



Complex deepwater fold-belts in the SW Sable Subbasin, offshore Nova Scotia

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Summary

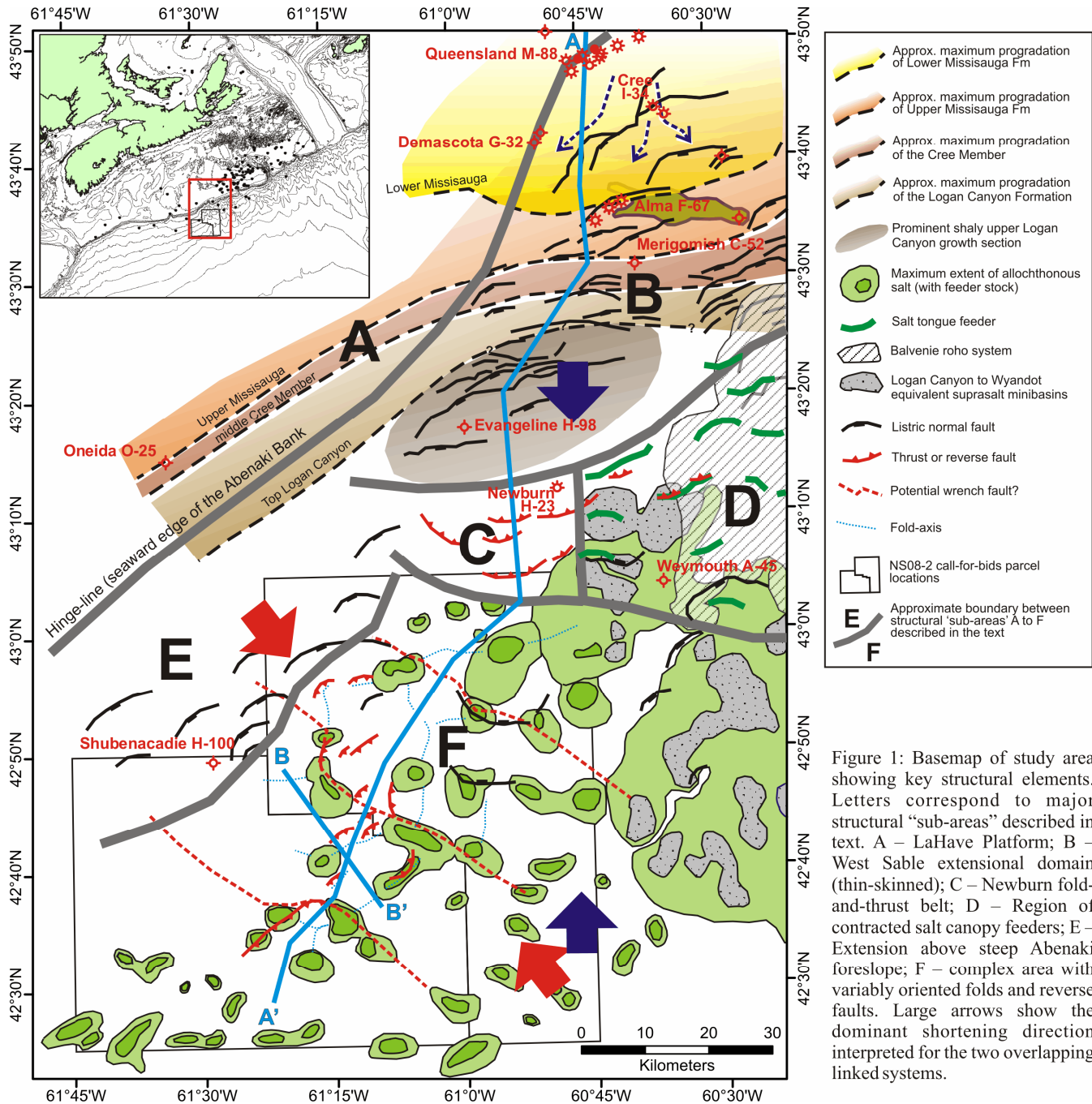
As exploration for oil and gas moves into deeper water areas off Nova Scotia, improved understanding of local salt tectonics is needed to better understand the types, timing and genesis of potential hydrocarbon-bearing structures. Numerous large contractional structures (folds, thrust/reverse faults) were identified in deepwater areas along the central Scotian Margin, and their development is the focus of this paper.

Introduction

The Scotian Basin, located offshore Nova Scotia, has undergone a complex structural history strongly influenced by salt tectonics. Spatial variations in salt-sediment-basement interaction across the margin have produced several distinct salt tectonic domains documented in previous studies. This paper focuses on the central Scotian slope, near the boundary between tectono-stratigraphic subprovince II (dominated by isolated salt diapirs) and III (major salt canopy system) as defined by Shimeld (2004). More than 5300 km² of time-migrated 3D seismic data span the subprovince II to III boundary, allowing detailed mapping of primary structures like folds and faults, and providing information about sediment thickness distribution through time. The types and distribution of structures, and their interpreted genesis, help constrain the deformation history across what appears to be a key geological boundary off Nova Scotia. Based on the orientation and distribution of Jurassic and Cretaceous structures, as well as salt tectonic lineages, the study area is subdivided into six structural 'sub-areas' (A through F - Fig. 1) that appear to define two overlapping linked extensional-contractional systems.

Linked system 1 – north to south extension-contraction (normal to Sable Island delta clastic input)

Sub-area B is dominated by thin-skinned extension recorded by E-W to NE-SW oriented listric growth faults that sole out at multiple levels. The deepest detachments occur above the autochthonous salt layer (or its corresponding weld), with some faults soling out at shallower levels, either above overpressured(?) shale or allochthonous salt intervals (or corresponding secondary welds) (Fig. 2). Extension in Sub-area B is associated with a major clastic depocenter that records the S to SW advance of Jurassic and Cretaceous deltaic systems in the western Sable Subbasin (Fig. 1). Up-slope extension was balanced to the south by contraction, where folds, thrust faults, and squeezed salt feeders were mapped in Sub-areas C, D, and F. The contractional response varies along strike, across the subprovince II and III boundary. To the west, in Sub-area C, contraction produced a ~30 km long arcuate pattern of detachment folds in Jurassic(?) and Cretaceous strata, collectively referred to here as the "Newburn fold-and-thrust belt" (NFTB) (Fig. 1). The detachment folds are floored by seaward-vergent thrust faults that detach at similar stratigraphic levels as the listric faults in Sub-area B (Fig. 2). This implies a direct link between up-slope extension and down-slope contraction. The contractional structures are consistent with a north-south shortening direction, and likely formed in response to differential sediment loading in Sub-area B, combined with gravity gliding above an inclined basement floor. The tops of some detachment folds were truncated during Late Creta-



ceous erosion, indicating that fold growth took place prior to this time. To the east, in Sub-area D, a high concentration of welded seaward-leaning salt stocks is preserved between modestly deformed Jurassic and Cretaceous strata. In contrast to Sub-area C, here the contractional response to up-slope extension was largely accommodated through the closure of salt feeders, prompting the widespread expulsion of allochthonous salt into an amalgamated salt tongue canopy system above Sub-area D. This canopy later formed a prominent detachment surface for the "Balvenie roho system" during mid- to Late Cretaceous canopy roof sedimentation, expelling salt further S and SW into its current position (NE part of Sub-area F - Fig. 1). Strata between welded salt feeders in Sub-area D are commonly tilted seaward or form monoclinical folds associated with counter-regional expulsion rollovers/half-turtles. Such features are believed to have formed during passive loading of salt, but local reverse motion and potential drag folds along secondary welds (amplifying some monoclinical folds), suggest that later shortening was accommodated by Jurassic and Cretaceous strata after the salt source was depleted and feeders were welded. Cretaceous strata below the

detached and reactivated salt sheets in the NE part of Sub-area F are broadly folded, with potential salt-cored anticlines and rare feeders, but poor seismic imaging inhibits detailed structural mapping here.

Linked system 2 – northwest to southeast extension-contraction (normal to the steep Abenaki slope)

Normal to the stable LaHave Platform (Sub-area A), Jurassic strata on the steep Abenaki slope (Sub-area E) are commonly offset along low angle listric growth faults that detach within a relatively thin interval of autochthonous salt or across deeper-seated listric faults between rifted basement blocks. In contrast to Sub-area B, the relatively slow Jurassic sedimentation rates in Sub-area E imply that extension was not driven by differential sediment loading, but instead was prompted by over-steepening of the margin during thermal subsidence after continental break-up. The down-slope contractional response in Sub-area F was quite complex, producing squeezed salt stocks, folds with variably oriented axes, and reverse/thrust faults (Fig. 3). Most reverse/thrust faults are landward-vergent (in contrast to detachment folds in the NFTB), and are consistent with a dominant NW to SE shortening direction (roughly a 45° counterclockwise difference in shortening direction compared to ‘linked system 1’). Fold axes, however, show a 90° range in orientation (varying from E-W to N-S), reflecting a combination of other processes. The basement morphology below autochthonous salt is irregular, with abrupt offsets presumably produced by a complex arrangement of synrift horsts and grabens/half-grabens. Prior to shortening, Jurassic strata between the J350 and J265 markers were the first to load autochthonous salt in Sub-area F, forming a series of sub-circular minibasins (Fig. 3). Remnants of autochthonous salt form sub-circular rims around some early minibasins, with vertical salt diapirs preferentially extruded along the edges of basement blocks during down-building. Locally, inverted minibasins formed as salt evacuated and strata were ‘folded’ around positive-relief basement highs (similar to turtle structures, but above a non-planar basal surface). Hence the orientations of some folds reflect the orientation of basement highs. Preexisting salt diapirs are also known to localize deformation, forming structural trends oblique to regional shortening (Rowan and Vendeville, 2006; Hudec and Jackson, 2007). The onset of contraction (at about the J265 marker) took place when salt diapirs were already present in Sub-area F, continuing through much of the Cretaceous as variably oriented folds formed saddles linking squeezed diapirs. Finally, some degree of thick-skinned deformation in response to continued motion between rifted basement blocks may also have influenced the structural evolution in Sub-area F. We speculate that strike-slip motion along NW-SE oriented wrench faults (with associated releasing and restraining bends) could account for some of the sharp changes in fold axis orientation and basement relief.

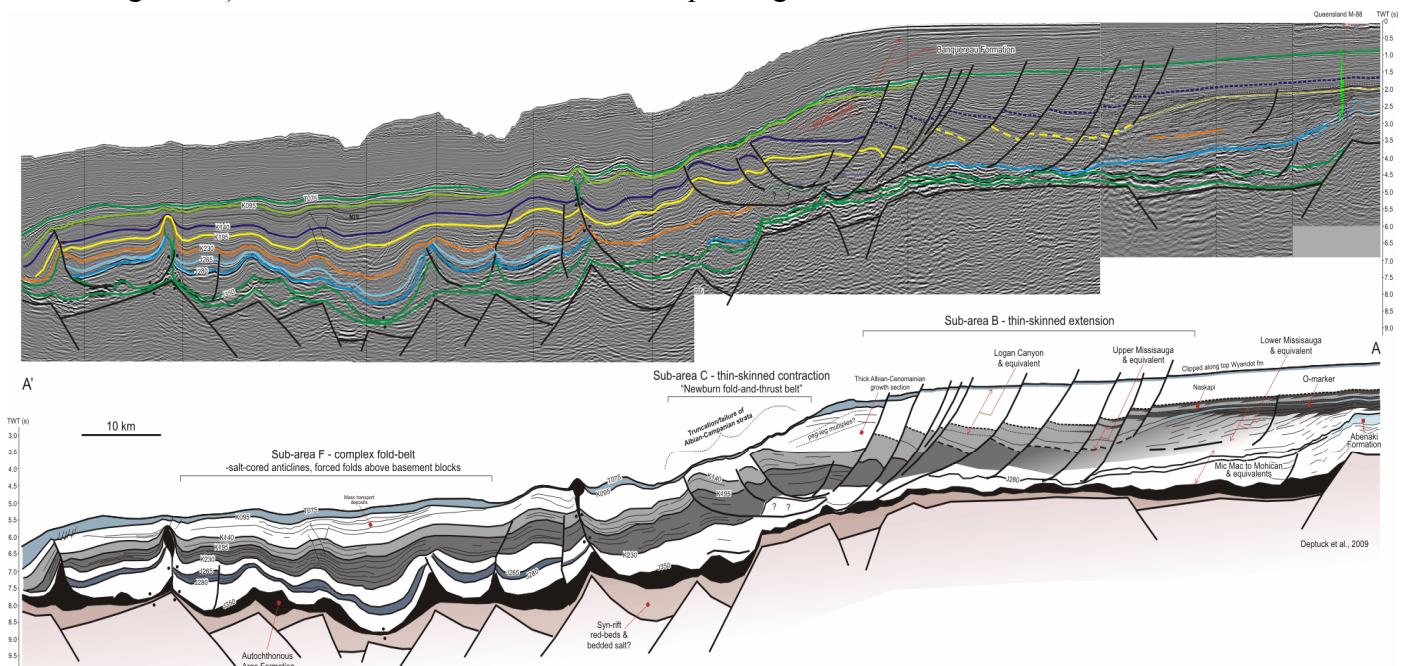


Figure 2: Proximal to distal composite seismic profile (A to A') assembled from multiple 3D seismic surveys. Note that the Cenozoic section on the bottom image is not shown (profile clipped along an Upper Cretaceous chalk marker).

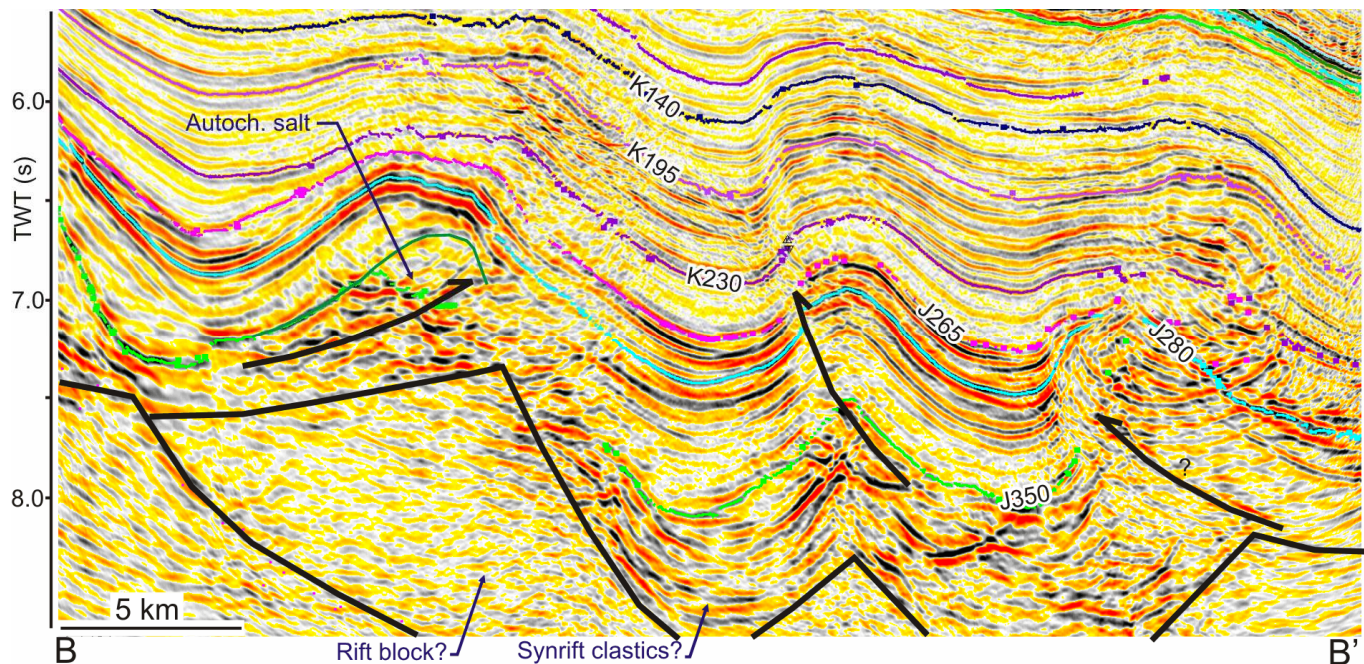


Figure 3: Seismic profile B – B' across complex fold-belt in Sub-area F. See Figure 1 for location.

Conclusions

The study area is located at the transition from a major salt canopy system to the east and a region dominated by isolated salt diapirs to the west (Fig 1). Jurassic and Cretaceous strata in the study area can be separated into two overlapping linked systems, each composed of a thin-skinned extensional component balanced down-slope by contraction. There is about a 45° change in the dominant shortening direction between the two linked systems that probably reflects the change in orientation of the structural hinge-zone and influx direction of clastic depositional systems (Fig. 1). Variations in the structural response to shortening appear to reflect a number of factors, including the density of salt feeders (and by inference the original thickness of autochthonous salt). Where salt feeders are sparse or absent (e.g. Sub-area C), shortening was accommodated along a series of seaward-vergent detachment folds. Where there was a higher density of salt feeders (e.g. area inboard of salt-tongue canopy system), shortening was accommodated by the closure of seaward leaning salt stocks, salt extrusion, and local reverse motion on resulting welds. The increased complexity of contractional structures in Sub-area F probably reflects the irregular morphology of the autochthonous salt detachment surface (floored by high-relief rifted basement blocks), as well as the presence of pre-existing isolated salt diapirs that nucleated deformation, resulting in variably oriented structures (Rowan and Vendeville, 2006). Some of the structural complexity may also originate from strain partitioning associated with strike-slip motion along irregular wrench faults, though this idea requires further investigation.

Acknowledgements

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