# TRIANGLE ZONE MODEL FOR THE SALT-BASED FOLDBELT IN CANADA'S WESTERN ARCTIC ISLANDS

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## ABSTRACT

Potentially viable kinematic models are presented for a Paleozoic salt-based foreland foldbelt in the western Canadian Arctic Islands. In one model, a throughgoing upper décollement is assumed to have first become active during an embryonic stage of folding. The implied triangle-zone structure is up to 200 km wide with a taper angle between upper and lower décollement surfaces of 1.6°.

## INTRODUCTION

The structural style of a widely exposed lower aleozoic salt-based foldbelt in Canada's Arctic Islands is known from surface geology, satellite imagery, stereoscopic air photos, and about 15,000 line kilometers of industry-reflection data. Illustrations of the unique style of salt-based foreland shortening are provided by Fox (1985), Harrison and Bally (1988), and Harrison (1991, in press). The present account summarizes some typical structural features of the belt and provides two competing kinematic models for the late Famennian-Tournaisian phase of thin-skinned shortening. These models are similar to those first proposed by Harrison and Bally (1988) but differ insofar as throughgoing lower and upper décollement surfaces are invoked in the present interpretation. It will be shown that the extent and nature of the deformation process in shallow-buried preorogenic clastic rocks, and the relative timing of slip on the upper décollement play equally important roles in the triangle zone model for the foldbelt.

## GEOLOGIC SETTING

The following geological summary is abstracted primarily from Trettin (1991) and references contained therein. The Franklinian Mobile Belt of Arctic Canada and North Greenland involves ("Franklinian Sequence") Cambrian to Devonian strata lying north and northwest of coeval undeformed strata of the Arctic Platform. This orogen is continuous with the early to late Paleozoic Appalachian and Caledonian mountain belts of the North Atlantic borderlands and also is known in north Yukon and north Alaska. In the Canadian Arctic, the Franklinian Sequence embraces island arc, starved basin and flysch sequences, basin slope, shelf, and foredeep sediment, all compressively deformed during southerly directed accretion of Pearya and similar lower Paleozoic suspect terranes of the circum-Arctic region. Deformation that produced the southerly facing arcuate salt-based folds (Parry Islands Fold Belt) of Bathurst and Melville islands in the western Arctic Islands (Fig.1) is attributed to the Ellesmerian Orogeny, sensu stricto. Deformation timing is bracketed by the deposition of mid- to late (but not latest) Famennian strata preceding folding and late Viséan and younger rift-related postorogenic ("Ellesmerian Sequence") strata of the embryonic Sverdrup Basin. At the surface, the foldbelt is dominated by siliciclastic formations of a Middle and Upper Devonian foreland clastic wedge exposed in peneplained upright anticlines and synclines up to 350 km long.

## TECTONIC UNITS

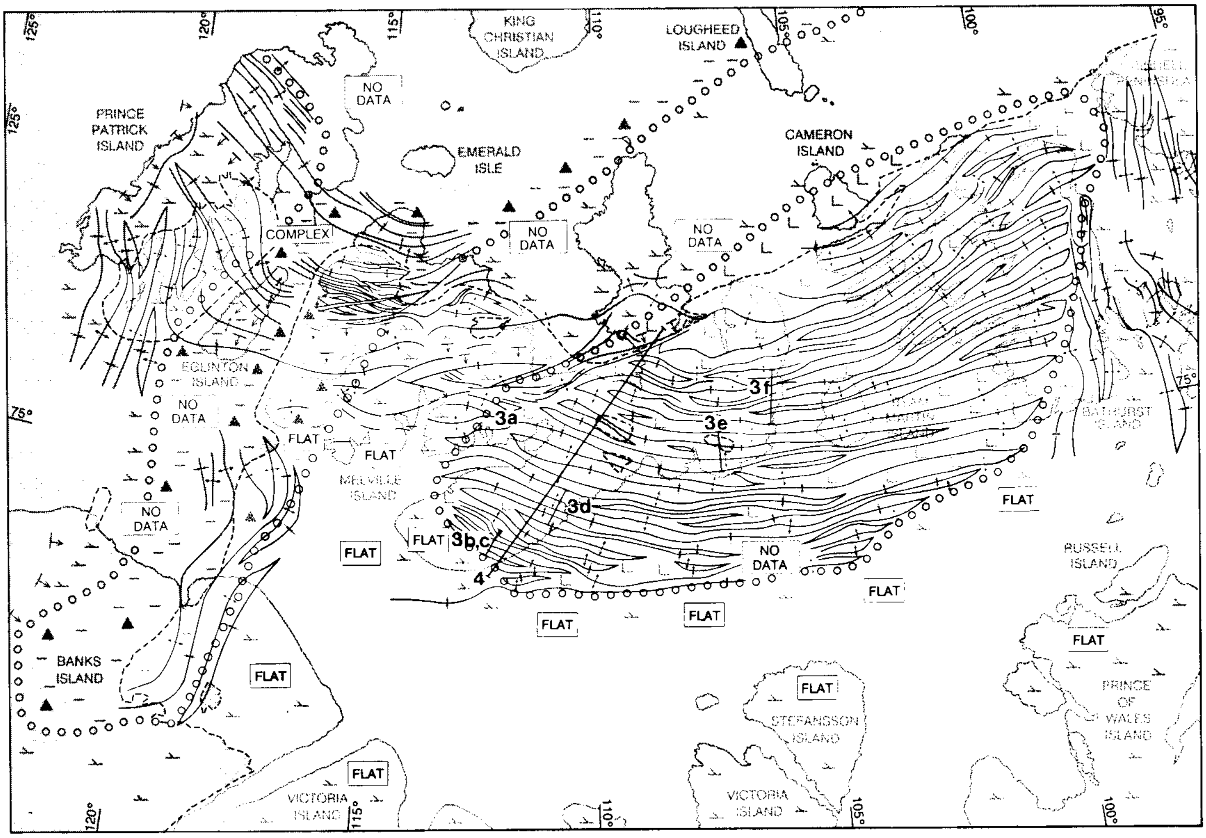
The Devonian clastic wedge lies in the highest part of the local Franklinian Sequence, which in this area comprises a five-unit tectonic "sandwich" 10 to 14 km thick (Fig.2). These units include upper and lower rigid layers located, respectively, above and below upper and lower ductile layers. The two ductile layers envelope a medial rigid beam, the thickness of which is qualitatively proportional to the wavelength of the surface mappable fold system. Structural character of each of the five tectonic units is reviewed below.

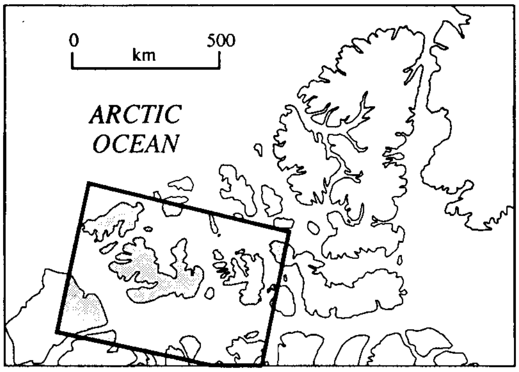
### *Lower Rigid Layer*

The lowest of the five tectonic units is the lower rigid layer (Fig.2). It comprises 5 to 8 km of seismically stratified rocks of presumed Early Cambrian through definite mid-Arenig age and includes shelf dolostones in the upper part. This layer mostly represents a stable and flat-lying deformation floor beneath the thin-skinned foldbelt. However, deep-seated folds (also of latest Devonian to Early Carboniferous age) affect this entire succession beneath central and northern Melville Island and also beneath the eastern side of the foldbelt on eastern Bathurst Island. In addition, thrusts and transpressional strike slip faults have been interpreted passing through the lower rigid layer emerging onto the throughgoing décollement at the base of the overlying lower ductile layer.

### *Lower Ductile Layer*

The lower ductile layer embraces up to 700 m (restored thickness range) of Ordovician evaporites at the base of the foldbelt (Figs.2 and 3). In detail, the





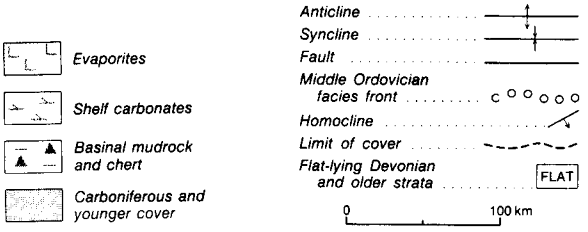


**Fig.1. Fold trends of the Franklinian Mobile Belt of the western Canadian Arctic Islands together with late Arenig-Llanvirn depositional facies belts and postorogenic cover (modified from Harrison, in press). Only Early Carboniferous and older structures are plotted and, where known, either have been mapped on surface or obtained from seismic profiles and projected through mid-Carboniferous and younger cover.**

evaporites are represented by a tectonized mix of rock salt (halite), anhydrite, and dolostone. Surface exposures and core, collected from several anticlinal culminations, feature boudinaged thin beds, ductile minor folds, near vertical stratification, tectonic brecciation, recrystallized halite, and vein fill. Seismic profiles reveal thickness variations for the lower ductile layer that range from 20 to 350 percent of original depositional thickness. Pronounced thinning occurs beneath the surface synclines, and thickening is featured in salt "welts" below anticlines. Evaporites also have been carried upwards on reverse faults that pass through the overlying medial rigid beam. A key structural element of the lower ductile layer is a throughgoing basal décollement identified at and below 3.5 km on Bathurst Island and between 5.0 and 5.8 km on Melville Island. This décollement carries up to 27 km of southerly directed slip as measured above the northern depositional limit of evaporites within the lower ductile layer.

*Medial Rigid Beam*

The medial rigid beam represents a stiff panel of shelf carbonates and lesser graptolitic shales 1.0 to 3.0 km thick and bound above and below by ductile layers. The lower part of the beam features incipiently cleaved shelf carbonates with intense calcite-veining and tectonic brecciation, particularly in pop-up structures and in the footwall of major and minor faults. The upper part of the beam displays incipiently cleaved graptolitic shales,

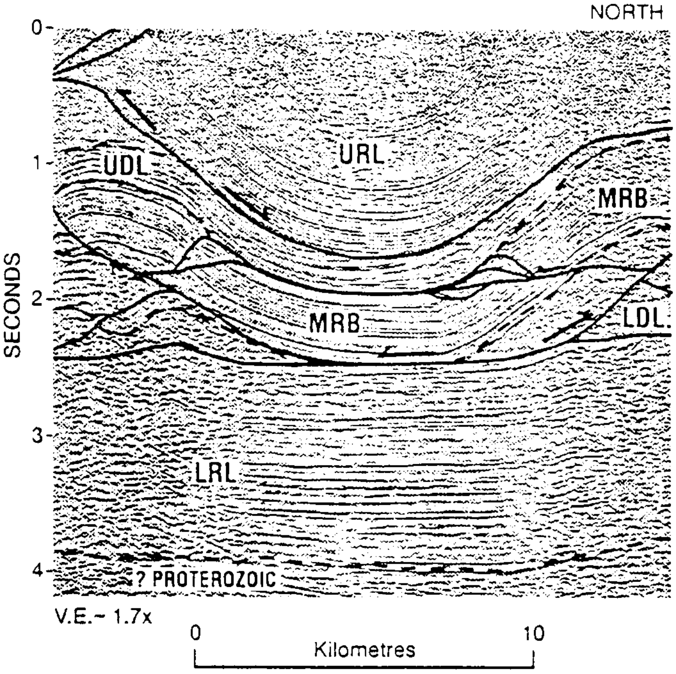


**Fig.2. Seismic expression of tectonic units within the salt-based foldbelt. LRL: lower rigid layer; LDL: lower ductile layer; MRB: medial rigid beam; UDL: upper ductile layer; URL: upper rigid layer.**

turbidites, and lesser shelf carbonate. Fissile strata are intensely kink-banded, and evidence of bedding-plane slip is common. Major and minor thrusts in this part of the beam lie preferentially along kink-band boundaries. Larger structures in the beam include fault propagation folds and related thrust ramps that link lower and upper décollements within the bounding lower and upper ductile layers, respectively. Foreland- and hinterland-vergent thrusts, concentrated in the subsurface and below each regional-scale anticline, are equally represented in the beam. Each fault displays up to 3 km of net displacement. Oppositely vergent thrusts also are stacked vertically beneath surface anticlines and linked to each other along various intermediate detachment surfaces within the beam.

### *Upper Ductile Layer*

Clinoformed basin fill mudrocks (up to 900 m) lie at the base of the Devonian clastic wedge and represent an upper ductile layer (second unit from the top in the tectonic sandwich under discussion). Tectonic thickening, up to 300 percent, is featured in upright cuspate-shaped shale welts below some surface anticlines. Other low-amplitude anticlines feature compactional thinning of the upper ductile layer. Otherwise, the unit appears (on seismic profiles) to be relatively undeformed beneath most synclines. The surface exposures feature isoclinal minor folds, boudinaged thin sandstone beds, and tightly spaced fractures generated within centimeter-scale kink bands and along bedding-parallel slip surfaces. An important, possibly throughgoing, décollement surface lies above or within the upper ductile layer and, in the north, may carry up to 11 km of slip where it intersects the postorogenic sub-Carboniferous unconformity.

### *Upper Rigid Layer*

The upper rigid layer embraces the sandstone-dominated formations of the Devonian clastic wedge (2.1-3.6 km thick). Although these strata are orogen-derived, there is no local evidence of synorogenic sediment accumulation or thrust-associated growth faulting. The dominant structural features are upright anticlines and synclines with common wavelengths of 12 to 17 km. Fold amplitude and wavelength decrease to the foreland limit of deformation, which is gradational at the surface with the flat-lying strata of the Arctic Platform to the south. Differential compaction of the upper rigid layer over some anticlines also may contribute to the lower amplitude of some foreland folds. Noticeably rare in the upper rigid layer are minor structures such as cleavage, minor folds, kink bands, slip surfaces, or strain fabrics. Primary depositional features are well preserved.

## KINEMATIC MODEL

The absence of minor deformation fabrics from the upper rigid layer is a critical observation because palinspastically restorable cross-sections of the foldbelt also display a magnitude of shortening in the upper rigid layer that is everywhere only about half that recorded in the medial rigid beam (Harrison, 1991, in press). The following kinematic model assumes that the apparent lack of shortening within the upper rigid layer is to be accounted for by modest levels of mineral dissolution, porosity reduction, and/or tectonic thickening. In more general terms, the deformation history for the foldbelt includes the growth by horizontal shortening of a family of simple, evolving into complex, duplex anticlines during cratonward expansion of the orogen. Seven distinct stages are inferred from numerous actual structural examples, as illustrated in Fig.3. Not considered are superimposed and distinctly younger phases of deformation.

### *Foldbelt Inception*

The first fold is created in this deformation history through the application of a small differential shear stress to the basal salt layer leading to ductile failure (Fig.3a). This could have occurred when one or more deep-seated contraction faults reached the lower ductile layer on thrust ramps known to exist below the northern depositional limit of salt.

### Embryonic Folds

Subhorizontal compressive stress is transmitted through the rigid beam during the embryonic stage of deformation leading to the creation of low-amplitude kinks in the beam (Fig.3b). Salt in the lower ductile layer is simultaneously sucked into anticlines to form simple short-wavelength welts that resolve initial hinge-area room problems. The upper ductile layer compacts differentially over anticlines, and the upper rigid layer remains apparently undeformed, although syntectonic compaction (by porosity loss), syntectonic mineral dissolution, and/or microscopic scale tectonic thickening also are possible.

### Birth of Folds

The folds are seen to be "born" when embryonic buckles experience irreversible brittle failure in the medial rigid beam (Fig. 3c). These first obvious faults nucleate along kink-band boundaries and in the hinge areas of some anticlines in order to resolve worsening room problems created by continued shortening. Failure planes in the beam include either one or both upright conjugate shears. Low-amplitude folding begins in the upper rigid layer.

### Juvenile Folds

During the "juvenile" stage of folding (Fig. 3d), there is a full linkup of upper and lower ductile layers by thrust ramps in the beam, formation of intraformational imbricates near thrust tips in the upper ductile layer, and continued long wavelength and low-amplitude folding of the upper rigid layer. Distinct structural styles are created in the beam by the varying shape and occurence of footwall cutoffs, intermediate detachments, thrust imbrication at different stratigraphic levels, and antithetic thrusts in various hanging-wall and footwall positions.

### Mature Folds

The salt-based folds reach full maturity in conjunction with a dramatic increase in amplitude of surface anticlines (Fig.3e). The upper ductile layer, previously thinned by differential compaction over anticlinal hinges during the embryonic stage, is now squeezed into anticlinal hinge areas to resolve room problems created by concentric-style buckling of the upper rigid layer. The results are anticlinal mudrock welts of the upper ductile layer stacked vertically above evaporite welts of the lower ductile layer. Parasitic structures also are increasingly common in the beam during this stage.

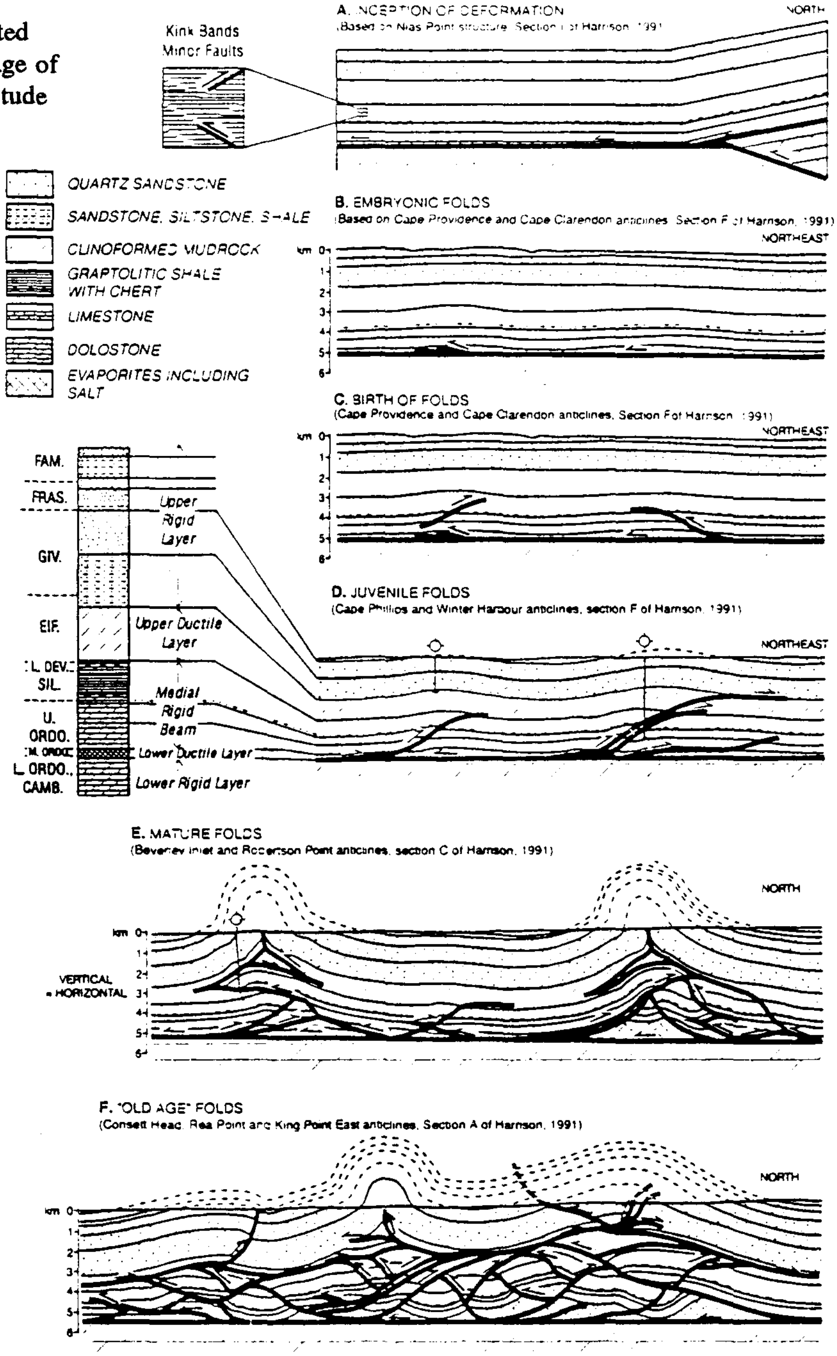


**Fig.3. Life history of salt-based folds (after Harrison, in press). Location of sections marked on Fig.1.**

### *Folds in "Old Age"*

In old age, all evaporite has been exhausted from beneath some synclines (Fig.3f). Dolostone interbeds in the lower ductile layer have been brecciated and boudinaged above the basal detachment, as the competent roof of the lower ductile layer in the syncline approaches the undeformed competent carbonate floor. Larger displacements are developed on individual thrusts within the medial rigid beam. Parasitic structures are everywhere common beneath both surface anticlines and synclines. The disharmony between surface folds and complex subsurface structure is caused by a completed linkage of upper décollement slip planes beneath synclines and between adjacent anticlines within the upper ductile layer. Buckling of the upper competent layer is replaced by brittle failure of surface anticlines and thrust faulting of siliciclastic formations starting within the lowest beds of the upper rigid layer. This is the tectonic response to severe hinge-region room problems created within and above the upper ductile layer during the previous, mature stage of deformation.

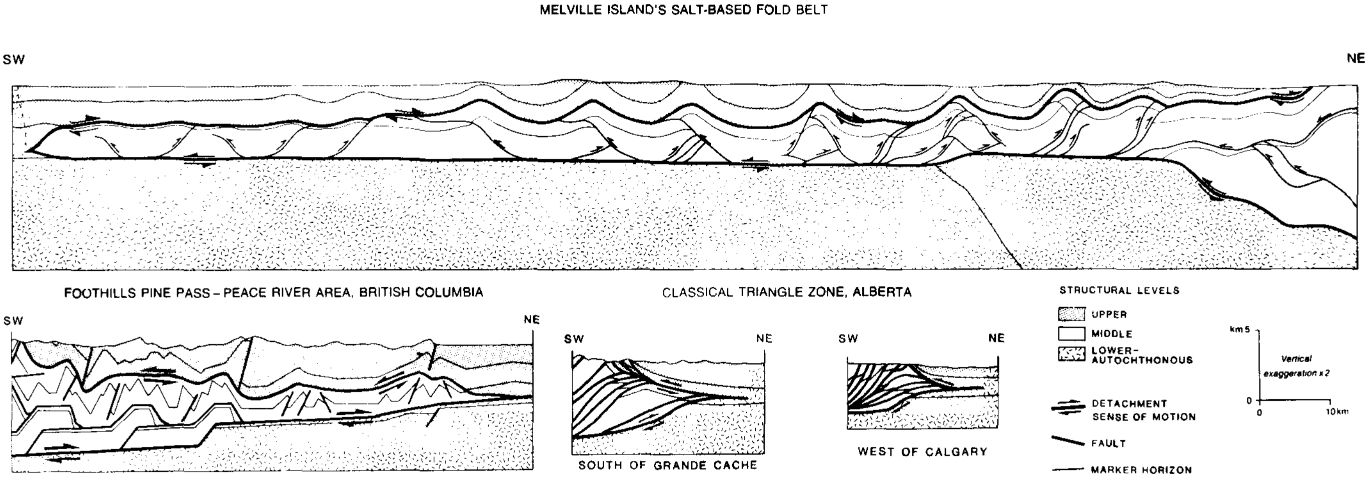


**Fig.4. Possible structural geometry of Melville Island's salt-based foldbelt (after Harrison, in press; see Fig.1 for line of section) and similar triangle-zone geometries (from McMechan, 1985, and contained references) of Pine Pass-Peace River area of British Columbia and of the foothills belt near Grand Cache and Calgary.**

### *The End of Folding*

The end of deformation in this area must occur when available shear stresses are exhausted or are no longer large enough to overcome the frictional resistance of sticking points at the level of the lower ductile layer within synclines. Continued expansion of the foldbelt toward the craton also is hindered at the southern limit of the basal detachment, where rock salt and anhydrite undergo a facies change to dolostone.

## TRIANGLE-ZONE MODEL

The kinematic model presented above invokes a delay in the development of the throughgoing upper décollement surface to later stages of fold formation. The model assumes that strain is initially absorbed in the upper rigid layer through various undocumented mechanisms of volume loss (about 5-10% is needed) and tectonic thickening (about 5%). An alternative solution would be to assume that the upper rigid layer already is fully compacted and cemented prior to folding. Without the requisite large or small scale deformation fabrics in the upper rigid layer (to match those documented in the beam), the upper décollement surface must develop as early as the embryonic stage of folding within the hinterland folds. Thus, in this model, both the lower and upper rigid layers are considered fundamentally autochthonous with respect to the Arctic Platform. The intervening mobile units that include the two ductile layers and medial rigid beam have been inserted as a tectonic wedge between throughgoing upper and lower décollements. Thus, most of the requisite slip is carried back through the hinterland portion of the foldbelt. This then produces a deformation model for the salt-based foldbelt that features a triangle zone up to 200 km wide with a taper angle of only 1.6° measured between upper and lower décollement surfaces (Fig.4). In contrast, the Pine Pass triangle zone of the northern Canadian Cordillera is about 65 km wide and tapers at 7°, and the classic triangle zone on the edge of the foothills belt near Calgary is only 7 km wide and tapers at about 16° (Pine Pass and foothills data taken from the cross-sections of McMechan, 1985, and references contained therein).

## DISCUSSION

A drawback to the triangle-zone model lies in the potential mechanical impedances to continuing slip on an upper décollement that has been folded in the hinterland at an earlier stage in the kinematic history. In order to complete the triangle-zone structure to its full width, the hinterland portion of the décollement must continue to carry the slip that is generated by the embryonic folds newly emergent in the foreland. This slip must be pushed along and over the limbs of the previously folded hinterland décollement surface--fold limbs that dip at up to 35°.

In addition, early formed shallow structure, lying above the upper décollement, and deep structure originally located directly below in the early stages of foldbelt evolution, will become separated during the later stages as slip continues on the intervening décollement surface. This style of deformation has not been documented in the hinterland where it is to be expected. The alternative scenario, which might involve repeatedly folding, unfolding, and refolding the upper rigid layer as it slides along the folded upper décollement surface, also should leave its mark in the rocks.

It is hoped that the work to date will inspire a detailed examination of microscopic scale strain conditions and the timing of porosity loss with respect to folding in shallow buried foreland clastic rocks of the upper rigid layer. Also needed is a quantitative evaluation of the mechanical limits to physical size of triangle-zone structures such as the one proposed here for the salt-based foldbelt of Canada's western Arctic Islands.

## CONCLUSIONS

Kinematic models for the salt-based foldbelt of the western Canadian Arctic Islands allow for the development of a throughgoing upper décollement surface. If this surface has developed in the later stages of folding then certain (currently undocumented) mechanisms of microscopic strain, tectonic compaction, and/or porosity loss are required in shallow buried preorogenic strata to balance the greater apparent coeval shortening observed at deeper structural levels. Alternatively, if the upper décollement surface was active first during the earliest stages of fold development, then the eventual result is a negligible-taper triangle zone structure potentially embracing the entire 200-km width of the foldbelt. This kinematic model may suffer potential mechanical problems if slip is permitted on an upper décollement surface that has been folded in the hinterland at an earlier stage.

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