The 'slope detachment zone' on the western Scotian Slope, offshore Nova Scotia: structural style, timing, and implications for margin evolution*

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ABSTRACT

The 'slope detachment zone' (SDZ) is a region of raft tectonics developed above a variably thick autochthonous salt layer on the western Scotian Slope. Detachment of cover strata was likely initiated in the Early to Middle Jurassic and is probably coincident with the development of the margins hinge zone, across which basement depth plunges abruptly. Associated thin-skinned faulting and folding continued above the autochthonous salt layer or its primary weld until the mid to Late Cretaceous. Decoupling of the deformation styles in the basement and cover strata in some cases resulted in reversals in the polarity of extensional faults above and below salt. Deformation of cover strata and the patterns of salt withdrawal were strongly influenced by basement topography, but it is not yet clear to what extent thick-skinned extension influenced the structural evolution of the SDZ.

KEYWORDS: Nova Scotia, Salt, Raft Tectonics, Thin-skinned Deformation, Autochthonous Salt

1. Introduction – Slope Detachment Zone

Regional 2D and 3D seismic mapping efforts reveal a *ca.* 350 km long and *ca.* 15 to 55 km wide structurally distinct region covering more than 13 000 km^2 on the central and western parts of the Scotian Slope, offshore Nova Scotia. This region, referred to here as the 'Slope Detachment Zone' (SDZ), runs parallel to, and outboard of, the Jurassic carbonate bank and is characterized by the distinct scarcity of allochthonous salt diapirs in present day water depths that are generally between 500 to 2500 m (Fig. 1). It encompasses roughly 30% of the total area of the Scotian Slope in water shallower than 2500 m, and as such it is of significant economic and academic interest (in terms of understanding deep water petroleum systems and margin configuration and evolution). Because there are few overhangs associated with allochthonous salt diapirs in the SDZ, crustal seismic markers and faults, the autochthonous salt layer, and cover strata are locally well imaged on reflection seismic profiles. The landward edge of the SDZ closely corresponds to the structural hinge zone that parallels the Upper Jurassic carbonate bank. It separates a relatively stable platform with localized rift basins to the north, from heavily faulted and significantly thinned continental crust to the south. Its distal limit, as defined here, corresponds to the landward edge of the 'slope diapiric province' (Wade and MacLean, 1990) comprised dominantly of allochthonous salt diapirs and walls (Fig. 1). This short paper provides an introduction to the dominant structural styles in the SDZ, and provides some preliminary constraints on timing and significance.

2. Basement structure

Within the SDZ, strong decoupling is recognized between the structural styles above and below a seismically amorphous interval interpreted as an autochthonous salt layer corresponding to the Upper Triassic to Lower Jurassic Argo Formation (Fig. 2). The basement morphology below the autochthonous salt layer (or its associated primary weld) is commonly rugose, with abrupt offsets believed to have been produced by a complex arrangement of horsts and grabens or half-grabens that developed during rifting (note that in this paper the

term 'basement' refers to any rocks below the autochthonous salt layer or its primary weld, and the term "autochthonous 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). The absolute relief of basement structures is highly variable across the SDZ, but locally exceeds 1 s two-way time. Using velocities derived from refraction seismic (Wu et al., 2006), the present-day graben-to-horst relief thus can be in excess of 2.5 km (using upper crust velocities of 5 to 6 km/s).
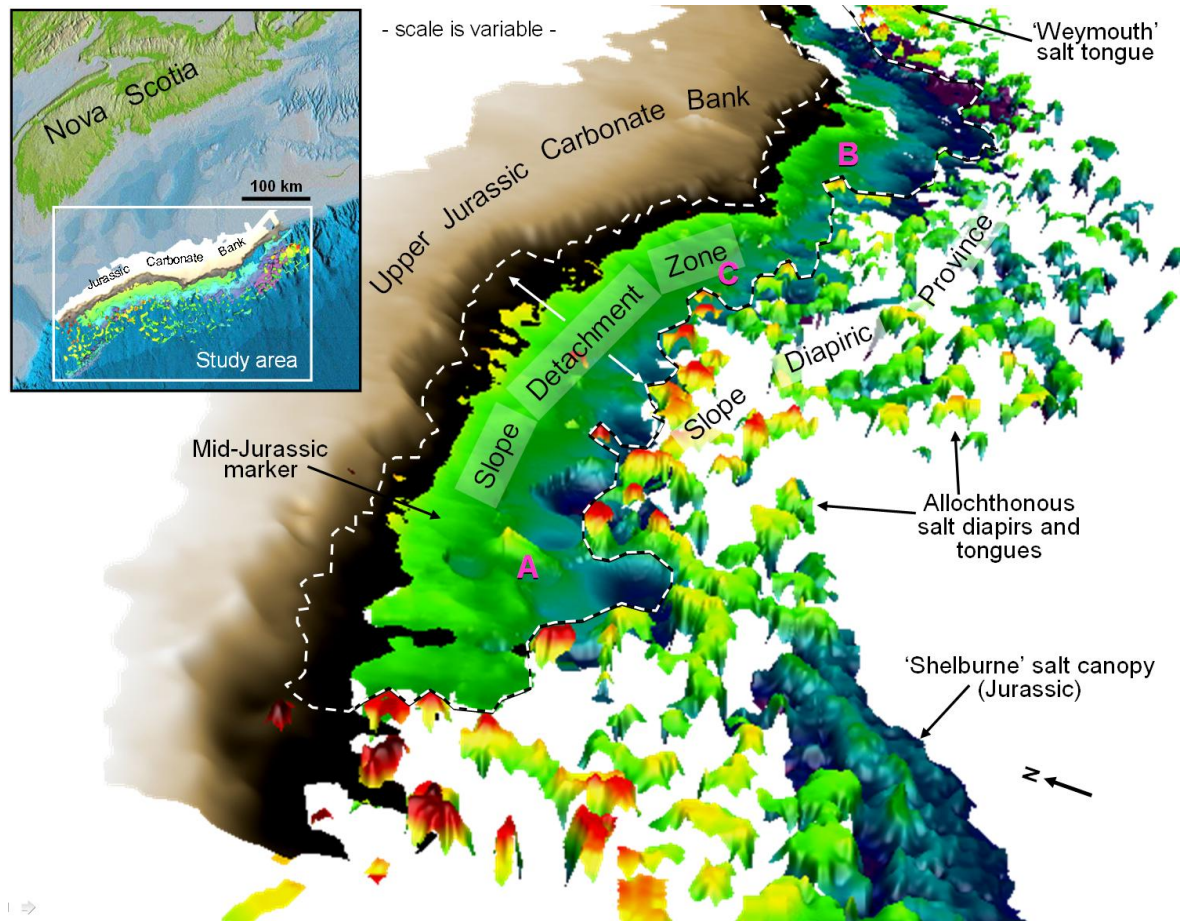

FIG.1 – Perspective view from the southwest showing the relationship between the carbonate bank edge, slope detachment zone, and allochthonous salt bodies (collectively referred to as the 'slope diapiric province' by Wade and MacLean, 1990) on the SW Scotian Margin. The 'slope detachment zone', located between the seaward edge of the Jurassic carbonate bank and the landward edge of the slope diapiric province (dashed boundary), is characterized by the distinct absence of allochthonous salt diapirs. It is an area dominated by raft tectonics above a thin autochthonous salt layer. Location of the study area is shown in the inset. "A" identifies the location of figures 2, 4, and 5 and "B" identifies the location of figure 3. "C" identifies region of thicker autochthonous salt in the central parts of SDZ.

In area "A" (Fig. 1) extensional basement faults dip towards the NW and bound *ca.* 1 to 4 km wide basement blocks with NE trending long axes that can be followed along strike for up to 20 km. In area "B" basement faults are more difficult to map but two NE trending basement highs are believed to correspond to horsts or the rotated hanging walls of half-grabens that can be followed along strike for > 25 km. In general, these positive-relief basement structures appear to have focused salt expulsion from negative-relief grabens or half-grabens (Figs. 2-3). The orientation of these basement lineaments is consistent with the orientation of a series of synrift horsts and grabens or half-grabens north of the SDZ below

the carbonate bank (Emerald, Naskapi, Mohican, and Mohawk basins and ridges of Welsink et al., 1989).
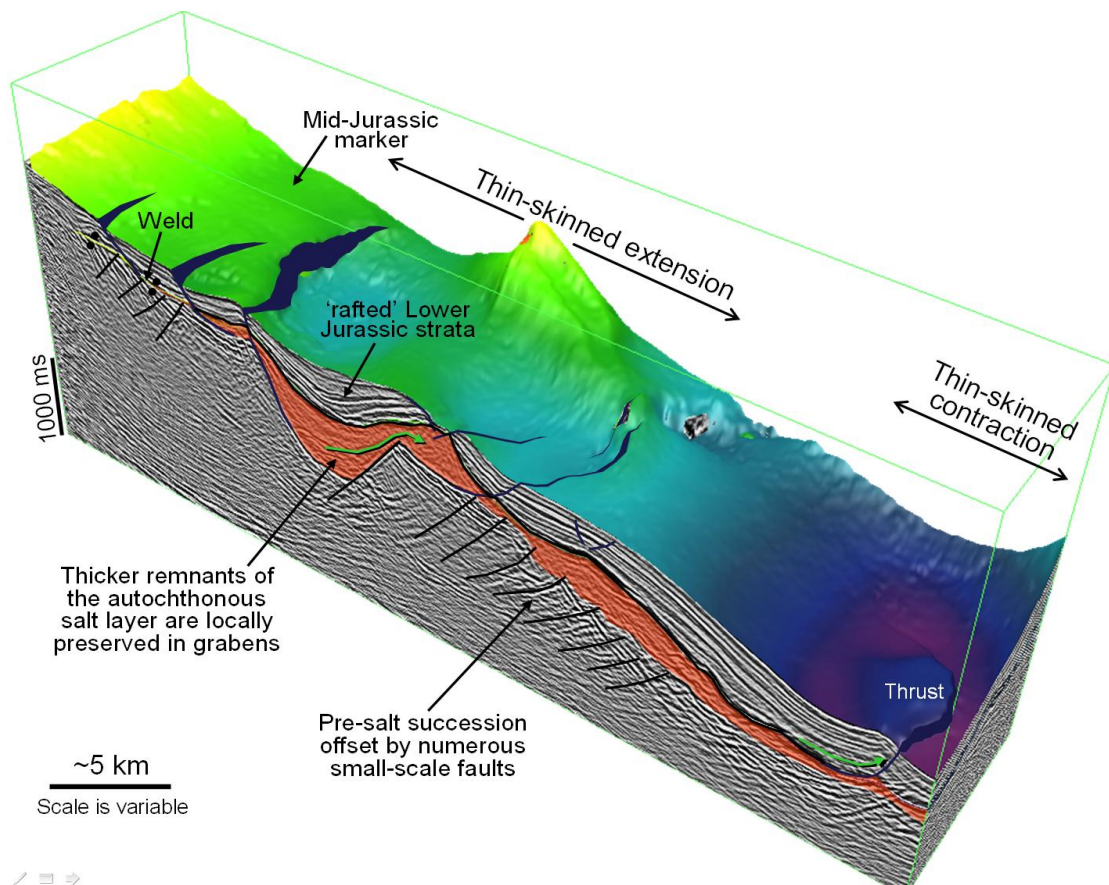

FIG.2 – Perspective view 3D seismic image across the SDZ showing both thin-skinned extension (upslope) and contraction (down-slope) of Lower Jurassic strata above the autochthonous salt layer. Thicker remnants of the autochthonous salt layer are locally preserved within grabens, and the edges of faulted basement blocks commonly localize diapirism. See figure 1 for location (A)

3. Deformation in Jurassic cover strata

The deformation style within the Lower to Middle Jurassic cover strata above the autochthonous salt layer (or its primary weld) is dominated by thin-skinned detachment and associated raft tectonics. Both extensional and contractional structures are recognized (Fig. 2). Jurassic strata are commonly offset along listric growth faults that sole out in the autochthonous salt layer. These faults define the headward parts of detached 'slabs' of Jurassic strata, and are commonly composed of a series of shorter arcuate fault traces that link-up across relay ramps in the cover strata to produce longer detachment trends extending along strike for > 60 km. Detachment above the autochthonous salt layer appears widespread across the SDZ and Jurassic cover strata are commonly offset at very low angles. Rafts of pre-kinematic Lower Jurassic strata can be offset horizontally by > 8 km across these faults, but more typically have translated < 2 km relative to the most proximal listric fault. Arcuate salt rollers (plan view) within the autochthonous salt layer are common, with some rollers forming linear salt highs that coincide with the sheared margins of rafted slabs. The headscarps of some detached slabs coincide with the steep flanks of underlying basement fault blocks, presumably because of the increased propensity for gravity sliding (detachment) in such areas (e.g. Fig. 3). Where the autochthonous salt basin extends northward below the Jurassic

carbonate bank, parts of the outer bank foundered in a similar manner, with rotated limestone dominated blocks as thick as 1.2 s (twt) detaching above the autochthonous salt layer.

In general, slab detachment is normal to the Jurassic carbonate bank, however, the orientation of positive-relief basement blocks locally alters the detachment trajectory (e.g. on the left side of Fig. 3, a NE trending basement horst diverts the detached cover strata toward the SW). Rotation on some steeply dipping raft blocks raised their down-dip parts above regional grade, producing local angular discordances where rafted Jurassic strata abruptly terminate (e.g. Fig. 2) and are draped by Cretaceous strata. In most cases these angular discordances were generated by fault offsets in the cover strata, but in some instances they could be the product of erosion. Inflated salt or high relief basement blocks may underlie these highly rotated rafts. Locally, detachment appears to be antithetic (faults dipping towards the hinge zone), particularly in the central parts of the SDZ (area "C" in Fig. 1) where a thicker interval of autochthonous salt appears to be preserved below cover strata (compared to the NE and SW parts of the SDZ).

In the southern parts of the SDZ, there is an increased tendency toward contractional structures, including detachment folds, fault propagation folds, reverse faults and thrust faults. The down-slope contractional response in some areas is quite complex, producing squeezed salt stocks, folds with variably oriented axes, and reverse/thrust faults with variable vergence. Fold axes commonly vary abruptly (by as much as 90º) over short distances (Deptuck et al., 2009). In some instances down-building strata within grabens were buttressed against the flank of a basement block, and equivalent strata deposited above the adjacent horst were partially overthrust above the graben, producing repeated sections. Contractional structures continue into the slope diapiric province where diapirs and minibasins are commonly squeezed (Shimeld, 2004).
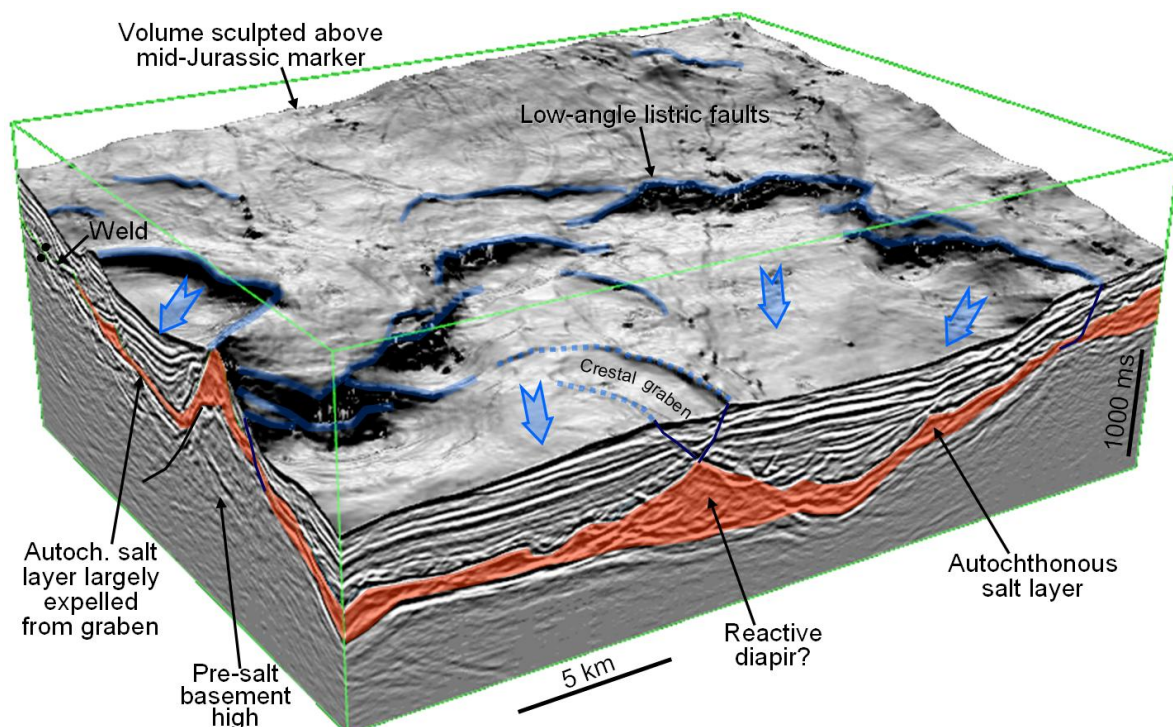

FIG.3 – Perspective view 3D seismic image across the SDZ illustrating the dominant style of slope detachment, with low-angle listric faults that sole out in the autochthonous salt layer. Blue arrows show direction of slab detachment. Note the preferential expulsion of salt along the edge of the pre-salt basement high. See figure 1 for location (B).

4. Timing of thin-skinned detachment

The timing of onset of slope detachment is difficult to determine because few wells are available to calibrate the age of seismically defined stratigraphic intervals above the autochthonous salt layer. The earliest deposits above the autochthonous salt layer also show evidence of thinning and thickening that are associated with a period of passive down-building into autochthonous salt and the minibasins that developed appear to predate the onset of raft tectonics. It can be difficult to distinguish these thickness variations from synkinematic growth strata associated with the raft tectonics and gravity gliding. Still, some general constraints are available. Strata of probable Early Jurassic age are characterised by a combination of prekinematic rafts and potentially synkinematic growth strata, and hence development of the SDZ could have started as early as the Early Jurassic. Most Middle to Upper Jurassic stratigraphic intervals show growth across the listric faults along the headward parts of rafts, making it clear that detachment was underway by this period. However, it is also clear that detachment of rafts was a diachronous process. For example, foundering pre-kinematic Upper Jurassic strata on the outer carbonate bank clearly took place in the latest Jurassic or earliest Cretaceous, long after the onset of rafting in, for example, area "B". Detachment of thick carbonate blocks on the outer margin of the bank probably represents a younger retrogressive response along the margin hinge zone, across which the slope steepens abruptly.
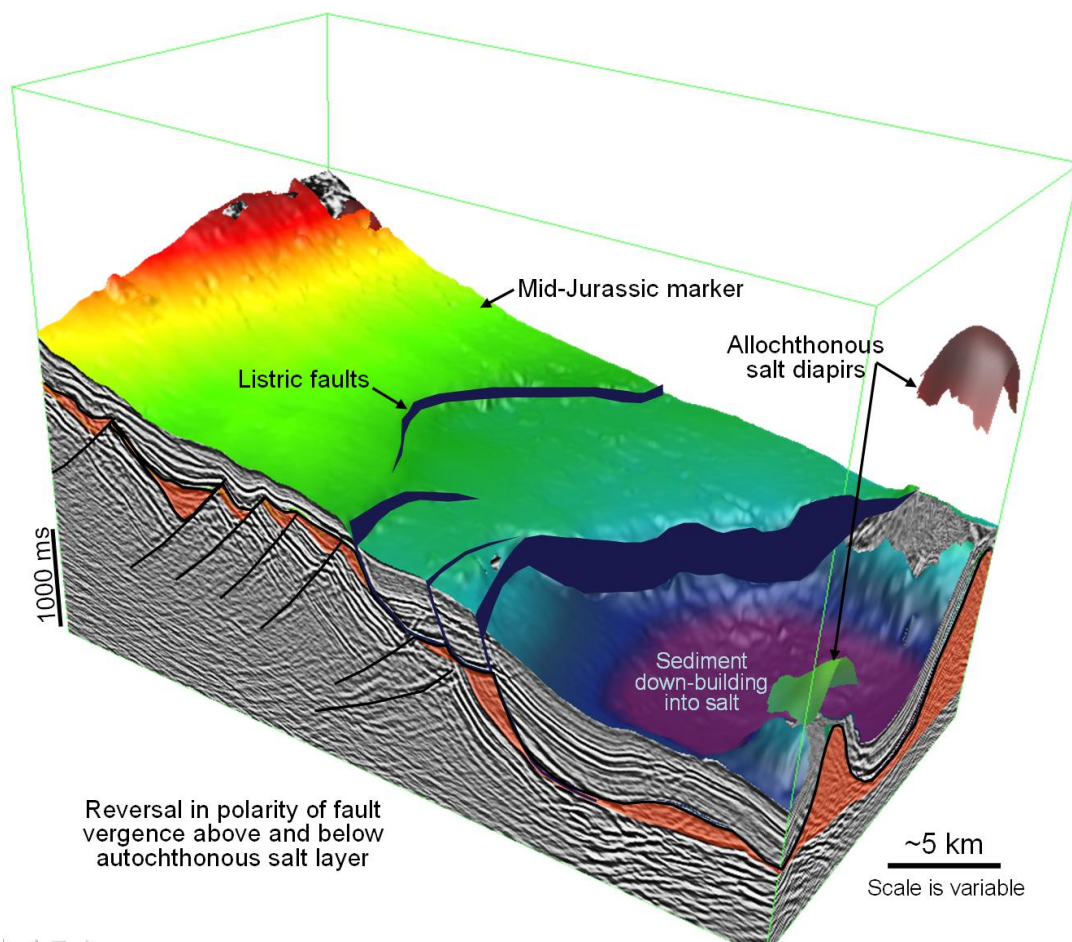

FIG.4 – Perspective view 3D seismic image showing a series of landward-dipping extensional basement faults forming a series of small half-grabens overlain by a thin interval of autochthonous salt. Lower Jurassic cover strata detach above the salt with faults dipping in the opposite direction. Right side of image transitions into the slope diapiric province with allochthonous salt diapirs.

Some listric faults continued to offset strata as young as Late Cretaceous. Likewise, fold development associated with detachment in the autochthonous salt layer in some cases also continued to deform strata as young as Late Cretaceous. As such, the onset of slope detachment may have started as early as the Early Jurassic, but was almost certainly in full swing by the Middle to Late Jurassic, and appears to have continued in a more subtle way into the mid to Late Cretaceous.
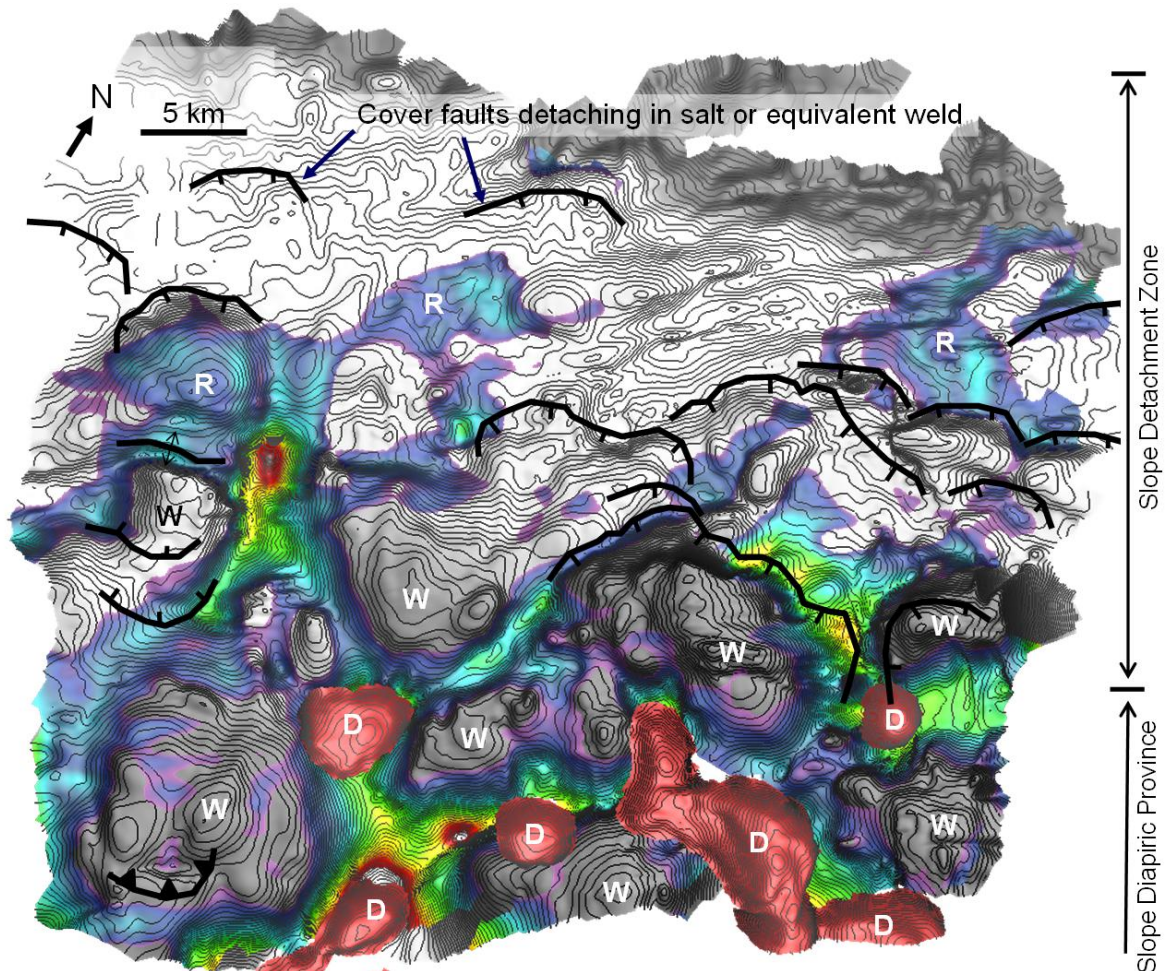

FIG.5 – Autochthonous salt time-thickness map draped on the top autochthonous salt structure map in area "A". Also shown are the faults in the cover strata that detach in the autochthonous salt layer. Red = areas where salt is greater than 1500 ms thick. Using 4400 m/s (see Shimeld, 2004), this corresponds to salt that is thicker than 3.3 km. Areas not coloured show salt that is below 100 ms (twt) or 220 m thick; R = remnants of salt preserved in grabens or half grabens (see Fig. 2); W = welded minibasins haloed by rims of inflated autochthonous salt; D = allochthonous salt diapirs on landward edge of slope diapiric province.

5. Why so few allochthonous salt diapirs in the SDZ?

The lack of allochthonous diapirs over much of the SDZ is believed to reflect regional variations in the original depositional thickness of autochthonous salt layer, with more salt originally accumulating in the slope diapiric province. A 3D seismic volume from area "A" (Fig. 1) spans the width of the SDZ, extending from the margin hinge zone to the landward edge of the slope diapiric province. It provides insight into the complex transition from areas of the LaHave Platform with no salt, to deepwater areas with a high density of allochthonous

salt bodies. A salt thickness map from area "A" shows a proximal to distal transition from thin or absent salt, to locally preserved (and partially expelled) intervals of thicker salt within grabens and half-grabens (R) (e.g. Fig. 2). These pass down-slope into sub-circular minibasins rimmed by halos of inflated autochthonous salt (W) (e.g. Fig. 4). Most salt was expelled from the centers of these basins, the seaward margins of which marks the first occurrence of allochthonous salt diapirs and the transition into the slope diapiric province (Fig. 5). Further seaward still (to the SE), most minibasins are flanked on all sides by expelled allochthonous salt bodies. In area "A" and elsewhere along the SDZ, there is little evidence to suggest that much salt moved more than a few km seaward from the source bed during sediment loading and detachment. Instead, significant Jurassic and Cretaceous sediment down-building took place primarily along a chain of sub-circular minibasins similar to the ones shown in Fig. 5. These minibasins parallel the seaward boundary of the SDZ, with down-building accommodated by salt expulsion focused along the landward edge of the slope diapiric province (e.g. Fig. 4). Some of these minibasins developed into turtle structures. A few salt diapirs lean seaward, but salt climbs no more than a few km across time-equivalent stratigraphic intervals. Likewise, expulsion rollovers are not observed and sediment down-building dominates the slope diapiric province seaward of the SDZ (Shimeld, 2004).

The northwestern part of Fig. 5 (left side of Fig. 2) is interpreted to approximate the depositional edge of the original autochthonous salt basin in area "A". Although local areas of increased salt thickness are found in basement grabens and half-grabens, the general transition from thin or no salt above an irregular, tightly faulted basement terrain, to sub-circular depressions rimmed by swelled autochthonous salt, is interpreted to correspond to an overall increase of salt thickness towards the primary salt basin (Fig. 5). The chain of minibasins along the leading edge of the slope diapiric province probably defines the approximate boundary across which autochthonous salt was more widely deposited and consistently thick. A significant downward step in basement elevation commonly takes place across a complex series of faulted basement blocks below these minibasins (e.g. Fig. 4), and may have provided more accommodation space for salt to accumulate.

The development of extensional and contractional structures in the cover strata is believed to have been prompted by tilting of the generally tapered margin of the primary salt basin (i.e. the SDZ) during Jurassic thermal subsidence after continental break-up. As such, the onset of raft tectonics is inferred to coincide with the initial development of the margins hinge zone, an Early Jurassic feature that overprinted pre-existing rift basins (Wade and MacLean, 1990). Landward of the hinge zone, localized fault-bounded salt accumulations below the carbonate bank (e.g. Mohican Graben complex, see Wade and MacLean, 1990) were largely unaffected by tilting. The reversal in polarity of thin-skinned extensional faults above the autochthonous salt layer in the SDZ, on the other hand, provides direct evidence for an abrupt change in subsidence seaward of the margin hinge zone initiated some time after sediment down-building onto the autochthonous salt layer had already begun.

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