SILURIAN FOREDEEP AND ACCRETIONARY PRISM IN NORTHERN ELLESMERE ISLAND: IMPLICATIONS FOR THE NATURE OF THE ELLESMERIAN OROGENY

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ABSTRACT

Much of northernmost Ellesmere Island represents a distinct terrane whose pre-Silurian geologic history is unlike that of the rest of the Canadian Arctic archipelago. At the boundary between this terrane (Pearya) and the northern margin of paleo-North America, stratigraphic relationships and structural features provide evidence for a previously unrecognized period of tectonic activity that could represent the earliest stages of the poorly understood Devonian to Carboniferous Ellesmerian orogeny. The terrane boundary in the Yelverton Inlet area (82° N., 82-85° W.) is a structurally complex zone of south-verging folds and thrusts involving (1) a Lower Silurian turbidite sequence, (2) crinoidal carbonate rocks containing post-Middle Ordovician conodonts, and (3) andesitic tuffs and flows.

Field relations suggest that the turbidites and carbonate and volcanic rocks are essentially coeval and were deposited in close proximity. Similar carbonate-volcanic complexes occur along the entire length of the boundary zone and may represent a once-extensive arc system. South of the terrane boundary, the turbidites overlie a platformal passive margin sequence, recording progressive drowning of the North American continental shelf, possibly due to tectonic loading during collisional orogenesis. The turbidites display structural features that resemble those observed in drill cores from modern forearc and accretionary prism settings.

INTRODUCTION

The pre-Silurian geologic evolution of northernmost Ellesmere Island differs significantly from that of the rest of Ellesmere Island and other islands in the Canadian archipelago. First, basement gneisses of northern Ellesmere Island record Middle Proterozoic (1.1 Ga) metamorphism, whereas basement complexes in southern Ellesmere yield Early Proterozoic (Aphebian) ages (Trettin et al., 1987). Second, the lower Paleozoic strata in the north show no affinity with coeval rocks on the rest of Ellesmere Island until latest Ordovician time (Trettin, 1987). In particular, a pronounced Middle Ordovician angular unconformity in northern Ellesmere Island chronicles a major deformational event, while the Ordovician sequence in the central and southern Ellesmere Island records continuous sedimentation. Only beginning with the Silurian section can Paleozoic formations be correlated from the north to the south. On the basis of these distinctions, Trettin (1987) identified much of northernmost Ellesmere Island as a separate, allochthonous terrane that has been named Pearya, after the polar explorer.

STRATIGRAPHY AND STRUCTURE OF THE TERRANE BOUNDARY ZONE

The inferred boundary between Pearya and the rest of Ellesmere Island is a structurally complex, east-northeast-trending zone some 250 km long and on average 10 km wide (Fig.1). Turbidites, crinoid-bearing limestones and dolomites, and andesitic to dacitic volcanic rocks, generally of subgreenschist facies, are the principal rock types involved in the thrusts and folds of the suture zone. The best exposures of these assemblages are at Fire Bay, in the Mt. Rawlinson area, and at Yelverton Inlet, the main focus of this study (Fig.1). U-Pb zircon ages obtained for the volcanic rocks at these localities are Late Ordovician, ranging from 454.7 +9.7/-4.5 Ma (middle Caradoc) for andesites from Mt. Rawlinson to 447 ± 2 Ma (Ashgill) for those at Yelverton Inlet (Trettin et al., 1987; R. Parrish, pers. commun., 1991). The carbonate rocks at Yelverton contain conodonts (CAI = 5) that can be identified only as post-Middle Ordovician in age (G. S. Nowlan, pers. commun., 1991). The upper part of the main turbidite sequence, known informally as the Imina Formation (Trettin, 1969), contains Early Silurian (Llandovery) graptolites. Field relationships at Yelverton Inlet indicate that the three main rock types in the suture zone are at least partly coeval. The crinoidal limestones are interbedded with volcanic flows and tuffs. The Imina Formation contains up to ca. 15 percent euhedral feldspar grains, consistent with a nearby volcanic source. Quartz, detrital carbonate, and metamorphic lithic fragments make up the remainder of the clastic fraction and may have been derived largely from Pearya (Trettin, 1979). Though generally fine-grained (silt to fine sand), the Imina Formation locally includes meter-scale blocks of carbonate and volcanic material. These apparent olistostromal deposits suggest that the turbidite sequence was deposited close to a volcanic edifice and fringing reef from which coarse detritus was periodically shed into deep water (Bjørnerud, 1989). We suggest that the volcanic and carbonate rocks represent an arc complex built on the Pearya terrane and that the Imina Formation turbidites represent an associated forearc sequence (Fig.2).

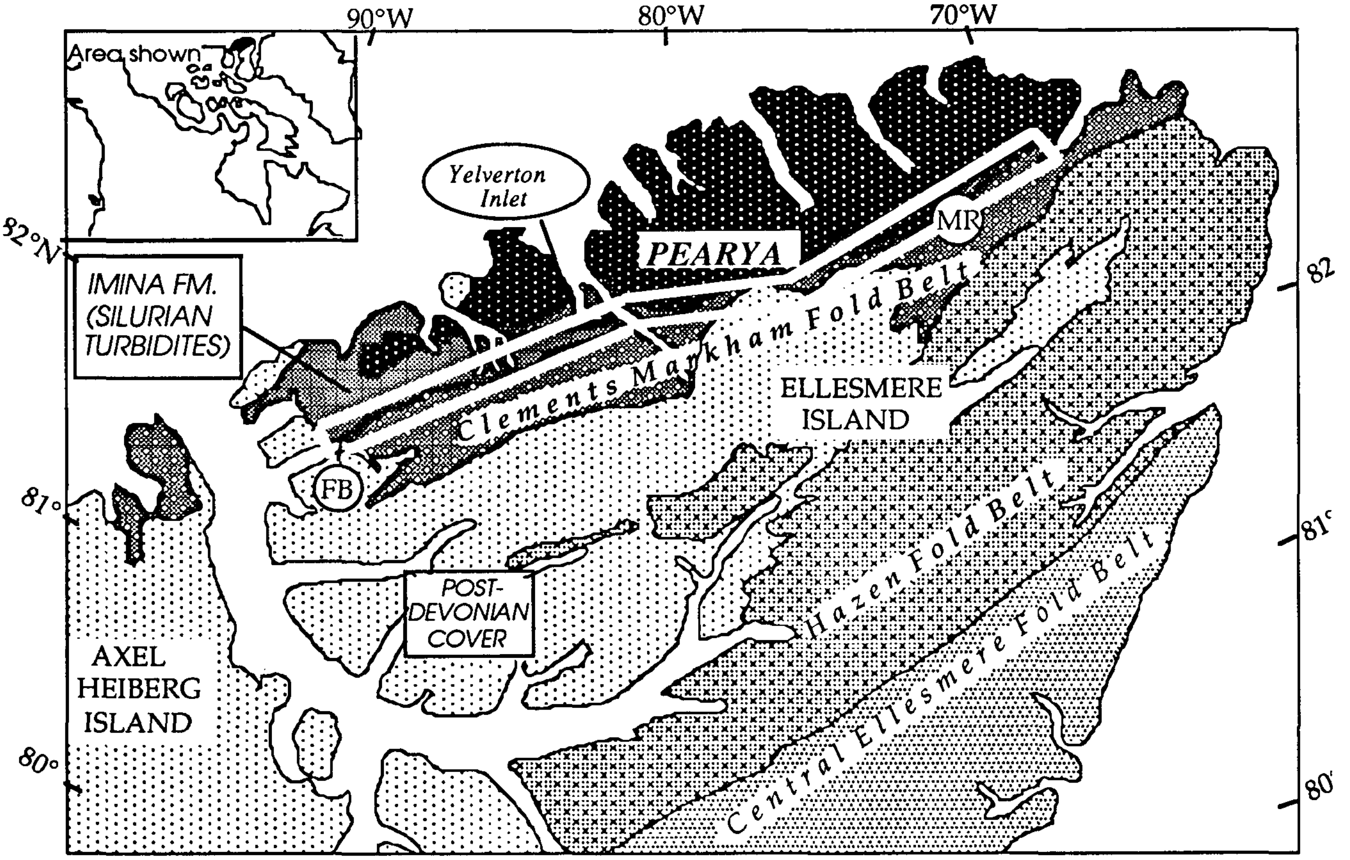

Fig.1. Simplified geologic map of northern Ellesmere Island showing main structural provinces. Pearya-North America terrane boundary zone is outlined in white. Exposures of Silurian turbidite-carbonate-volcanic complex at Fire Bay (FB), Mount Rawlinson (MR), and Yelverton Inlet are indicated. Also shown are principal subdivisions of the Ellesmerian fold-and-thrust belt, distinguished on the basis of age and depositional setting of rocks involved in the deformation. The Clements Markham, Hazen, and Central Ellesmere Fold Belts represent deep-water basin, shelf slope-rise and platformal depositional settings, respectively. All were inundated by Silurian flysch. (After Trettin, 1987.)

Regional Patterns of Flysch Sedimentation: Tectonic Implications

South of the suture zone, Silurian turbidites overlie slope-rise and platformal deposits of autochthonous Ellesmere (Middle to Upper Ordovician Hazen Formation [Fm.]; Trettin, 1979), recording progressive drowning of the north-facing passive margin (Fig.1). These turbidites are correlative with Lower Silurian flysch units in the Peary Land Group of North Greenland (Surlyk and Hurst, 1984), which similarly overlie a paired slope-rise and platform sequence. In both Ellesmere Island and North Greenland, flysch sedimentation migrated southward (toward the paleo-North American continent) through time and was controlled in part by syn-depositional normal faults (Surlyk and Hurst, 1984; Trettin, 1979). Sandstone compositions suggest a northerly source, but paleocurrents were dominantly westerly and parallel to the continental margin (Surlyk and Hurst, 1984; Trettin, 1979). These patterns of flysch sedimentation are very similar to those attributed to subduction-related flexure in the Ouachita orogen (Stanley and Jackfork Fms.; Houseknecht, 1986) and the Taconic orogen of New York (Pawlet Fm.; Rowley and Kidd, 1981). The temporal patterns of flysch deposition in northern Greenland and Ellesmere Island suggest flexural subsidence due to tectonic loading from the north (Bradley and Kidd, 1991) related to northward subduction of the passive margin of paleo-North America beneath the Pearya landmass (Fig.2).

Structural Features in the Imina Formation

Deformational structures in the Imina Formation also indicate that the turbidites were deposited in a

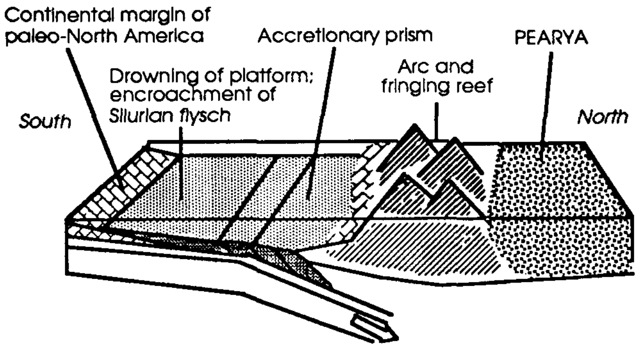

Fig.2. Inferred Early Silurian tectonic setting of northernmost Ellesmere Island.

tectonically active environment. Detailed studies of the Imina Formation in the Yelverton Inlet area have revealed a variety of structural features that apparently developed in response to high fluid pressures before the sediments were lithified. Although some of these prelithification structures (e.g., convolute bedding, contorted cross-bedding, flame structures, and slump folds) can be attributed to simple compaction and (or) gravitational sliding, others reflect regional deviatoric stresses. A minimal requirement for documenting a "tectonic" paleostress field is evidence for unequal horizontal stresses in different directions. In a simple gravitational stress field, the maximum principal stress (σ_1) is vertical and equal to the weight of the overburden while stresses in the horizontal plane are essentially isotropic. At very shallow depths, however, unequal horizontal stresses could arise due to topographic relief. Therefore, a more restrictive criterion for recognition of a tectonic paleostress regime would be evidence that σ_1 was horizontal or subhorizontal.

In the Imina Fm., prelithification structures that meet one or both of these criteria include (1) subhorizontal clastic dikes, (2) reverse faults along which bedding has been entrained, and (3) small-scale cuspate isoclinal folds (Bjørnerud, 1991). Each of these structures will be described in turn. Clastic dikes in the Imina Fm. typically are 1 to 5 cm wide and consist of well-sorted sand-sized particles. Dilational offset of bedding traces on either side of the dikes (Fig.3a) suggests that they are tensile hydrofractures intruded by fluidized sediment. This places constraints on the orientation of stresses at the time of dike formation because hydrofractures form perpendicular to the minimum principal stress (σ_3) and parallel to the maximum principal stress (σ_1). At one locality, a swarm of clastic dikes lies at small dihedral angles to bedding. If bedding is rotated back to horizontal, the restored dikes dip about 30° toward the southwest. This implies a subhorizontal σ_1, and thus a tectonic stress regime. If the dikes were originally subhorizontal, they also indicate that fluid pressures were close to lithostatic.

Another variety of prelithification structures in the Imina Formation are small, mutually cross-cutting reverse faults along which sandy sedimentary layers have been entrained (Fig.3b). The disruption of the layering is unlike that due to ordinary fault drag. Instead, the transected beds are flared in two directions and the layers have been dilated where they are intersected by the faults. When bedding is restored to horizontal, the inferred σ_1 direction (acute bisector of the faults) plunges moderately to the south. The large angle of intersection between the shear fractures (80°) indicates a very low angle of internal friction (ϕ) for the sediment, also consistent with incomplete compaction.

A third type of prelithification structure in the Imina Formation are cuspate, similar isoclinal folds with axial planes at moderate to high angles to bedding (Fig.3c). The cuspate hinge zones of the folds define spaced cleavage planes that are traceable tens of meters both within and across the layering. The folds involve both fine- and coarse-grained layers, and the cusps all point in the same direction. They are unlike cuspate folds formed by layer-parallel shortening of layers with contrasting competence, because the cusps of such folds tend to point toward the competent layers. The structures in the Imina Formation suggest little competence contrast between layers. The folds are similar folds, and the axial planar cleavage is not refracted across lithological boundaries. The "ductile" geometry of the folds appears inconsistent with the subgreenschist-facies metamorphic grade of the Imina Formation. Most significantly, there is no microscopic evidence for intragranular strain in spite of the strong thinning of fold limbs. These observations suggest that the folds developed before the sediments were lithified and that strain was accommodated by pore fluids rather than the grains. The folds may have formed when focused fluid expulsion along evenly spaced hydrofractures deflected sedimentary layers into cuspate culminations (Fig.3c). If so, the folds actually formed under layer-parallel *extension* because the hydrofractures would have opened in the direction of the least principal stress. While it is not possible to constrain the orientation of the maximum principal stress (σ_1 could lie anywhere in the fracture plane), their consistent orientations over distances of hundreds of meters suggest that they formed in response to an anisotropic (tectonic?) horizontal-stress field.

In summary, a variety of structures in the Imina Formation bear evidence for tectonic deformation of unconsolidated sediment. We suggest that these structures developed in an accretionary prism as the uncompacted turbiditic sediments were scraped off a downgoing oceanic plate, an interpretation consistent with the depositional setting of the Imina Formation (Fig.2). Indeed, some of the structures observed in the Imina Formation resemble features observed in Ocean Drilling Program (ODP) and Deep Sea Drilling Project

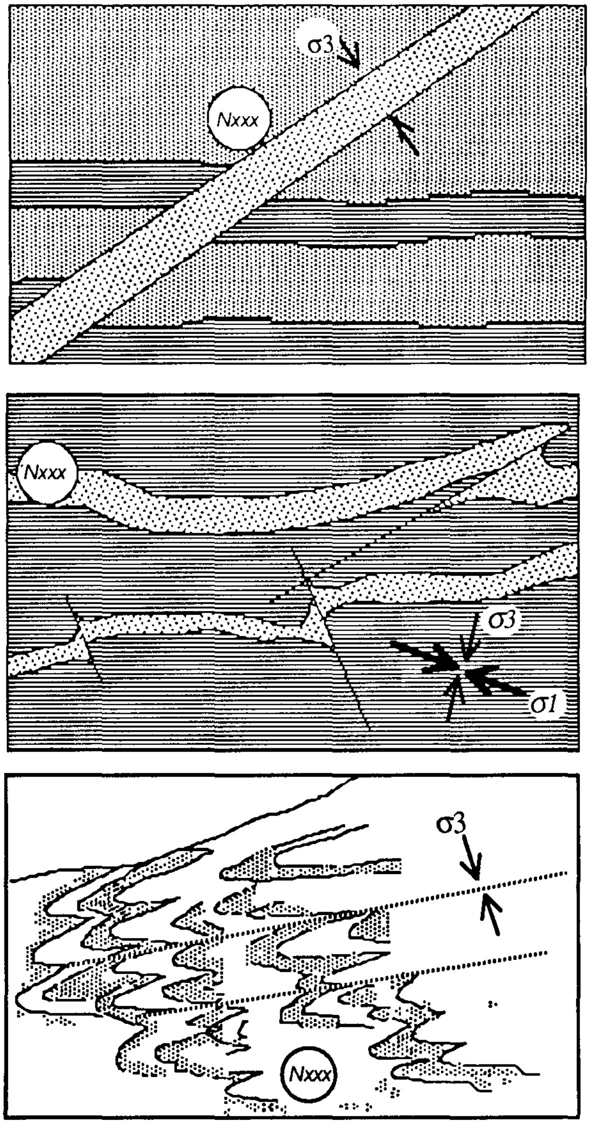

Fig.3. Line sketches from photographs of prelithification structures in the Imina Fm showing inferred stress orientations. a. *Clastic dikes.* View of a vertical outcrop face; lens cap shows scale. Bedding (subhorizontal) dips away from viewer. Dike is indicated by stippled pattern. If dike formed when bedding was horizontal, low dihedral angle between dike and bedding suggests that maximum principal stress (σ_1) was subhorizontal and fluid pressures were near-lithostatic. *b. Reverse faults with entrained bedding.* View of a steeply dipping outcrop face. Note unusual dilational strain of sandy layers (stippled) where they intersect faults. σ_1 is acute bisector of faults. Near-orthogonality of faults suggests low angle of internal friction. c. *Cuspate similar folds.* View of a steeply dipping outcrop face. Outcrop-scale geometry of folds suggests intense ductile strain, but subgreenschist facies turbidites lack evidence of intracrystalline deformation. This suggests that folds predate lithification and may be related to fluid expulsion along hydrofractures. Bedding was rotated to nearly vertical orientation during later large-scale chevron folding.

(DSDP) cores from modern forearc and accretionary prisms. Near-lithostatic pore pressures have been documented in the toe regions of active accretionary prisms (e.g., Westbrook and Smith, 1983), and clastic dikes have been observed in cores from many of these settings (Lundberg and Moore, 1986). Prelithification shear fractures also are common in cores from modern prisms, and entrainment of sand along fault planes similar to that seen in the Imina Formation has been observed in a core from the Middle America Trench west of southern Mexico (Watkins et al., 1982). Finally, the distinctive cuspate folds in the Imina Formation are similar to some types of "stratal disruption" described in the ODP and DSDP cores (Lundberg and Moore, 1986).

It should be noted that most of these cores come from depths of 500 to 600 m below the seafloor and none deeper than 1.5 km. It is likely that the ancient accretionary complex preserves structures from depths not yet sampled in modern prisms.

The prelithification features in the Imina Formation are overprinted by large-scale chevron folds and major thrust faults. The south-directed thrusts create structural repetitions of the carbonate and volcanic units and the Imina Formation and may record the final closure of the basin between the Pearya arc and the northern edge of paleo-North America (Fig.2).

SUMMARY AND CONCLUSIONS

The stratigraphic and structural observations along the southern boundary of the Pearya terrane in northern Ellesmere Island provide evidence for a previously unrecognized period of Silurian tectonism:

(1) The association of Lower Silurian turbidites with coeval shallow-water carbonates and andesitic to dacitic volcanic rocks along the terrane boundary is consistent with an arc-forearc setting.

(2) The turbidites began to override platformal sequences on the paleo-North American passive margin in Early Silurian time, suggesting tectonic loading by north-directed subduction. Syn-depositional normal faults within the turbidites also point to loading-related flexure.

(3) Deformation of the turbidites began shortly after their deposition, probably as they were incorporated into an accretionary prism.

This period of convergent tectonism could be considered an early phase in a protracted tectonic cycle that culminated in the enigmatic Ellesmerian orogeny.

ACKNOWLEDGMENTS

Thanks are due Hans Trettin (GSC, Calgary) and the Canadian Polar Continental Shelf Project for making this project possible. Acknowledgment also is made to the Donors of The Petroleum Research Fund, administered by the American Chemical Society, for support of the study. J. Dumoulin, P. Haeussler, and K. Tracy provided helpful reviews of the manuscript. Finally, special thanks to L. Treadwell for making it possible for this work to be completed.

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