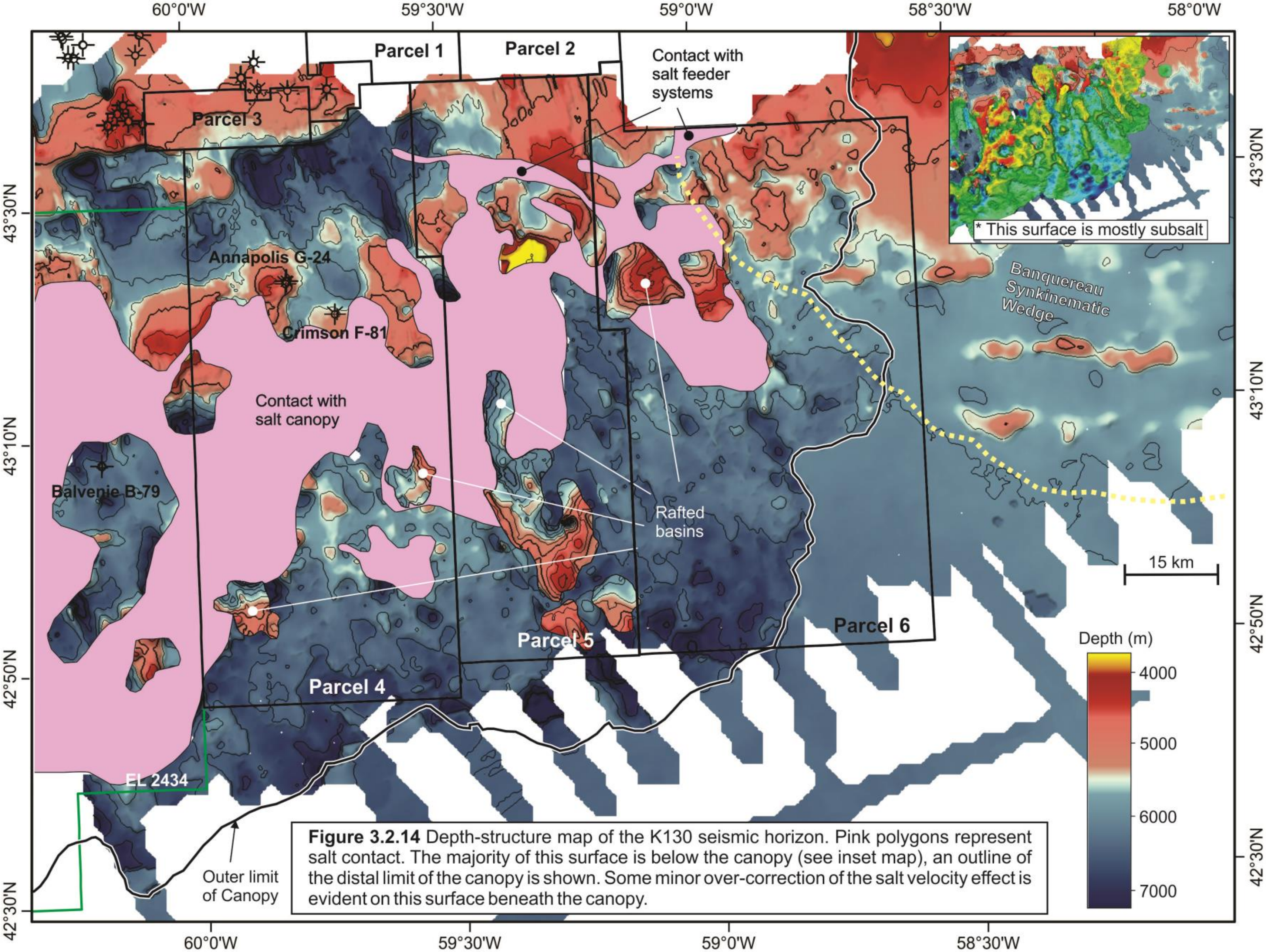


Figure 3.2.14 Depth-structure map of the K130 seismic horizon. Pink polygons represent salt contact. The majority of this surface is below the canopy (see inset map), an outline of the distal limit of the canopy is shown. Some minor over-correction of the salt velocity effect is evident on this surface beneath the canopy.

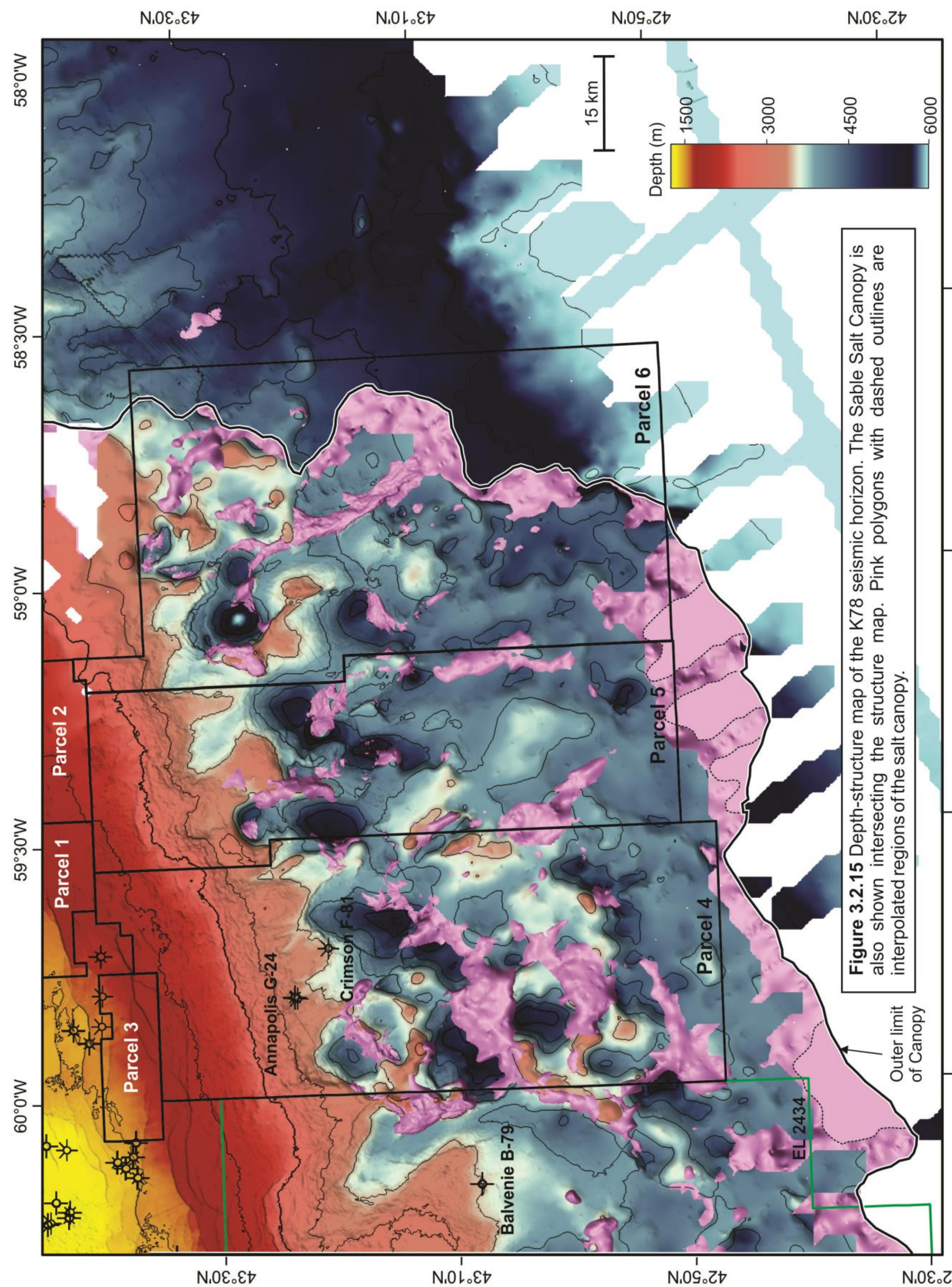


Figure 3.2.15 Depth-structure map of the K78 seismic horizon. The Sable Salt Canopy is also shown intersecting the structure map. Pink polygons with dashed outlines are interpolated regions of the salt canopy.

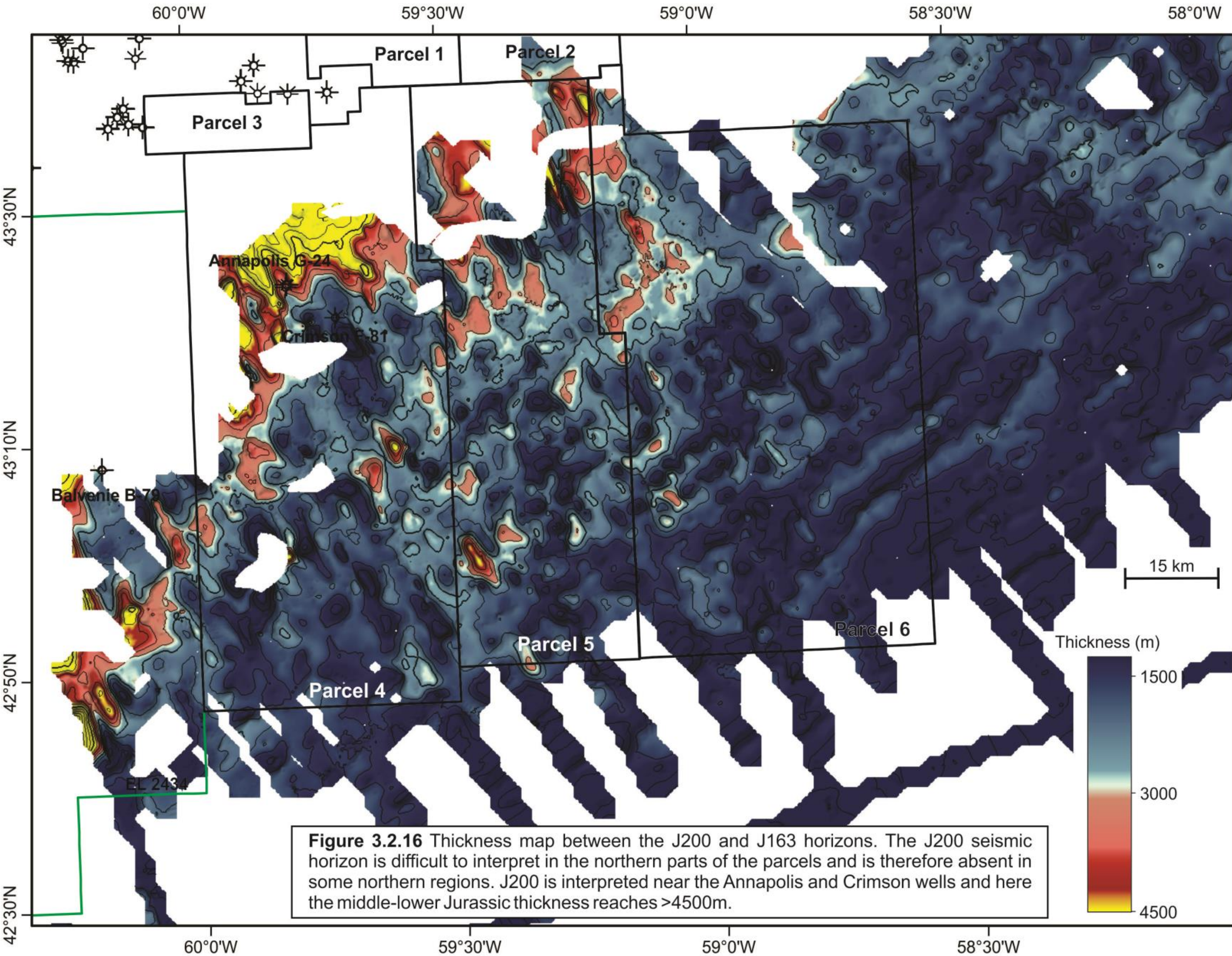


Figure 3.2.16 Thickness map between the J200 and J163 horizons. The J200 seismic horizon is difficult to interpret in the northern parts of the parcels and is therefore absent in some northern regions. J200 is interpreted near the Annapolis and Crimson wells and here the middle-lower Jurassic thickness reaches >4500m.

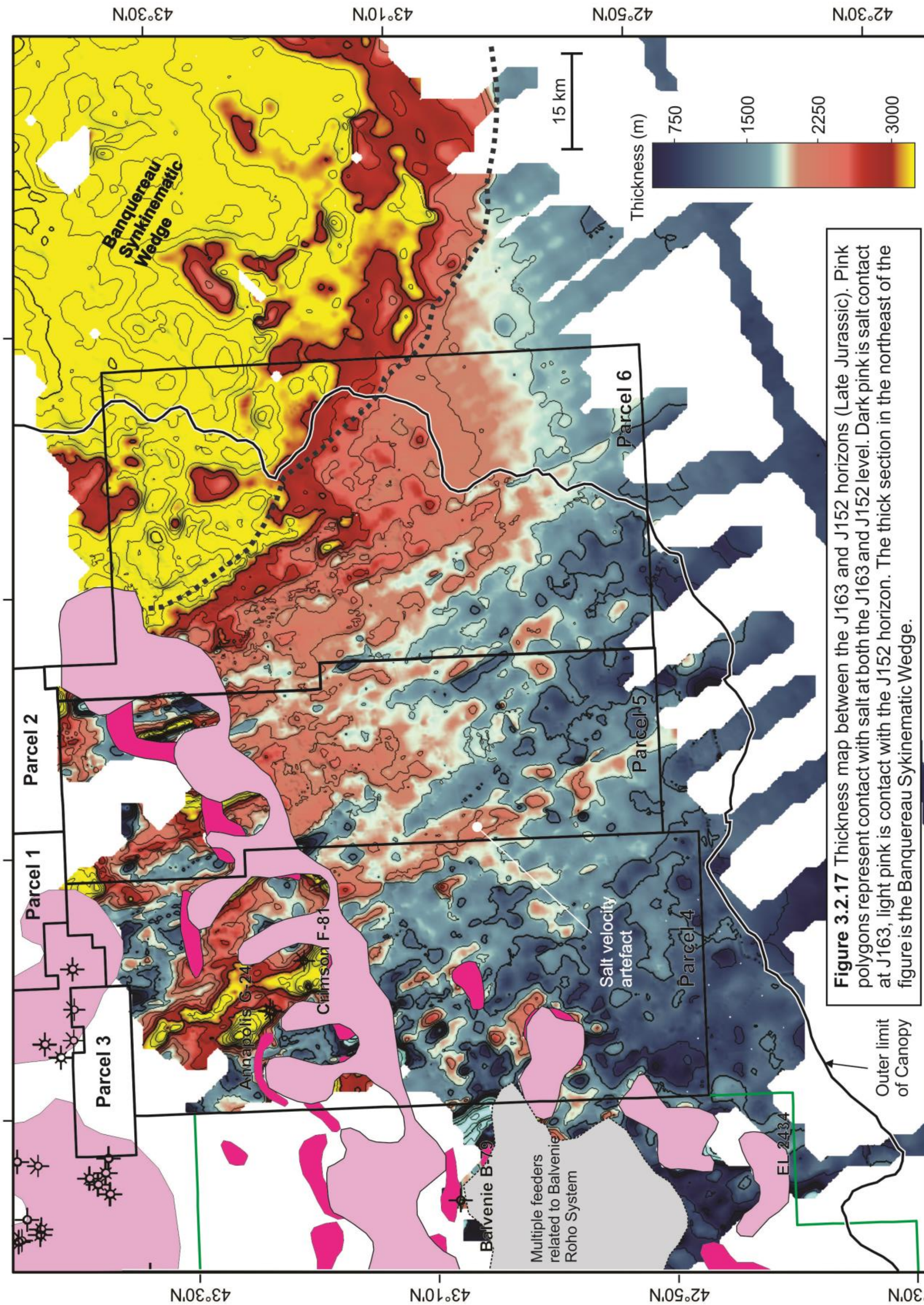


Figure 3.2.17 Thickness map between the J163 and J152 horizons (Late Jurassic). Pink polygons represent contact with salt at both the J163 and J152 level. Dark pink is salt contact at J163, light pink is contact with the J152 horizon. The thick section in the northeast of the figure is the Banquereau Sykinematic Wedge.

separated by an interval of generally thin Hauterivian/Barremian oolitic limestones known as the “O” Marker (K130). The thickness map in Figure 3.2.18 illustrates the thickness of the Lower Member with accumulations greater than 3km found landward of the developing canopy. These expanded sections are a result of downbuilding into the salt basin and ponding of turbidite deposits along the upper slope. This interval was penetrated by the Annapolis and Crimson wells and in the former confirmed the presence of gas-charged, reservoir quality turbidite sandstones. A prominent thin is noted above the BSW. Although some turbidite fan systems may have avoided the bathymetric high created by this detachment system, the southwestward shift in sedimentation is believed to more strongly reflect a shift in the Lower Cretaceous delta systems on the shelf, perhaps in response to the Avalon Uplift (see Deptuck et al., 2014). In deep water, this sequence contains numerous stacked submarine channel belts referred to as the Missisauga Fan Complex. Fan deposits buttressed the southwestern parts of the BSW, and the succession can be correlated further west still where it underlies the Sable Slope Canopy. Potential sediment entry points are also recognized above the canopy in Parcels 4 and 5, along future sutures between different salt sheets.

The Upper Missisauga and Logan Canyon formations are represented by the K130 (Hauterivian/Barremian) to K78 (Campanian) thickness map (Figure 3.2.19). The map includes the salt canopy, so its southern parts have anomalous thicks and thins that are not representative of the true thickness of the stratigraphy. The northern edge however is absent of salt and therefore the east-west trending thick represents the true thickness of the Upper Missisauga and Logan Canyon formations. On the upper slope this sequence exceeds 4km in thicknesses, most of which is due to a deltaic package that progrades onto the upper slope within the Aptian-Albian.

3.3 Exploration Potential

Potential Reservoirs

The *Sediment Delivery Systems* section of the 2012 Call for bids (http://www.callforbids.cnsopb.ns.ca/2012/01/ns12-1-parcels/central-scotian-margin-parcels-12-7-11/sediment-delivery-systems) offers an in-depth study describing the shelf edge trajectories and canyon systems found within the central Scotian Margin. There is abundant evidence that the necessary sediment transport systems exist to transport coarse clastic deltaic deposits from the shelf to deeper waters. The Annapolis G-24 well encountered coarse clastics within the deep water equivalent of the Mississauga Formation. These are the highest quality and thickest sands encountered to date on the Scotian Slope. Considering both the well results at Annapolis and the mapped sediment transport systems, the risk for encountering coarse-grained turbidite deposits within these parcels is considerably lower than most other regions on the Scotian Slope.

Traps

Most traps within Parcels 4-6 are salt related. Figure 3.3.1 is a time-structure map of the Sable Slope Canopy with four colored polygons representing broad regions containing the following play types:

1. Minibasins and inverted structures loading the advancing salt sheet

2. Three way closures against salt stocks and subsalt traps

3. Minibasins and inverted structures loading salt stocks

4. Minibasins and inverted structures loading the salt canopy and subsalt traps.

Figures 3.3.2 a) and b) are enlarged versions of the depth-structure maps shown in Figures 3.2.13 and 3.2.14. These images are focused on the region landward of the canopy to illustrate the trend of

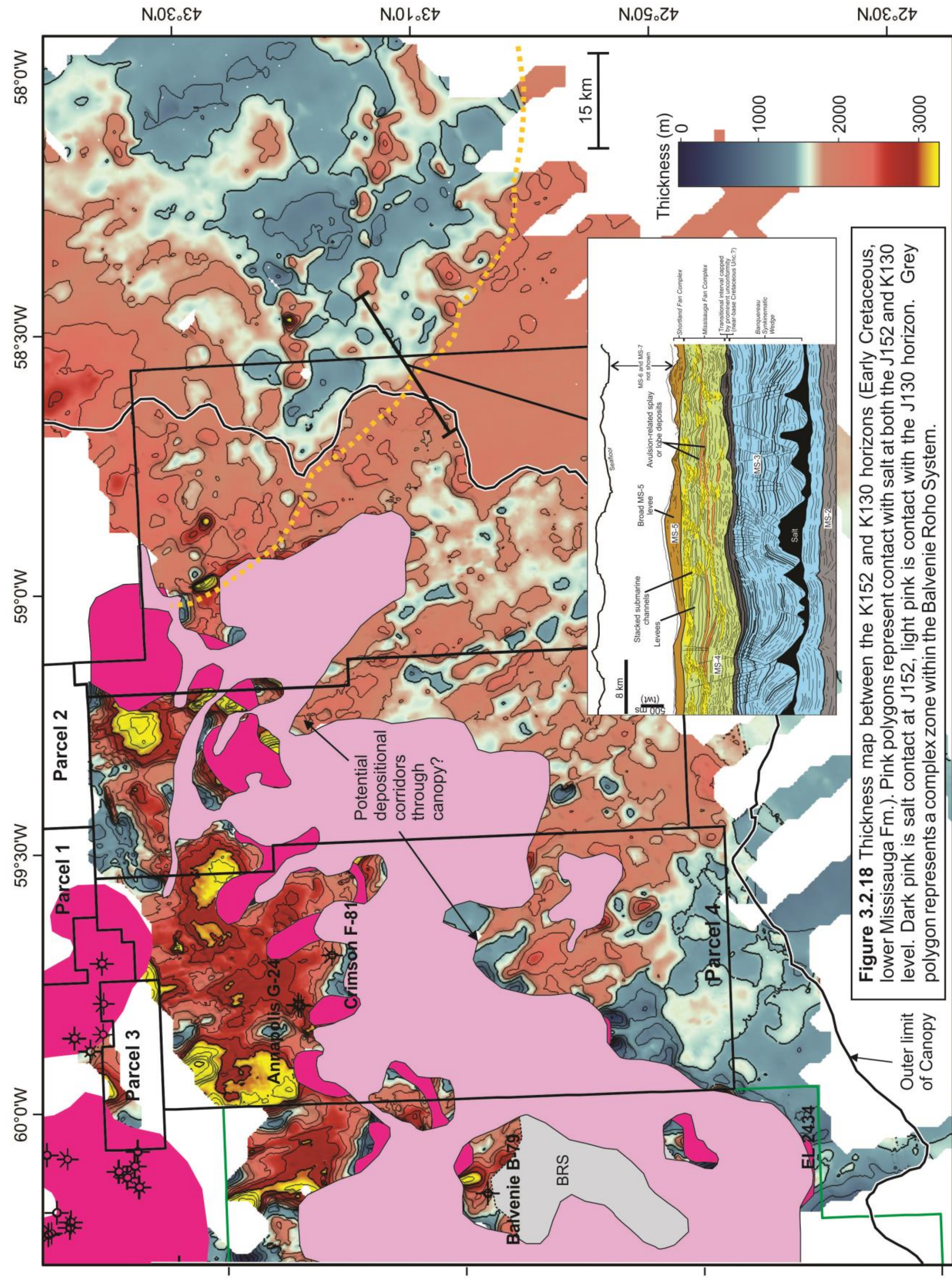


Figure 3.2.18 Thickness map between the K152 and K130 horizons (Early Cretaceous, lower Missisauga Fm.). Pink polygons represent contact with salt at both the J152 and K130 level. Dark pink is salt contact at J152, light pink is contact with the J130 horizon. Grey polygon represents a complex zone within the Balvenie Roho System.

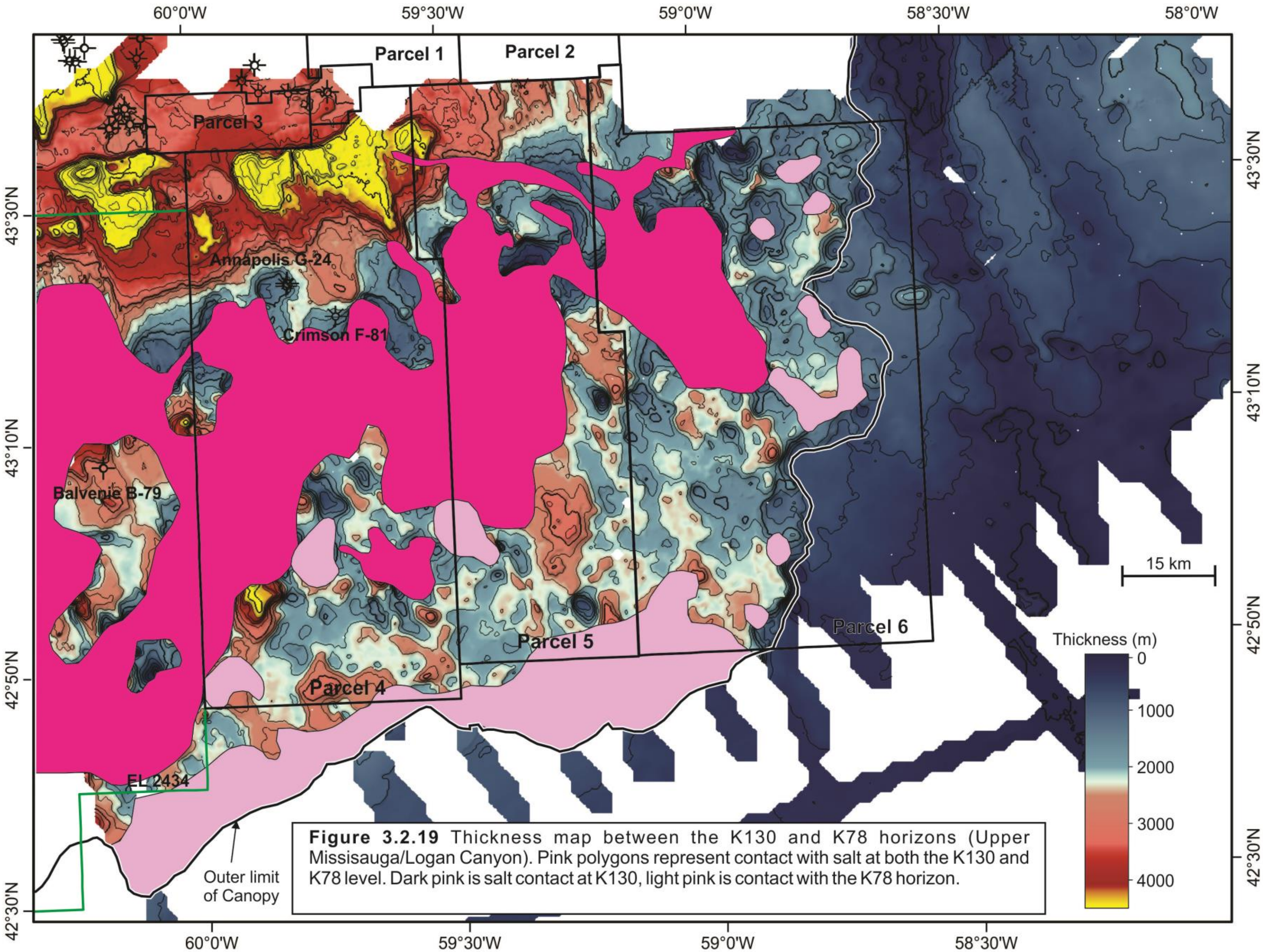


Figure 3.2.19 Thickness map between the K130 and K78 horizons (Upper Missisauga/Logan Canyon). Pink polygons represent contact with salt at both the K130 and K78 level. Dark pink is salt contact at K130, light pink is contact with the K78 horizon.

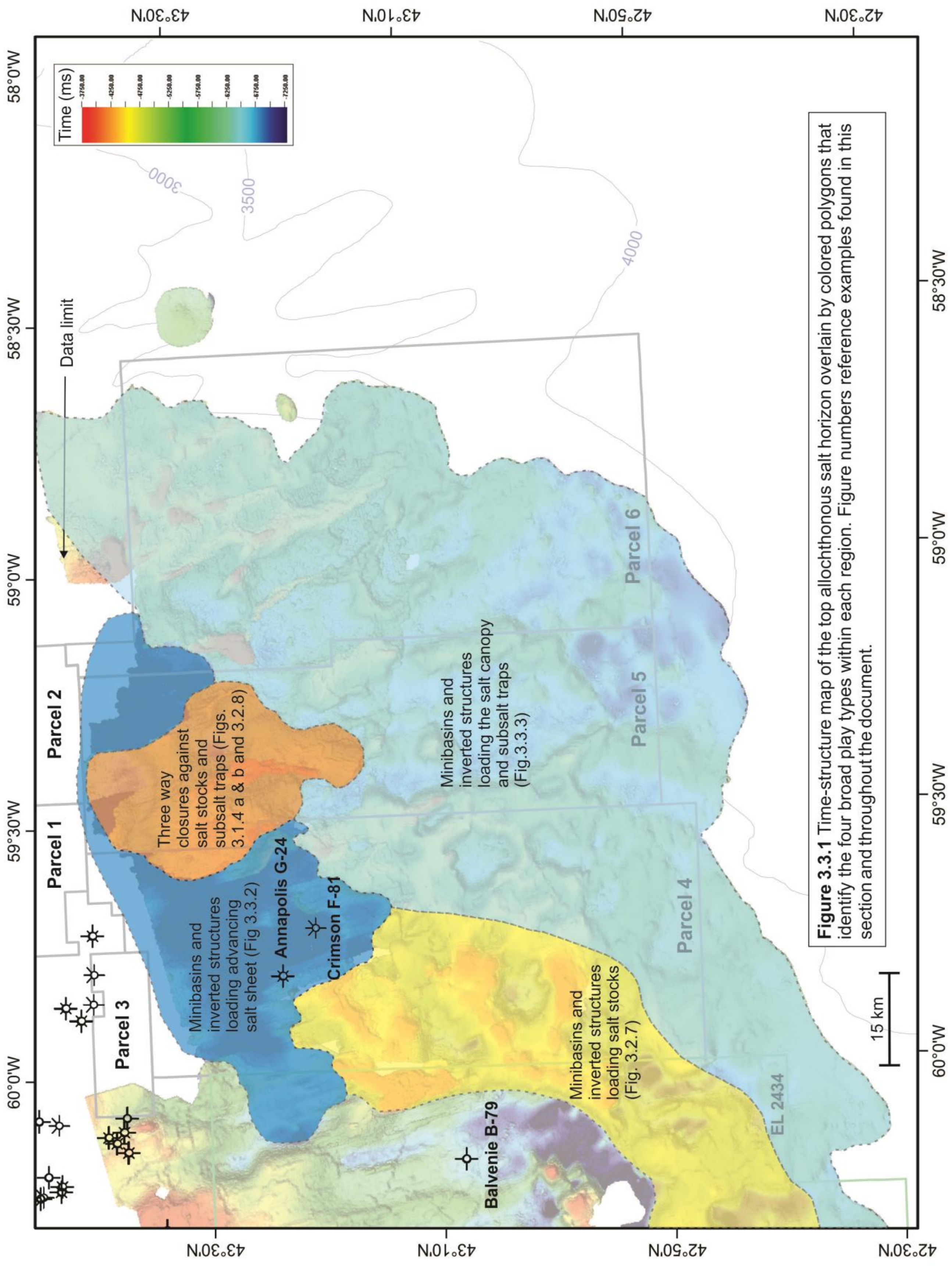


Figure 3.3.1 Time-structure map of the top allochthonous salt horizon overlain by colored polygons that identify the four broad play types within each region. Figure numbers reference examples found in this section and throughout the document.

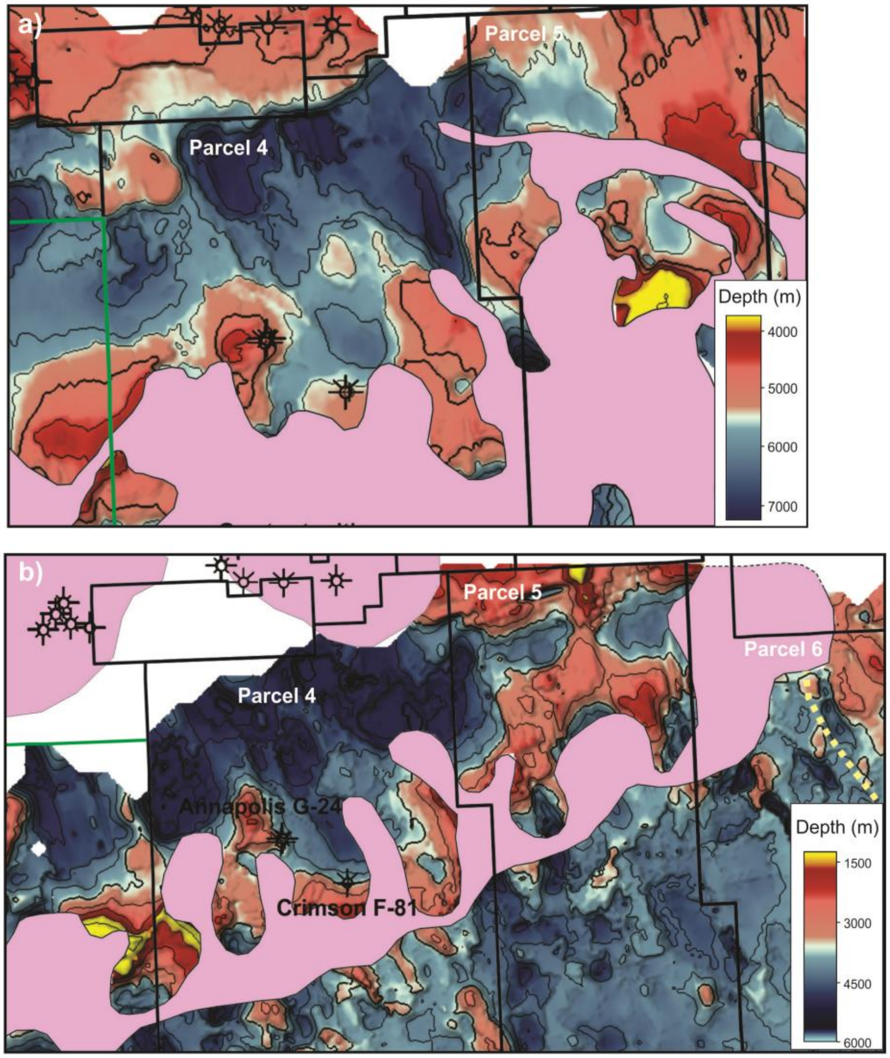


Figure 3.3.2 a) Enlarged view of the K130 structure map in the northern region of Parcels 4 and 5 where multiple Cretaceous age structural highs are evident inboard the developing salt canopy (same depth-structure map as shown in 3.2.14). **b)** Enlarged view of the J152 structure map in the northern region of Parcels 4 and 5 where multiple Jurassic age structural highs are evident inboard the developing salt canopy (same depth-structure map as shown in 3.2.15).

structural highs that developed here throughout the Jurassic and Cretaceous. Two of these highs are where the Annapolis and Crimson wells were drilled.

There are multiple three way closures against salt structures within the northern half of Parcel 5 (Figure 3.3.1). One particular closure, named Belleisle, consists of inverted Lower Missisauga strata. This structure, due east of the Annapolis and Crimson wells, is closed against salt and contains a thick Lower Missisauga section (Figure 3.1.4 b).

Aside from turtle structures located inboard the salt canopy, two other groups of turtle structures can be identified, those that load salt stocks (yellow polygon) and others that load the canopy (light blue polygon) (Figure 3.3.1). These are differentiated because they are located in two distinct locations. Salt stock loading basins/turtles are mostly present only within a narrow band extending through Parcel 4. Canopy loading basins/turtles are present in all three parcels, and an example of one of the larger turtle structures, Thorburn, is shown in (Figure 3.3.3).

Subsalt plays beneath the canopy are possible throughout Parcels 4-6. The thickness map shown in Figure 3.2.18 illustrates that thick deposits of Early Cretaceous age Lower Missisauga equivalents are located throughout the parcels. This is the sequence identified by Deptuck et al. (2014) as the Missisauga Fan Complex.

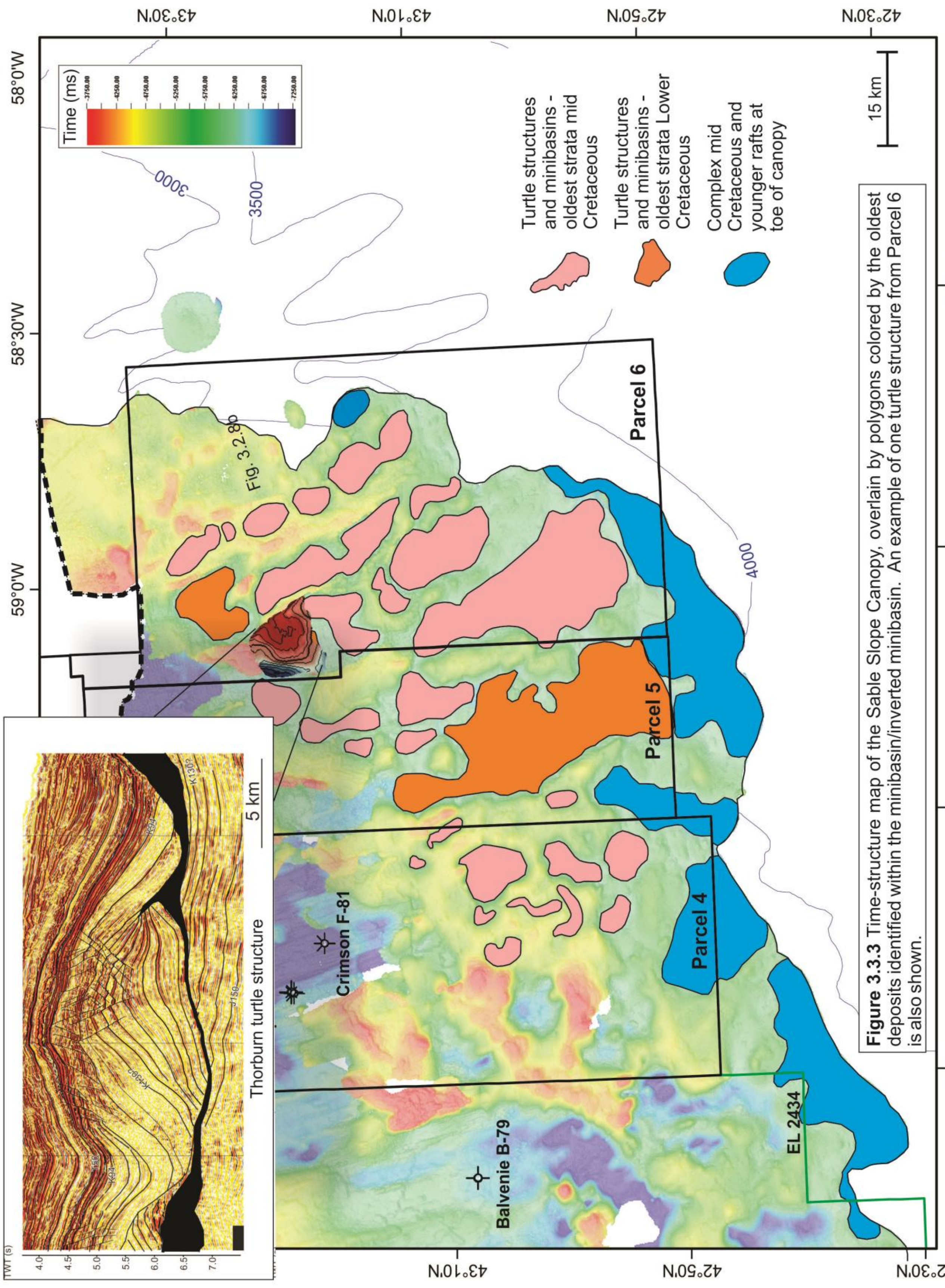


Figure 3.3.3 Time-structure map of the Sable Slope Canopy, overlain by polygons colored by the oldest deposits identified within the minibasin/inverted minibasin. An example of one turtle structure from Parcel 6 is also shown.

Potential Maturity of Cretaceous Source Rocks

As noted in the Source Rocks discussion (Section 4 of the website), the Naskapi Member has fair regional source rock potential with potential improvement in the deep water successions (e.g. Annapolis G-24: TOC~3%, HI=400). Figure 4.9 shows that this interval is mature within a southwest-northeast trending band that passes through the northern parts of the deepwater Call for Bids parcels. This trend of mature Aptian deposits is likely a result of increased burial depths due to an overlying Albian to Cenomanian sequence of clinoforms (see Figures 24 and 25 from Deptuck et al, 2014).

A second scenario to increase the maturity of younger high TOC intervals may also exist. Anomalously deep Early/Late Cretaceous salt withdrawal minibasins are present throughout the parcels (Figure 3.2.15). Naskapi member shales are present within some of these minibasins, and are also likely mature in these locations. This may extend the zone of maturity depicted in figure 4.9 further to the south.

Recent Atlantic IODP expeditions have encountered younger potential source intervals that may be present within these minibasins. In 2012 an IODP drilling program on the J-Anomaly Ridge east of the Scotian basin was targeting Paleogene Newfoundland Sediment Drifts (Figure 3.3.4). At site 1407, holes U1407A, U1407B, and 1407C all intersected an organic black shale interval that is interpreted to represent sedimentation during the Cenomanian-Turonian Oceanic Anoxic Event (OAE) 2 (Norris et al., 2014) (Figure 3.3.5). The black shale deposit related to this anoxic event has a maximum thickness across the three intersections of 44cm and TOC values that reach 11.6% (Norris et al., 2014). This is not the first North Atlantic intersection of the OAE 2 interval; Site 1276 within ODP leg 210 offshore Newfoundland also identified the OAE 2 interval, as well as site 603 of DSDP project 93 (Herbin et al., 1987). The TOC values reach 11.7% at site 1276 and 12.7% at site 603. (Arnaboldi and Meyers, 2006; van Bentum, 2012).

Recent studies of the Aptian Naskapi Member in cores offshore Nova Scotia have also identified what appears to be higher TOC shales related to the Selli Event (OAE 1a)(Chavez et al, 2016). The number of encounters of Cretaceous aged anoxic events in the North Atlantic has been increasing.

While these anoxic events have very high TOC values, the intervals are thin with very low thermal maturities. The Cenomanian/Turonian boundary lies near the base of the salt withdrawal minibasins where burial depths approach 4000 m and the thickness of the OAE 2 deposits are potentially greater (Fig 3.3.6). On the assumption that the OAE 2 is present within these minibasins, a preliminary run of this scenario using Petrel's "Quick Look- Maturation" program was completed. This simple model used a basic heat flow gradient of 30^{o}C/km (temperature gradient based on analysis of present day bottom hole temperatures from the Annapolis and Crimson wells) but did not account for any localised enhanced heating effects of nearby salt bodies. Most importantly, the K78 seismic horizon (a younger, shallower seismic horizon) was used as a proxy to represent the Cenomanian/Turonian seismic event. This K78 surface was bulk-shifted to be 500m deeper and more accurately represent the burial depths of the OAE 2 event (Figure 3.3.6).

The results of this simple model show the base of the minibasins have transformation ratios approaching 80% (Figure 3.3.7). The transformation ratios in Figure 3.3.7 are expected to be higher when more precise inputs for burial history and heat flow are used. Nevertheless, this model demonstrates that if this OAE 2 event is indeed present within the basal deposits of these minibasins, it may be reaching maturity. It is not considered to be a significant source rock in this region as the volumes generated from these localised areas would be relatively small; but scenarios accounting for a mature Turonian/Cenomanian (OAE 2) interval should be studied further.

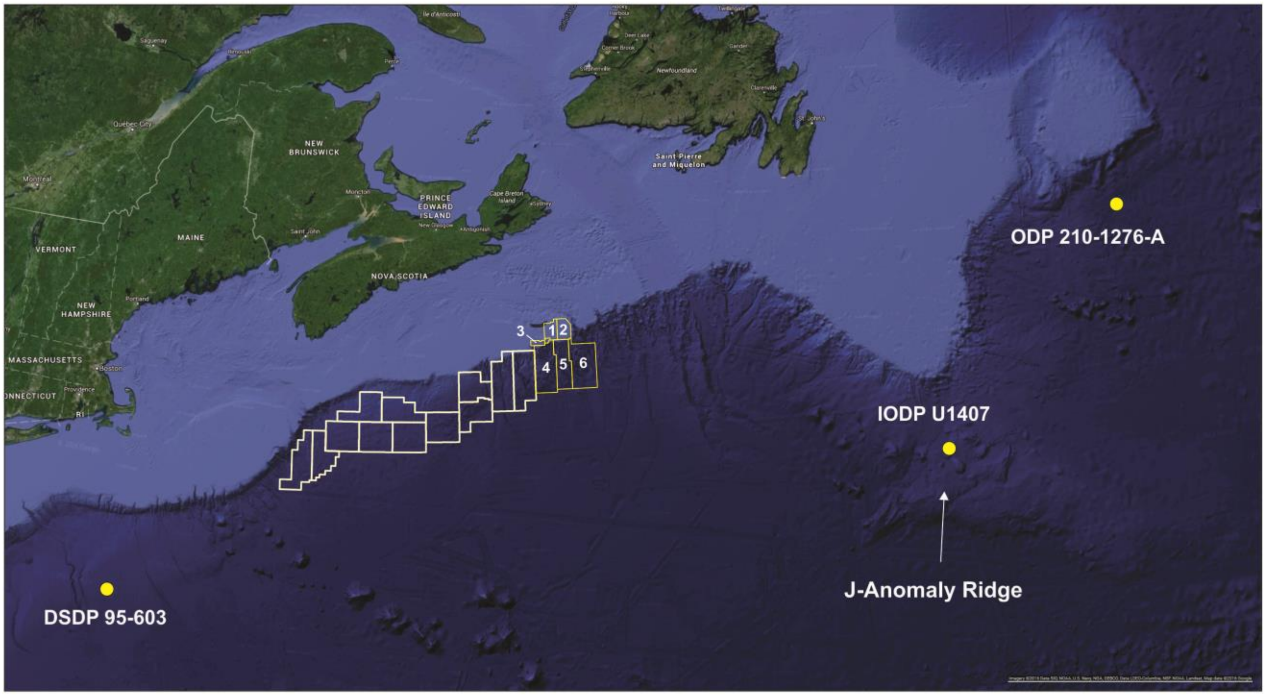


Figure 3.3.4 Locations of International Ocean Discovery Program (IODP) core holes that encounter Cretaceous Anoxic events, active offshore Nova Scotia Exploration Licences and the CFB NS16-1 parcels. Imagery from Google.

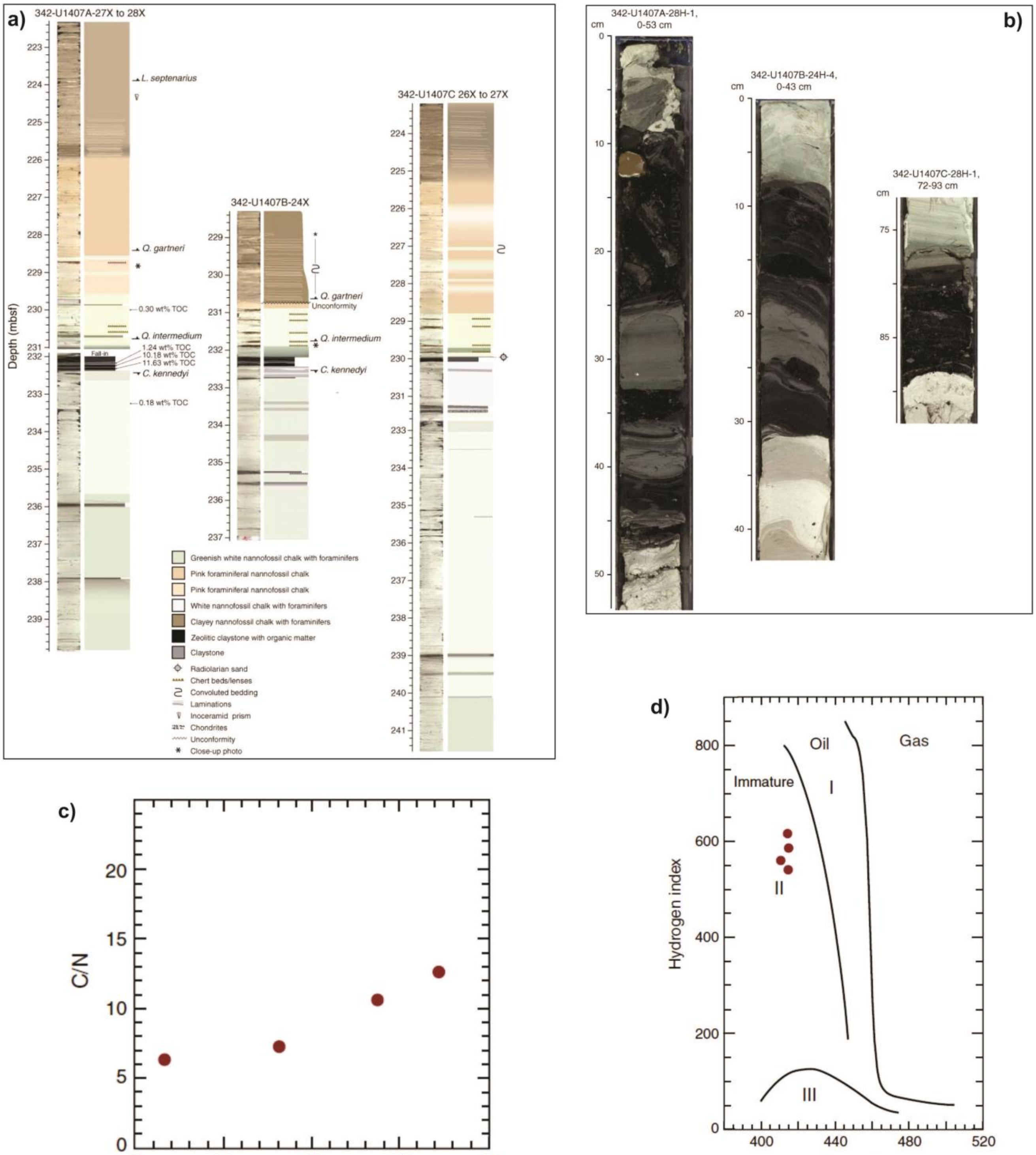
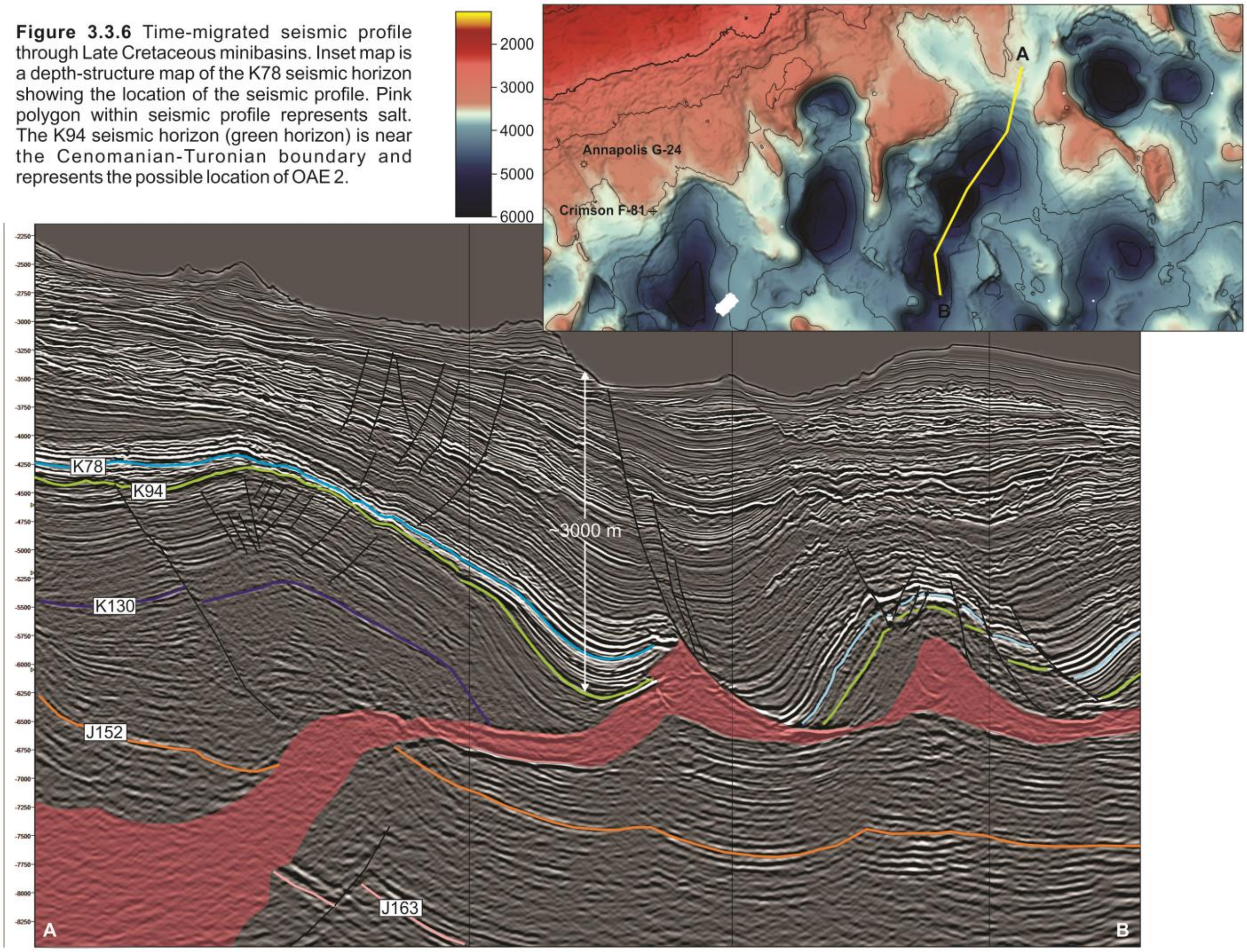


Figure 3.3.5 a) Core photographs of U-1407A, U-1407B and U-1407C. **b)** Core photographs of the black shale intervals encountered **c)** Total Organic Carbon (TOC) plot for the OAE 2 interval in core hole 1407A **d)** Hydrogen index plot for the OAE 2 interval in core hole 1407A (Figures and graphs edited from Norris et. al, 2014)

Figure 3.3.6 Time-migrated seismic profile through Late Cretaceous minibasins. Inset map is a depth-structure map of the K78 seismic horizon showing the location of the seismic profile. Pink polygon within seismic profile represents salt. The K94 seismic horizon (green horizon) is near the Cenomanian-Turonian boundary and represents the possible location of OAE 2.



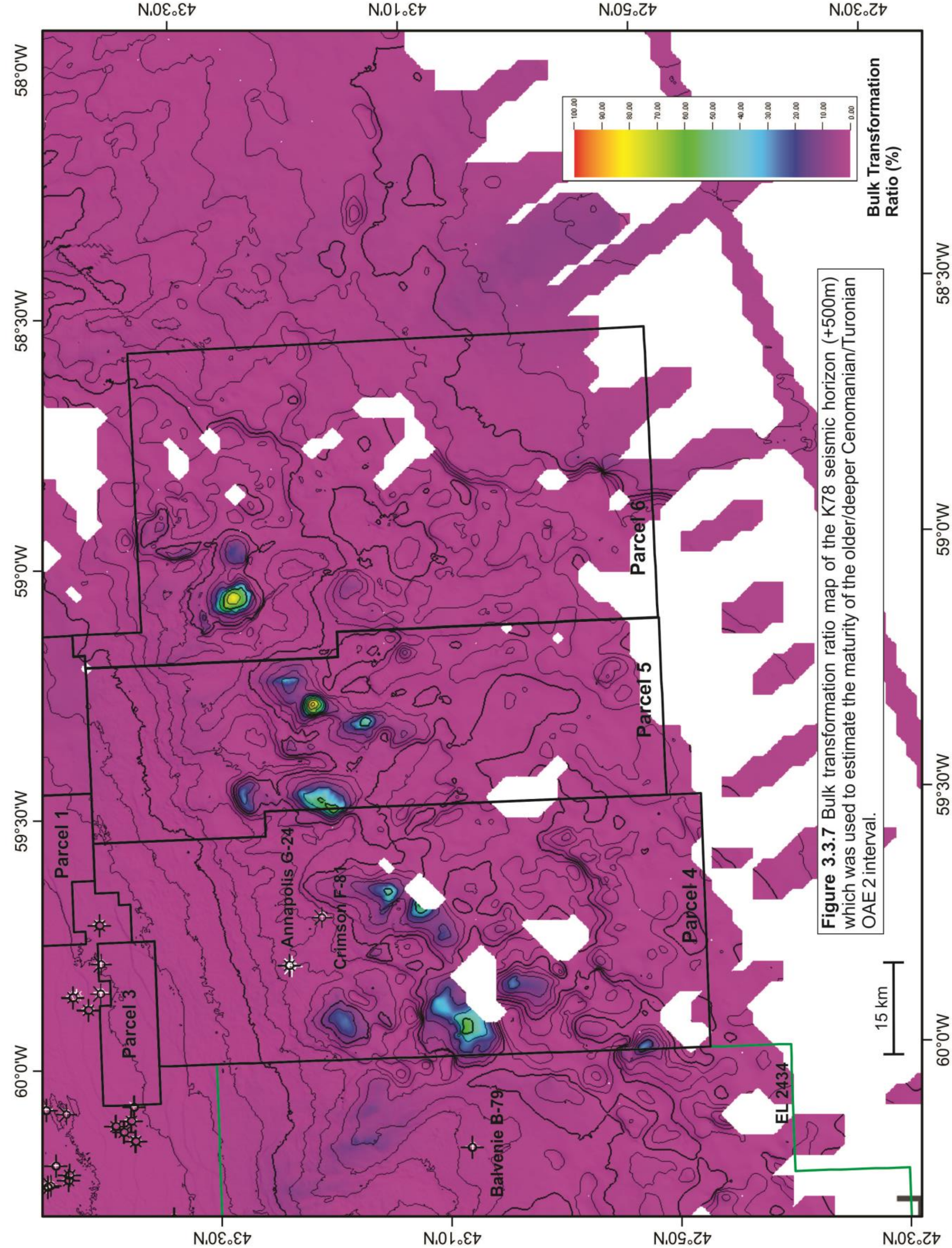


Figure 3.3.7 Bulk transformation ratio map of the K78 seismic horizon (+500m) which was used to estimate the maturity of the older/deeper Cenomanian/Turonian OAE 2 interval.

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