Development of a folded thrust stack: Humber Arm Allochthon, Bay of Islands, Newfoundland Appalachians

John W.F. Waldron, Amber D. Henry, James C. Bradley, and Sarah E. Palmer

Abstract: In the Humber Arm area of the western Newfoundland Appalachians, four distinct stratigraphic successions derived from the Laurentian continental margin are exposed. Each succession is believed to be characteristic of a separate thrust sheet. The platform sheet represents the ancient Laurentian shelf and its foreland basin cover; the Watsons Brook sheet is characterized by a succession including shelf-margin carbonates overlying foreland basin clastics; the Corner Brook sheet comprises continental slope and rise clastic and carbonate sedimentary rocks of the Humber Arm Supergroup; and the Woods Island sheet includes clastics of the Blow Me Down Brook formation that overlie mafic volcanics. Sheets are subdivided by thrusts into tectonic slices. Disrupted units and mélange, with scaly S_1 foliation, are found along the boundaries of some slices. Thrust sheets and related structures have been deformed by F_2 folds with axial planar S_2 cleavage. S_1 scaly foliations are transposed into parallelism with S_2. There is a transition in the style of F_2 folds across the area, from upright and subhorizontal in the west to overturned folds with west-dipping axial planes and steeply raking or reclined fold hinges in the east. Strongly curved fold hinges may reflect later shearing along the S_2 surfaces, producing sheath-like fold geometries. Shear zones close to the east edge of the outcrop of the Watsons Brook sheet display kinematic indicators indicating both D_2 reverse-sense and D_3 normal-sense dip-slip shears. Subsequent events produced L_4 and L_5 crenulation lineations on the S_2 surfaces. At minimum, several tens of kilometres of shortening affected the part of the margin preserved in the Humber Arm area; true shortening and transport amounts may have been much larger.

Résumé : Quatre successions stratigraphiques distinctes, provenant de la marge continentale laurentienne, affleurent dans la région de Humber Arm des Appalaches occidentales de Terre-Neuve. On croit que chaque succession est caractéristique d'une nappe de charriage distincte. La nappe de la plate-forme représente l'ancienne plate-forme laurentienne et le recouvrement de son bassin d'avant-pays; la nappe de Watsons Brook est caractérisée par une succession comprenant des carbonates de bordure de plate-forme reposant sur les sédiments clastiques du bassin d'avant-pays; la nappe de Corner Brook comprend des roches sédimentaires clastiques et carbonatées de la pente et du seuil continental du Supergroupe de Humber Arm; la nappe de Woods Island comprend les roches clastiques de la Formation de Blow Me Down Brook qui reposent sur les volcaniques mafiques. Les nappes sont subdivisées, par charriage, en des écailles tectoniques. Les unités et les mélanges perturbés, avec une foliation écailleuse S_1, se retrouvent le long des limites de quelques écailles. Les nappes de charriage et les structures connexes ont été déformées par des plis F_2 présentant un clivage axial planaire S_2. Les foliations écailleuses S_1 sont transposées parallèlement à S_2. Il y a une transition dans le style des plis F_2 à travers la région, de verticaux et subhorizontaux, à l'ouest, à des plis déversés dont les plans axiaux présentent un pendage vers l'ouest et des charnières de plis à pente abrupte ou inclinées à l'est. Des charnières de plis fortement recourbées peuvent refléter un cisaillement tardif le long des surfaces S_2, produisant des géométries de plis de type fourreau. Les zones de cisaillement à proximité de la bordure est de l'affleurement de Watsons Brook présentent des indicateurs cinématiques indiquant des cisaillements à rejet incliné D_2 en sens inverse et D_3 en sens normal. Des événements subséquents ont produit les linéations de crénulation L_4 et L_5 sur les surfaces S_2. À tout le moins, plusieurs dizaines de kilomètres de rétrécissement ont affecté la partie de la marge préservée dans la région de Humber Arm; le véritable rétrécissement et les distances de transport peuvent avoir été beaucoup plus grands.

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Introduction

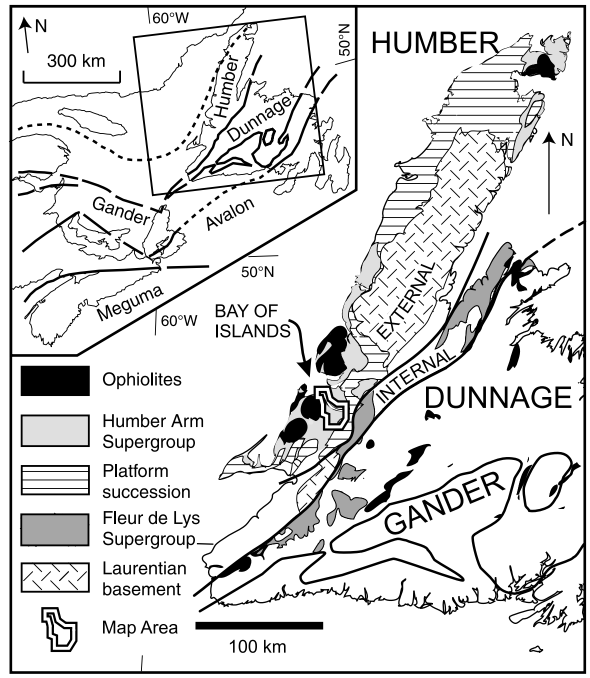
The Humber Arm area can be regarded as a "type area" for the major tectonic units that characterize the Humber Zone (Williams 1979) of the Appalachians (Fig. 1). The allochthonous nature of sedimentary rocks on the shores of the Bay of Islands was recognized by Rodgers and Neale (1963) and by Stevens (1965). Sedimentary rocks in the allochthon represent a combination of passive continental margin and foreland basin environments (e.g., Williams and Stevens 1974), preserving a record of rifting, continental margin subsidence, and continent–arc collision. Adjacent igneous and metamorphic rocks of the Bay of Islands ophiolite were amongst the first to be identified as fragments of ancient oceanic crust and upper mantle (Stevens 1970).

Regionally, stratigraphic and tectonic relationships in the Bay of Islands have been used as an analogue in understanding the evolution of the Laurentian margin throughout Atlantic Canada (Williams 1979) and the Appalachian–Caledonide system as a whole (Williams 1978*a*, 1978*b*). The Newfoundland segment preserves the most completely preserved cross-section of the margin of Laurentia and the adjacent Iapetus Ocean, including an Early Cambrian to Early Ordovician shelf succession overlain by Taconian foreland basin deposits, a variety of slope and rise facies that also span the Early Cambrian to Early Ordovician interval, and ophiolitic rocks that probably represent Iapetan Ocean floor, formed in a supra-subduction environment.

Western Newfoundland also shows a complex structural history that has analogues throughout the Humber Zone of the northern Appalachians, where Taconian (Ordovician) thrusts and mélange belts have been overprinted by later deformation, typically attributed to Acadian (Devonian) orogenesis (e.g., Cousineau and Tremblay 1993). However, in the on-land portion of the zone in Newfoundland, there is little sedimentary record of the interval from Middle Ordovician to Early Carboniferous. Hence, the history of deformation following the Taconian Orogeny is poorly known in the weakly metamorphosed, western (external) portion of the Humber Zone. Offshore evidence from the foreland basin suggests significant Late Ordovician loading of the Laurentian margin (Waldron et al. 1998). Farther east, in the internal Humber Zone, Cawood et al. (1994) use isotopic evidence to demonstrate an important episode of Silurian (Salinian) deformation. Folding and thrusting beneath the Gulf of St. Lawrence have been shown to affect rocks as young as Early Devonian, demonstrating an Acadian component to the deformation affecting the Humber Zone (Cawood and Williams 1988; Stockmal and Waldron 1990; Waldron and Stockmal 1991).

Early mapping and syntheses of the geology in the Bay of Islands area by Williams (1973) and by Dewey (1974) and co-workers, painted a relatively simple picture of the structure of the Humber Arm Allochthon as a stack of sheets overlying platform carbonates of the Laurentian margin and emplaced in the Middle Ordovician Taconian Orogeny. This picture has been accepted in most subsequent reviews and syntheses of the regional geology. However, it is clear from more detailed studies in both the allochthon (Bosworth 1985; Waldron 1985) and in the adjacent rocks of shallow-marine facies (Knight and Boyce 1991; Knight 1994*a*, 1994*b*, 1995, 1996*a*; Cawood and van Gool 1998) that neither the allochthon nor the platform

Fig. 1. Map of western Newfoundland showing location of mapped area (Figs. 2, 3). Inset shows location relative to zonal subdivisions of Canadian Appalachians.



rocks are tabular in their present-day configuration and that the contact between them is both faulted and folded, locally tightly. This later folding is responsible, for example, for the current distribution of platform carbonate exposure to the east of the "Humber Arm rocks" (Fig. 1), despite the clear evidence that the ancient platform margin was east-facing (present orientation), with deep-water environments lying to the east.

Following the discovery of oil in Port au Port Peninsula (Cooper et al. 2001), interest has focussed on the sedimentary units of the Humber Arm Allochthon as potential source rocks for petroleum. In addition, Lithoprobe seismic profiles (Quinlan et al. 1992) show reflectors beneath the allochthon that may represent inverted basins in structurally underlying platform rocks (Waldron et al. 1998), encouraging interest in possible deeply buried petroleum reservoirs.

In this paper, we seek to interpret the map-scale structure of the area south of the Bay of Islands (Fig. 2), located between the exposure of platform carbonates at Corner Brook and ophiolitic rocks of the Bay of Islands Complex to the west. We show that this area contains at least four distinct stratigraphic successions that probably represent original thrust sheets within the Humber Arm Allochthon. However, these sheets have been strongly folded and deformed in at least four subsequent generations of structures.

Stratigraphic framework

Stratigraphic nomenclature in western Newfoundland may be confusing, and many frequently used unit names lack formal definitions. In the following account, we use upper case initial letters ("Formation," "Group") to designate formal units, and lower case ("formation," "group") for informal units, following Williams et al. (1985). Our mapping on the shores of Humber

Fig. 2. Map of Corner Brook and area to the west, showing distribution of stratigraphic units, together with orientations of bedding and D_1 structures. Fm., Formation.

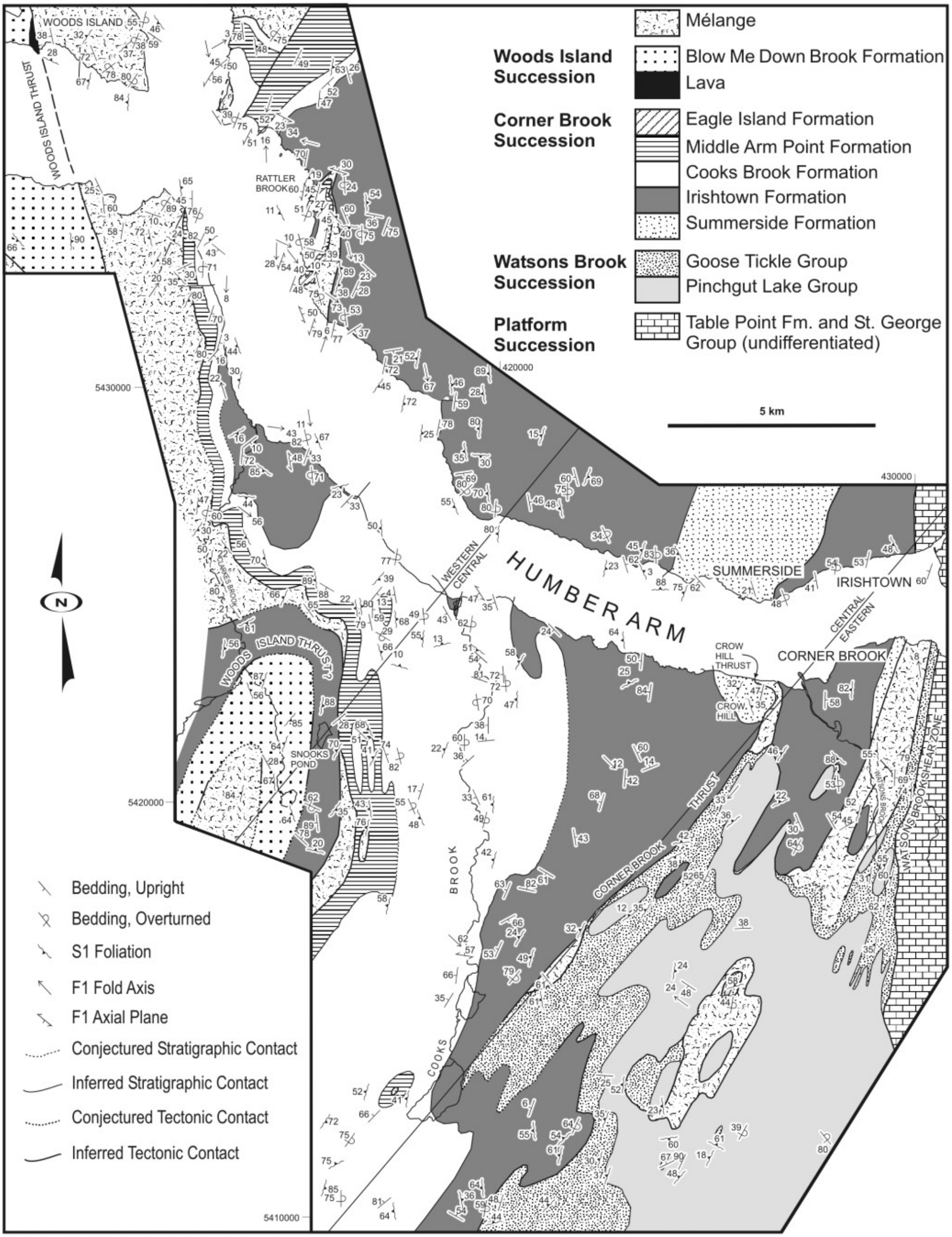
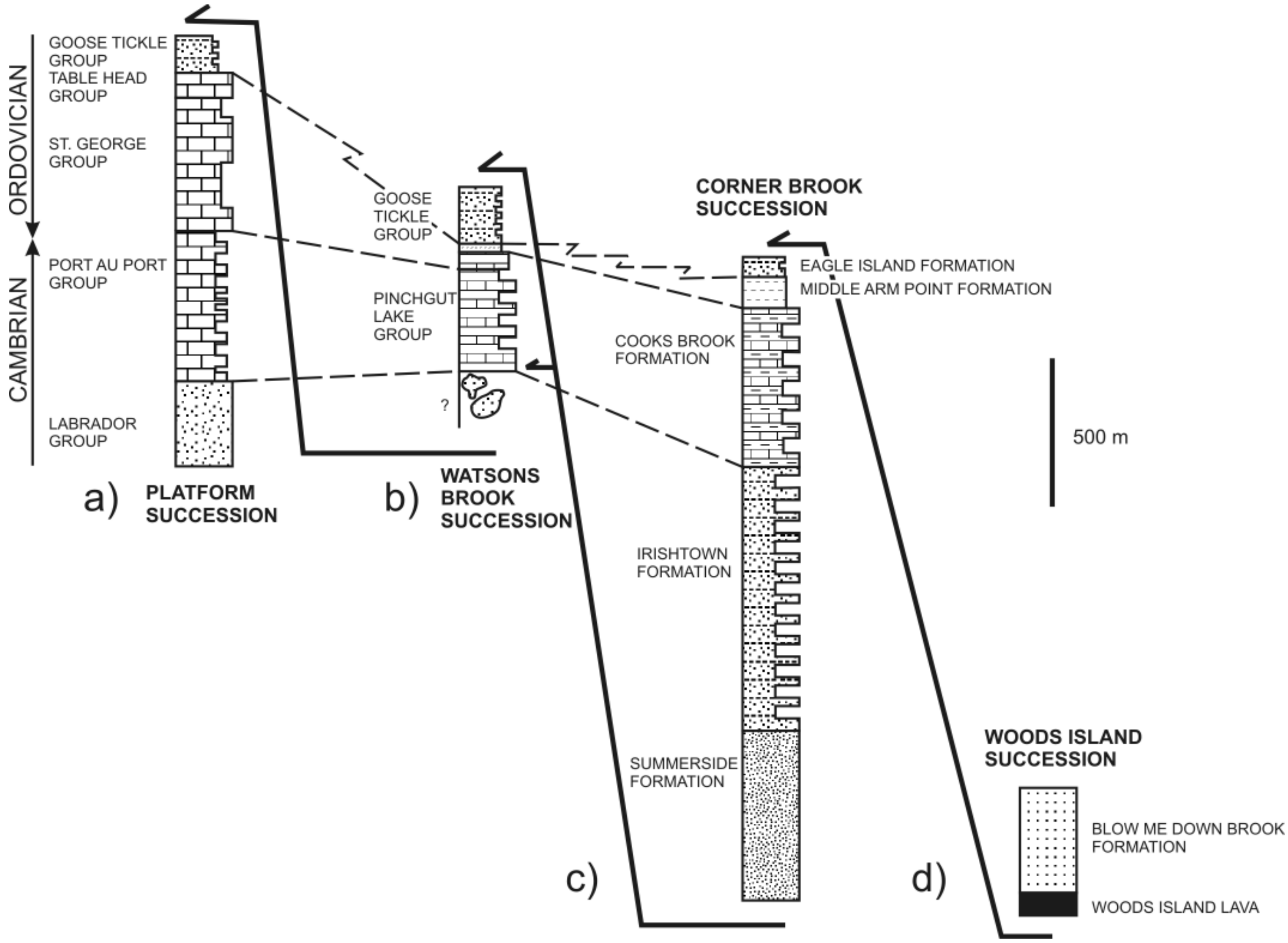


Fig. 3. Stratigraphic columns representative of the four successions described in the mapped area.



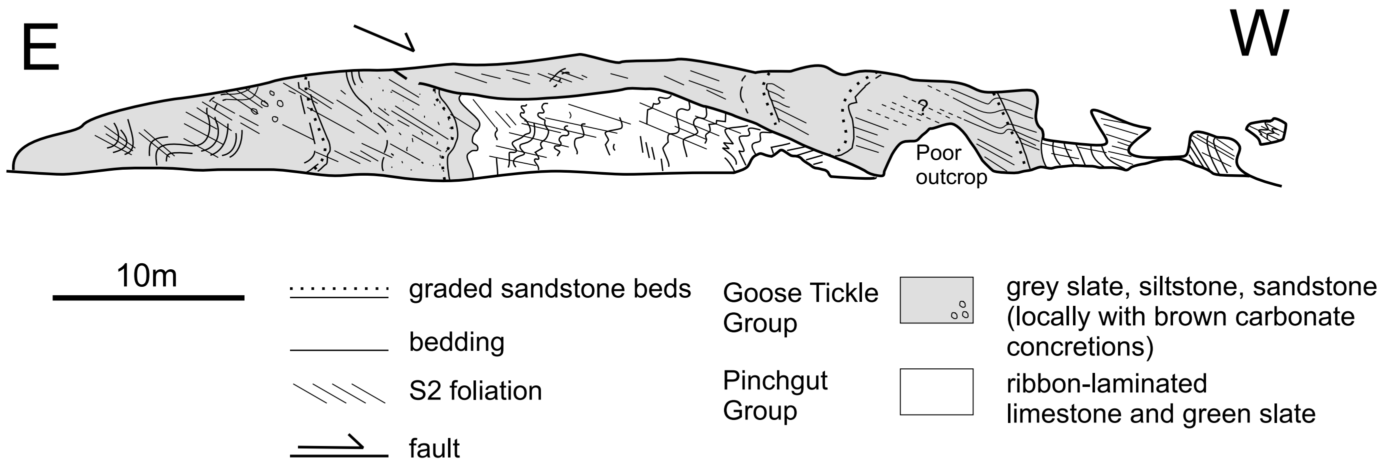
Arm has confirmed major elements of the deep-water stratigraphy (Fig. 3, columns c and d), identified and outlined by Stevens (1965, 1970) and Bruckner (1966). More recently, several significant modifications of the stratigraphy have emerged from paleontological and other work. Lindholm and Casey (1989) determined that two distinct units had been included in the Blow Me Down Brook formation of Bruckner: an Early Cambrian unit with the trace fossil *Oldhamia*, and an Early Ordovician unit with graptolites. The type area at Blow Me Down Brook was within the older of these two units, which therefore retained the name. It was left to Botsford (1988; Boyce et al. 1992) to propose the name Eagle Island formation for the Early Ordovician foredeep deposits.

Deformed carbonate rocks of "platform" facies were initially subdivided only at group level (e.g., Williams 1973). Mapping within the carbonates by Knight (1996*a*) has permitted the recognition of formation and even member-level units, within the Port au Port, St. George, and Table Head groups (Fig. 3 column a), known from less deformed areas of western Newfoundland. Overlying foreland basin clastic sedimentary rocks of the Goose Tickle Group have locally been recognized at the top of the platform succession, though these are intensely deformed and are difficult to separate from tectonically disrupted parts of the overlying thrust sheets.

Additional stratigraphic units were identified inland and to the south of Corner Brook by Williams and Cawood (1986). Carbonate units were assigned by them to the Pinchgut group; adjacent clastic rocks were designated the Whale Back formation. The carbonates were mapped in greater detail as the Pinchgut Lake group by Knight (1995; 1996*a*; 1996*b*), who interpreted them as a separate thrust sheet, internally folded, but resting tectonically upon the clastics, which he assigned to the Goose Tickle Group. Cawood and van Gool (1998) reduced the unit to formation status, defining a Pinchgut Formation, including both the clastic rocks and the carbonates. In the course of our mapping, we have recognized apparent stratigraphic continuity from carbonate rocks, upward through bioturbated slates, into grey-green cleaved sandstones and slates identical to the Goose Tickle Group at the top of the platform (Fig. 3 column b, Fig. 4). We follow Knight in retaining the term Pinchgut Lake group for the carbonate succession, together with interbedded and overlying slates, and map the overlying coarser clastic units as the Whale Back formation of the Goose Tickle Group.

The Pinchgut Lake group and its cover appear to represent

Fig. 4. Field sketch of outcrop at location A (Fig. 6) showing deformed stratigraphic contact between Pinchgut Lake group and Goose Tickle Group, offset by a low-angle normal fault.



environments transitional between platform and slope. The carbonates were correlated generally with the upper Port au Port Group and Lower St. George Group by Knight (1996*b*) and inferred to represent platform-margin environments. The overlying bioturbated slates resemble in facies the Middle Arm Point formation of the Corner Brook succession (see later in the text). These possibly represent an interval of "starved" slope or drowned platform environments, at the edge of the former shelf.

At one locality close to the inferred tectonic basal surface of the Pinchgut Lake group, we observed blocks in mélange of interlaminated argillite and white quartzose sandstone, with ripple cross-laminations (Fig. 5*b*). These blocks contrast with other clastic rocks in the area in lacking distinctly graded sandstone turbidite beds; finer and coarser sands and silts are gradationally interlaminated, suggesting shelf rather than slope environments. We infer that these blocks may represent the unit originally underlying the Pinchgut Lake group, the inferred equivalent of the Labrador Group in the platform succession (Fig. 3 column b).

As a result of these observations and interpretations, we recognize four distinct stratigraphic successions in the Corner Brook area (Fig. 3). Each succession is separated from the others by contacts that are entirely tectonic. Because of overlap in the inferred timing of the various successions, we interpret each as the product of a distinct environment on the continental margin of Laurentia, and suggest that each represents a distinct major thrust sheet, equivalent to the "nappes" described in the external Humber Zone of the Quebec portion of the orogen (e.g., St. Julien and Hubert 1975).

The four successions are (*i*) the platform succession, dominated by limestones, dolostones, and marbles of the Port au Port, St. George, and Table Head groups representing the former shelf and its foreland basin cover; (*ii*) the Watsons Brook succession, dominated by shelf-margin carbonates of the Pinchgut Lake group but also including the overlying and possibly underlying clastic units; (*iii*) the Corner Brook succession, comprising the Summerside, Irishtown, Cooks Brook, and Middle Arm Point formations named by Bruckner (1966), together with the overlying Eagle Island formation clastics; and (*iv*) the Woods Island succession, comprising the Blow Me Down Brook formation together with underlying or intercalated lava units.

Structure

Structurally, the Humber Arm Allochthon has had a complex history and presents challenges to the mapping geologist because, in some areas, the spacing of faults is closer than the spacing of outcrops. Also, because the metamorphic grade is low, deformation is heterogeneous, and brittle structures predominate, it is in many areas difficult to distinguish a clear overprinting sequence of structures. Nonetheless, in this study, it has been possible to separate generations of structures based on overprinting criteria in favourable outcrops, especially those along coasts and highways adjacent to Humber Arm (Figs. 2, 6). However, in small inland outcrops, where overprinting criteria are unclear, our identification of fabrics as S_1, S_2, etc. is in part based on analogies of structural style with better exposed sections.

Synsedimentary and penecontemporaneous structures

Structures associated with synsedimentary or penecontemporaneous deformation are relatively common. Many turbidite sandstone and limestone beds show load structures, convolute lamination, or ball-and-pillow structure. A widespread zone of sandstone injection structures is found at the base of the Eagle Island formation (see Botsford 1988). Elsewhere in the Eagle Island formation, there are folded sandstone beds having strongly thickened hinges (e.g., Waldron 1985), indicating deformation while sand was more ductile than surrounding mud, probably at a very early stage of diagenesis. However, the Eagle Island formation was tectonically deformed very soon after deposition: hence it cannot be assumed that soft-sediment structures are necessarily truly synsedimentary. Thus, in some cases, it is not possible to unequivocally distinguish "early" folds as either F_0 (slump folds) or F_1 (early tectonic folds).

Outcrop-scale D_1 structures

Fragmentation and mélange

The most characteristic deformational features of the

Fig. 5. Field photographs. (*a*) Typical view of mélange showing blocks, dissected by brittle fractures, in scaly matrix. (*b*) Detail from block in mélange of Watsons Brook sheet, showing sedimentary structures (overturned) in interbedded, interlaminated, quartzose sandstone and siltstone, possibly representing stratigraphic unit below Pinchgut Lake group. (*c*) Summerside formation slate on north shore of Humber Arm at Irishtown showing F_1 fold overprinted by cleavage S_2. (*d*) Pinchgut Lake group limestone showing F_1 fold overprinted by F_2 folds and S_2 cleavage at Lewin Parkway, locality A. (*e*) Pinchgut Lake group exposure in quarry at locality B, showing sheath-like folds: white arrows highlight two curved fold hinges. (*f*) Fibre filled en-echelon tension gashes at locality C, indicating thrust-sense shear. Hammer for scale in (*a*). Pencil for scale in (*b*), (*c*), (*d*), (*f*).

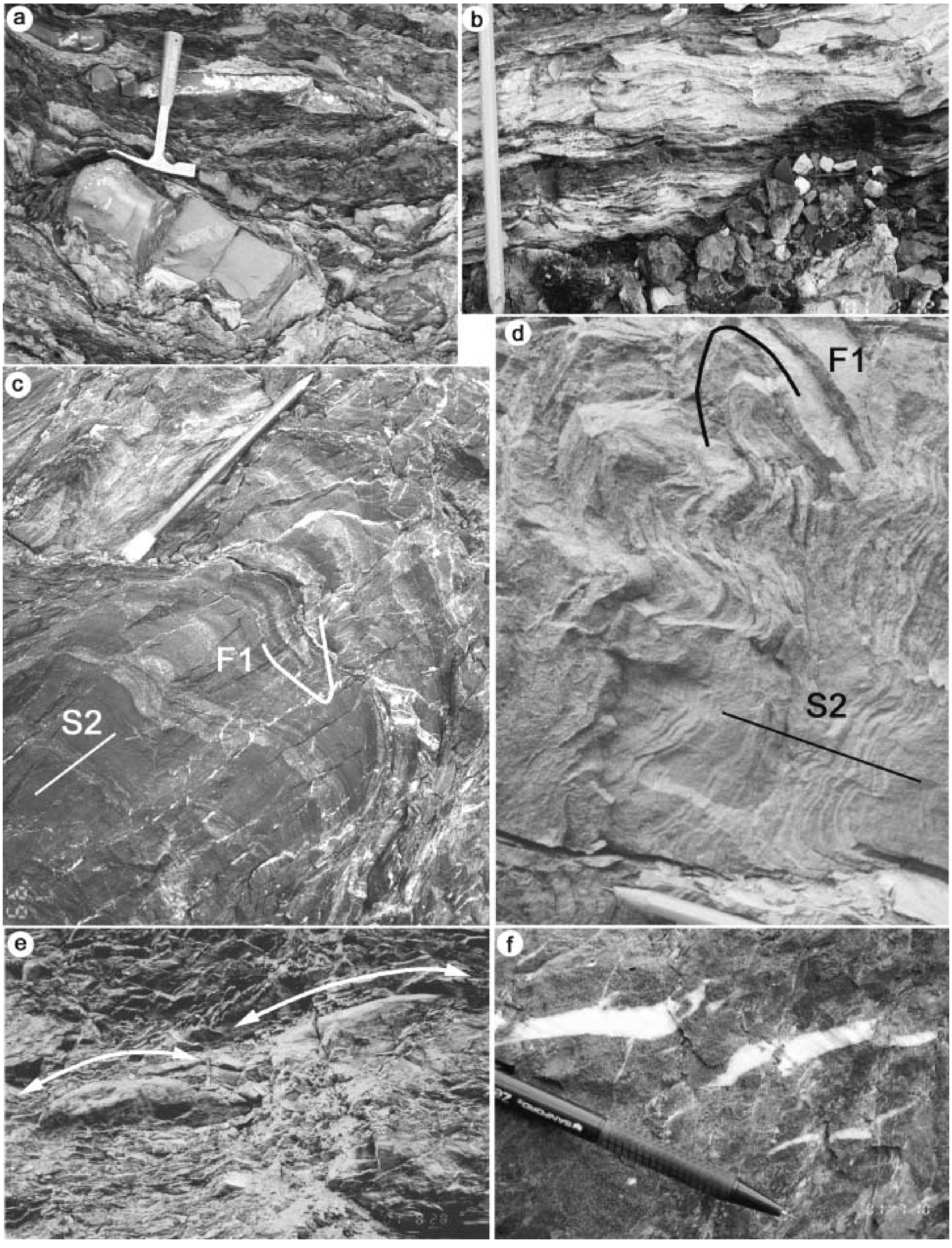
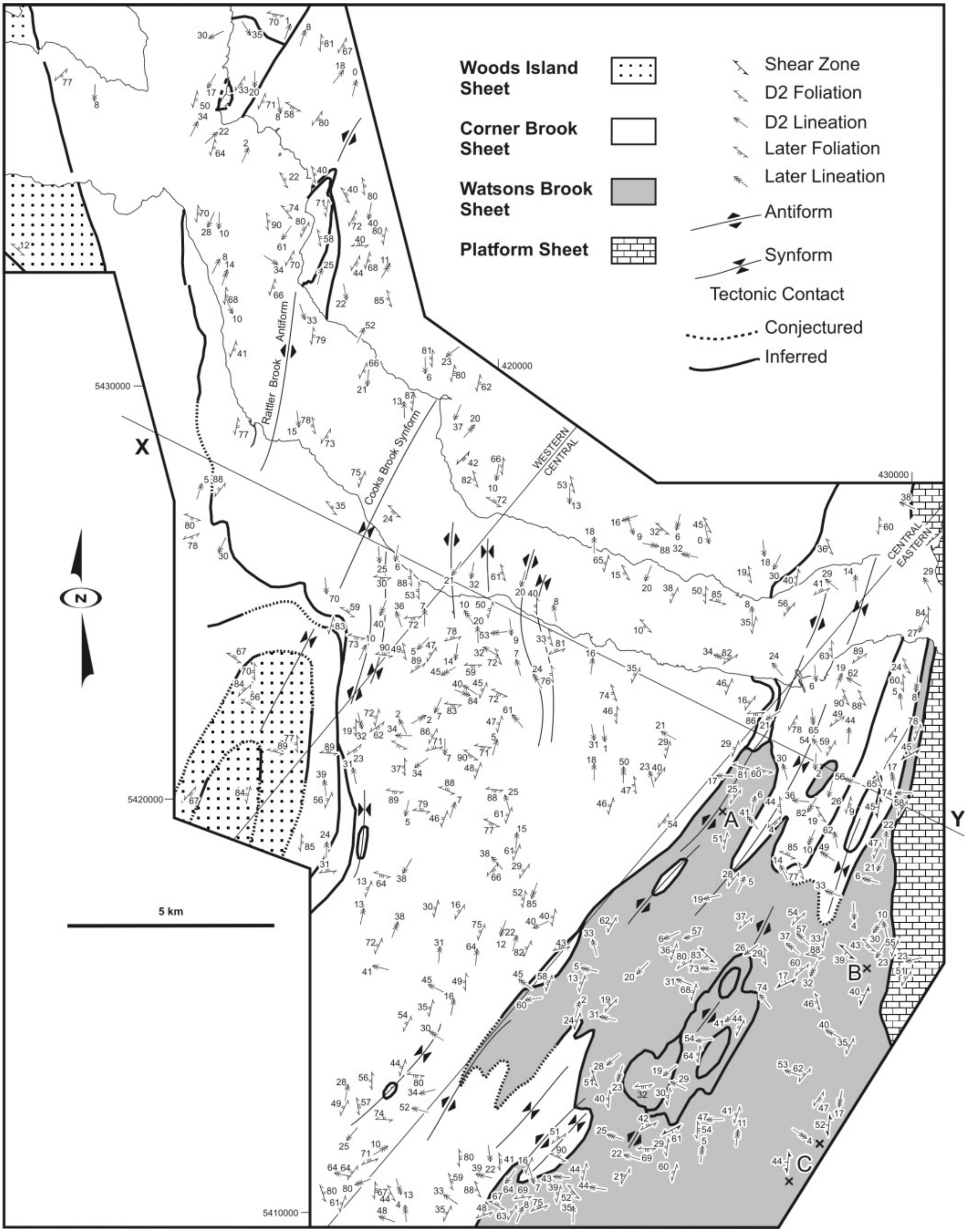


Fig. 6. Map of Corner Brook and area to the west, showing interpreted distribution of D_1 sheets, together with orientations of D_2 and later structures.



sedimentary portion of the Humber Arm Allochthon are zones where stratification has been disrupted, producing configurations of blocks of competent lithologies (sandstone, limestone) immersed in a matrix of deformed shale. All stages in the progressive boudinage of sandstone and limestone beds can be observed; typically the beds are disrupted by brittle extension and shear fractures. Zones where bedding has been largely disrupted (Fig. 5*a*) have variously been described as "mélange" or "broken formation." They typically display scaly foliations that resemble those described in modern accretionary wedges (Waldron 1985; Waldron et al. 1988).

In addition to fragmentation, significant mixing of lithologies has clearly taken place in some zones of early disruption. Lithologies characteristic of several different formations may be found together as blocks in a single outcrop. Blocks of mafic lava, resembling the lava in the Woods Island succession, are particularly characteristic, and in some cases are found between slices that have no lava preserved in situ. In this study, we restrict the term mélange to those domains where mixing at formation level can be demonstrated; some areas formerly categorized as mélange based on style of deformation (e.g., Waldron et al. 1988) are here excluded from that category, because the protolith appears not to have involved mixed formations.

Fabrics

Most of the coherently bedded fine-grained sedimentary rocks of the Humber Arm Supergroup display a strong bed-parallel fissility, which is axial planar to rare F_1 folds (see later in the text). This fabric is seen in thin section to be defined by preferred orientation of fine-grained phyllosilicates and probably represents the original compactional fissility of the shales, enhanced by the tectonic deformation that extended bedding to produce boudinage structures. In mélange and broken formation, the S_1 fabric is anastomosing and scaly. Polished slickenside surfaces are common; they branch around lenticular domains, in which the fissility fabric has variable orientation, indicating relative rotation of the domains during deformation. Therefore, this scaly fabric is interpreted as a composite fabric produced by cataclastic flow of already fissile shale.

In the Summerside formation, early fabric development appears to be different. Bed-parallel foliation is widespread in mudrocks, but sandstones typically show an S_1 cleavage characterized by seams of recessively weathered, quartz-poor material, spaced at 5 mm to 5 cm apart. This fabric is interpreted as a pressure-solution cleavage. At a number of locations that display folds, the orientation of this pressure-solution cleavage is consistent with an axial-planar relationship to F_1, but not to F_2. These relationships suggest that pressure-solution processes dominated the deformation of the Summerside formation during D_1 deformation, in contrast to the cataclastic flow that affected the remaining units of the allochthon.

Plots of poles to bedding and S_1 foliations generally show girdle distributions that are dominated by the effects of F_2 folding (Fig. 7). However, towards the east of the area, the distribution of S_1 cleavages becomes closely similar to that of S_2 (Fig. 8*a*), reflecting the transposition of S_1 scaly foliations into parallelism with S_2 (see later in the text).

Folds

F_1 folds are found at a number of locations in the Humber Arm Supergroup, though they are not as conspicuous as the pervasive F_2 folds (see later in the text). Typically, F_1 folds are isoclinal, intrafolial, asymmetric fold pairs with axial surfaces parallel to the regional envelope of bedding and S_1. Figures 5*c* and 5*d* show F_1 folds in the Watsons Brook and Corner Brook successions that are overprinted by F_2 folds, a feature also noted by Cawood and van Gool (1998, fig. 19).

Folds are also apparent in zones where bedding is disrupted by boudinage and even in mélanges. Tight to isoclinal folds are found within blocks, indicating that folding occurred before fragmentation. In some cases, the orientation of scaly fabric surrounding, or within, the blocks appears axial planar to the folds. However, in other examples, the bed-parallel fissility appears folded. Elsewhere, in highly disrupted zones, the scaly fabric, together with trains of bed-fragments, is also folded, indicating that folding postdated boudinage and fragmentation.

Despite these local overprinting relationships, we have not been able to establish a clear sequence of deformation events within the general spectrum of structures predating the regional cleavage (S_2), and have characterized them all as D_1. Potentially, future investigations might enable this spectrum to be broken down into D_{1a}, D_{1b}, etc.

Map-scale D_1 structures

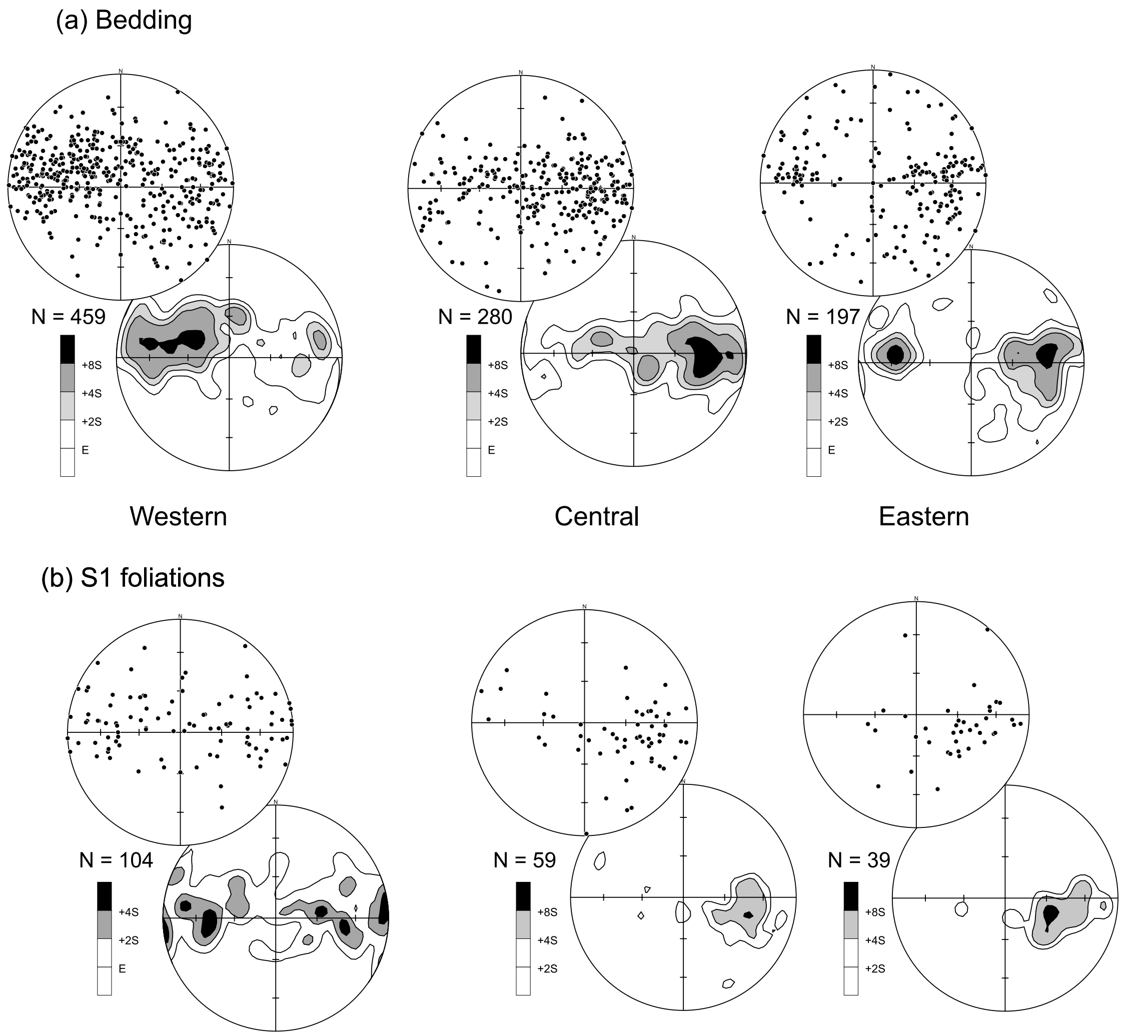
Within the area of mapping, all the successions (with the possible exception of the Woods Island succession) are present in more than one structural unit. In general, the tectonic contacts between units are subparallel to stratigraphy; they are inferred to represent thrust faults that formed during the telescoping of the continental margin. We term the fault-bounded units "slices." Because the different stratigraphic successions must represent separated environments on the continental margin, it is likely that where thrusts juxtapose parts of the same stratigraphic succession, they are of generally small displacement. In contrast, faults across which contrasting successions are juxtaposed are inferred to represent more major thrust surfaces. On this basis we recognize four major sheets, corresponding to the four stratigraphic successions outlined earlier in the text (Fig. 2). Figure 9 shows the inferred geometry of slices and sheets.

Watsons Brook sheet

West of the platform sheet, we recognize a Watsons Brook sheet containing at least two slices of Pinchgut Lake group and its cover. Most of the area of exposure is attributed to an upper slice; a tectonic window located at the culmination of a doubly plunging F_2 fold exposes mélange and a portion of a lower slice. Relationships at the eastern edge of the sheet are complex, involving tight interleaving of Pinchgut Lake group, Goose Tickle Group, and mélange, with a strong component of later shear modifying the original thrust contacts; additional slice boundaries may be present in this area.

We have not attempted to make stratigraphic subdivisions within the Pinchgut Lake group, but by tracing conglomerate bands and other distinctive facies, Knight (1996*a*) distinguished reversals of younging direction interpreted as regional F_1 folds. Therefore, it is inferred that the Watsons Brook succession

Fig. 7. Equal area plots showing orientation of bedding and early cleavage (see Fig. 2 for definition of areas). (*a*) Poles to bedding from western, central, and eastern areas. (*b*) S_1 foliations from western, central, and eastern areas.



was recumbently folded at an early stage in the emplacement process.

Corner Brook sheet

The overlying Corner Brook sheet is dominated by a single large slice (the Crow Hill slice), within which a deformed, but essentially intact stratigraphic succession from Summerside to Middle Arm Point formation is observed. The base of this slice is exposed as the Crow Hill thrust in Corner Brook, where it has a complex history of both eastward and westward movement (Bosworth 1985; Waldron et al. 1988; Cawood and van Gool 1998). Blocks of altered mafic pillow lava are seen in the thrust zone. Summerside rocks in the hanging wall are folded and locally show downward facing directions on S_2, indicating that the folds are F_1 folds. In addition, the location of hanging wall cut-offs and the trace of the Summerside–Irishtown boundary strongly suggest the presence of a west-facing recumbent F_1 fold above the thrust.

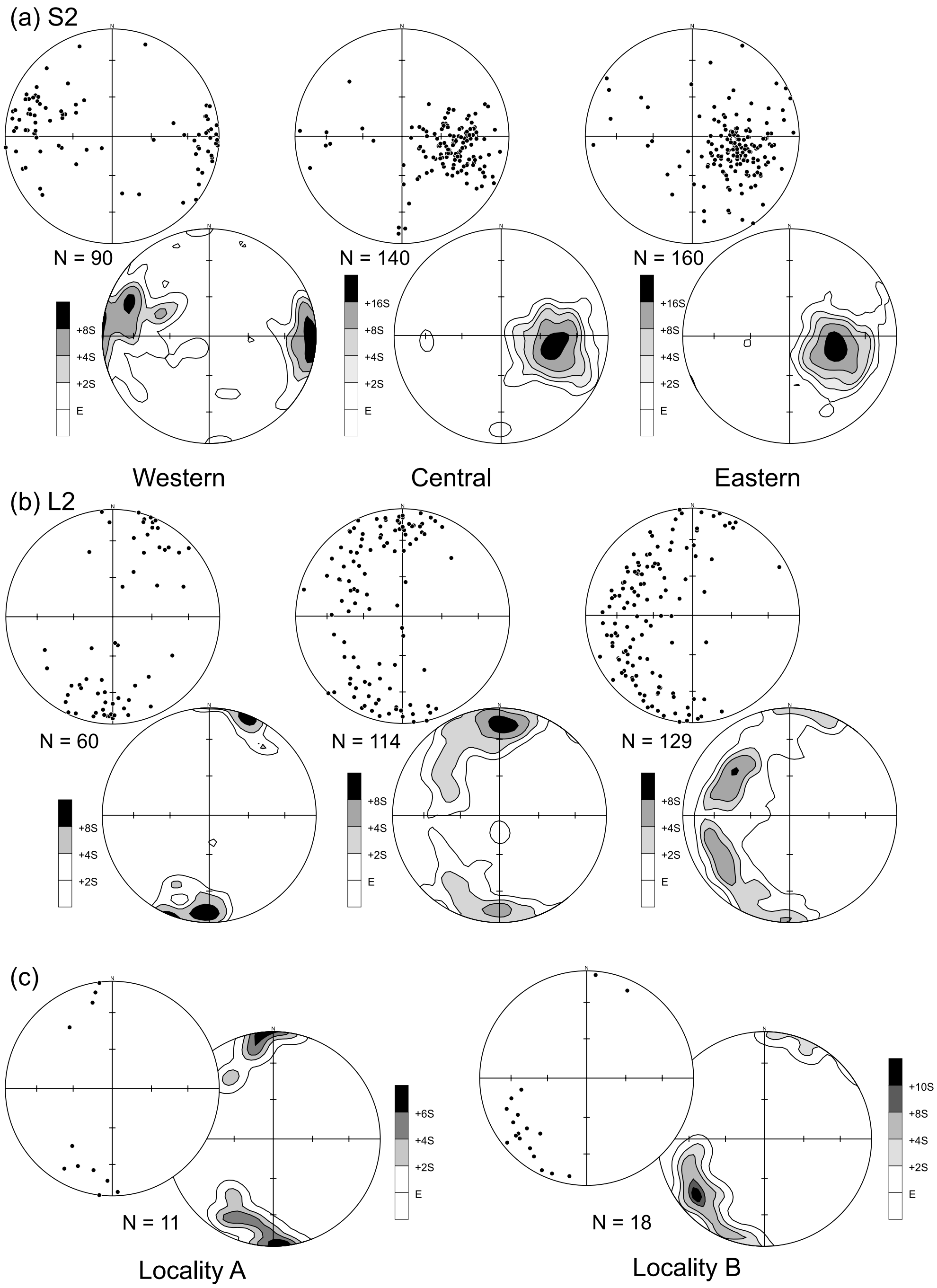
Below the Crow Hill thrust is a slice (Corner Brook slice) exposed only within the city of Corner Brook and in a corresponding area on the north side of Humber Arm at Irishtown. This slice preserves stratigraphy from highest Summerside to possibly basal Cooks Brook formation. It pinches out southward as the Crow Hill and Corner Brook thrusts merge.

A second structurally low slice, noted by Waldron (1985), is exposed in the culmination of a doubly plunging F_2 antiform at Rattler Brook, on the north shore of Humber Arm (Fig. 2). Within this window, a succession from upper Irishtown formation to basal Eagle Island formation is exposed. However, the succession on the west limb of the antiform is strongly attenuated, probably by boudinage analogous to that seen at outcrop scale. The Cooks Brook formation is reduced in thickness to ~50 m, and the Eagle Island formation is absent at the contact with mélange near Rattler Brook. Lava blocks are again present in the mélange zone.

The slice seen in the Rattler window could be continuous with the lower slice seen in Corner Brook; relations in both hanging wall and footwall would be consistent with a thrust climbing up-section to the west. However, the southward pinch-out of the Corner Brook slice would then have to be interpreted as a lateral ramp in the lower slice. Alternatively, the two slices could be separate slivers entrained at the base of the sheet, as shown in Fig. 9.

In the vicinity of Snooks Pond (Fig. 2), a slice consisting

Fig. 8. Equal area plots showing orientation of D_2 structures (see Fig. 3 for definition of areas). (*a*) S_2 foliations and F_2 fold axial surfaces; (*b*) L_2 lineations and F_2 fold hinges; (*c*) plots illustrating curvature of fold hinges at localities A and B.

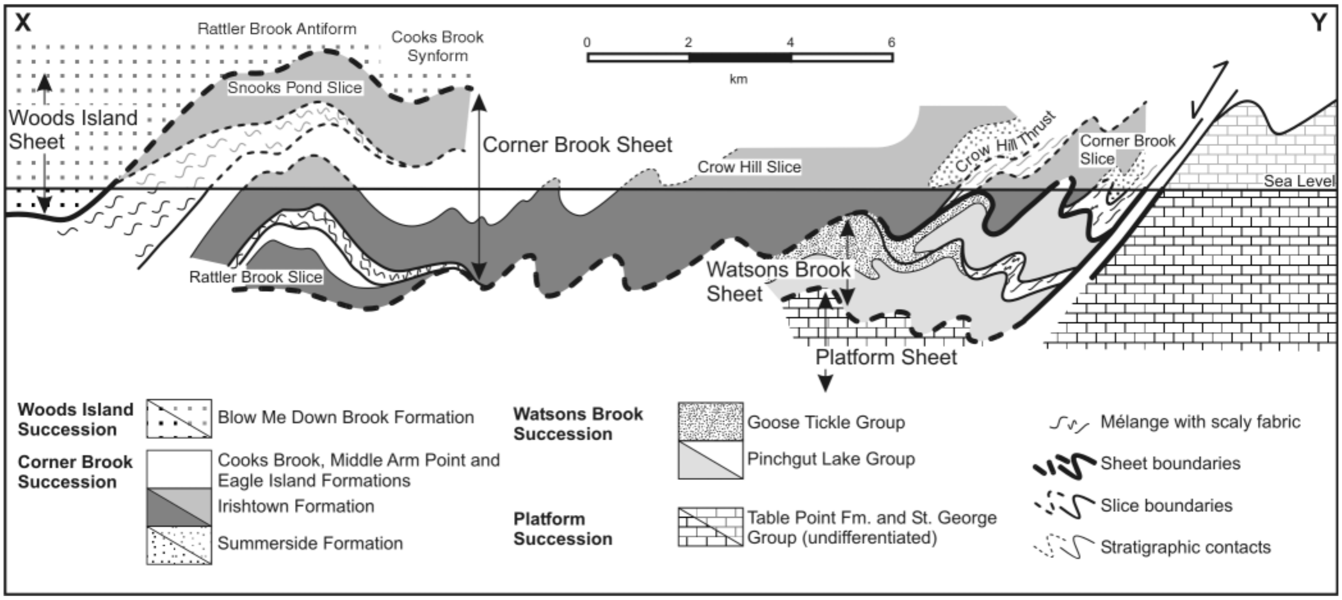


entirely of Irishtown formation apparently overlies the Crow Hill slice, separated from it by another broad belt of mélange containing blocks of lava. Other slices containing fragments of the Corner Brook succession occur in the area of Middle Arm Point and farther north; because of the number of high-angle faults in this area, it is difficult to correlate these with the structural units exposed south of Humber Arm.

Woods Island sheet

The highest sheet in the area, and the structurally highest sheet in the sedimentary part of the Humber Arm Allochthon, is dominated by the Blow Me Down Brook formation. The most continuous section is exposed on the coast of Woods Island. On the south coast of the island, the sandstones are seen in stratigraphic contact overlying a unit of mafic pillowed and massive lava, and lava breccia. We have inferred (Palmer et al. 2001) that this represents the base of the Woods Island succession. However, subsequent mapping has shown that the unit exposed on Woods Island is perhaps atypical of the formation as a whole; more deformed fragments contain a higher proportion of shale (T. Calon and E. Burden, personal communication, 2001). Therefore, it is possible that the

Fig. 9. Schematic cross-section through the Corner Brook area illustrating inferred structural relationships.



continuous section was preserved because of its unusually high proportion of competent sandstone. It is also possible that the lavas represent an intercalation within the Blow Me Down Brook formation, rather than their true basement.

The base of the sheet is exposed on the south coast of Woods Island, where the lavas sit above a highly sheared zone of mélange and sheared shale, dipping to the west. Additional slices of Blow Me Down Brook formation occur within the zone mapped as mélange that lies to the east. Several of these slices contain recorded occurrences of the characteristic trace fossil *Oldhamia* sp. (Lindholm and Casey 1990). Our recent mapping has shown that the Blow Me Down Brook formation also occurs in the core of a synformal structure west of Cooks Brook, where it is in tectonic contact above the Corner Brook succession (Fig. 2).

The Woods Island sheet is probably much more extensive than the small portion shown in Fig. 2. Lindholm and Casey (1989) and Williams and Cawood (1989) showed that sandstones of the Blow Me Down Brook formation and its correlatives form a belt in proximity to the eastern sides of the Bay of Islands ophiolite massifs throughout the Humber Arm Allochthon.

Regional S_2 cleavage and associated structures

S_2 cleavage

The eastern part of the area mapped is affected by penetrative cleavages that strike consistently north–south to northeast–southwest; the intensity of the cleavage decreases westward. Although the cleavage appears slaty and penetrative in many samples, in most outcrops, it is possible to find S_1 surfaces preserved in the finest grained lithologies; there, S_2 is responsible for finely spaced crenulation lineations on the S_1 surfaces. This observation is confirmed in thin section, where fine-grained lithologies preserve crenulated S_1 surfaces. In contrast, in silty and sandy lithologies, pressure solution at the margins of coarse grains has obliterated the S_1 cleavage. S_2 cleavage is heterogeneously distributed. In the western half of the area, S_2 is only sporadically developed, taking the form of a variably spaced steeply dipping crenulation of S_1. In the eastern part of the map area shown in Fig. 2, S_2 cleavage is intense, locally phyllitic, and dips gently to moderately west. This trend is well portrayed by plots of the orientation of S_2 (Fig. 8*a*).

In zones of disrupted bedding, and adjacent to slice boundaries, S_2 cleavage planes are markedly less planar than elsewhere, taking on a “crinkled” appearance similar to the scaly foliations described under S_1. We attribute this appearance to a difference in the style of development of S_2 in zones previously subject to intense D_1 deformation. Where bedding was intact, and S1 fabric planes continuous, S_2 developed through progressive crenulation of S_1. In areas where S_1 was a scaly fabric, and coherent competent beds were absent, S_2 developed by transposition of the fracture-bounded fragments within the scaly shale (shown schematically in Fig. 9). This transposition accounts for the variation in the distribution of poles to S_1 fabrics across the area (Fig. 7*b*). In the west, the girdle distribution resembles that of bedding, created by the effects of subhorizontal F_2 folds; in the east, the distribution of S_1 poles is essentially indistinguishable from that of S_2.

F_2 folds and L_2 lineations

F_2 folds are present at both outcrop and map scale. Folds at outcrop scale are typically open to tight, with axial surfaces striking north–south or NNE–SSW. Axial plunges are extremely variable. In some cases, F_2 folds have gentle plunges north or south, but elsewhere the fold hinges display steeper rakes, ultimately leading to the development of reclined folds. In general, there is a tendency for folds in the west to show shallow axial rakes, whereas steeper rakes and reclined folds are most abundant in the east (Fig 8*b*). At map scale, all the boundary surfaces between D_1 slices and sheets are strongly folded, with the result that original relationships at thrust faults are locally inverted (Fig. 9). Map-scale folds, especially at kilometre scale, appear to trend significantly more northeast than small-scale folds and fold axes deduced from stereographic

Fig 10. Thin section photographs. Except as noted, the foliation observed in hand sample is oriented horizontally in the photographs. (*a*) Undulose and dynamically recrystallized calcite from calc-mylonite at locality B (Fig. 6). Scale bar 0.5 mm. (*b*) Stretched quartz domain with oblique foliation indicating normal-sense (clockwise in this view) shear. Scale bar 0.5 mm. (*c*) Muscovite layer in calc-mylonite from locality B showing shear bands with normal-sense shear (counter-clockwise in this view). Foliation observed in hand sample is oriented top-left to bottom-right. Scale bar 3 mm. (*d*) Microstylolyte in calc-mylonite from locality C (Fig. 6). Scale bar 2 mm. (*e*) Montage of thin section photographs from sample showing opposing senses of shear, locality C. Scale bar 5 mm. (*f*) Enlargement of (*e*) showing clockwise shear (reverse sense in this view). Scale bar 0.5 mm. (*g*) Enlargement of (*e*) showing counterclockwise shear in muscovite-rich layer with shear bands. Scale bar 1 mm.

projections. A similar discrepancy, though less pronounced, can be detected between the strike of map-scale fold axial surfaces and the average strike of S_2 cleavage. It is possible that some map-scale F_2 folds may have nucleated over larger scale thrust-related D_1 structures, possibly ramps and flats in thrust sheets, producing a weakly developed interference pattern.

However, at a number of localities, we have seen folds in outcrop that have strongly curved hinges over distances of 50 cm to 5 m. At locality A (Fig. 6) in the Watsons Brook sheet, such folds show 90° variations in hinge rake, approaching the geometry of sheath folds (Fig. 5*e*). Figure 8*c* shows the distribution of fold hinge orientations at single outcrops, illustrating this dispersion within the general plane of the S_2 foliation.

Waldron (1985) noted the variations in the plunge of F_2 folds on the shores of Humber Arm and farther north and attributed it to later deformation by sporadically developed later folds. However, the present data set shows a much greater dispersion of rakes. This, combined with the observation of sheath-like fold geometries in areas where no clear later fabric is present, leads to the conclusion that large components of non-coaxial shear were responsible for the development of curved fold hinges. The timing of this shearing will be discussed later in the text, after consideration of shear zone geometries.

F_2 folds are locally seen refolding F_1 folds, producing fold interference patterns that are generally of type 3 in the classification of Ramsay (1967). In areas of steep F_2 rake, type 2 interference patterns might be predicted, but these were not observed. Possibly the shearing responsible for the reclined orientation of F_2 also rotated any F_1 fold hinges into steeply plunging orientations.

L_2 lineations include both intersection lineations between S_2 cleavage and bedding, and crenulation lineations, where S_1 is folded by F_2; in general the two types of lineation are parallel, and reflect the local orientation of F_2 fold hinges.

Shear zones

Intensely sheared, mylonitic limestones were seen at a number of locations within the Pinchgut Lake group limestones of the Watsons Brook sheet and are especially evident close to its eastern edge. We infer that the boundary between the platform and Watsons Brook sheet is marked by a broad west-dipping shear zone. Two localities with good exposure were selected for detailed study in an attempt to determine the history of shearing.

At locality B (Fig. 6), a quarry south of Corner Brook, ductile shear zones are observed to dip generally west to west-northwest, with stretching lineations that plunge to the west with rakes near 90°. In exposure on an east–west quarry face, asymmetric limestone blocks ~25 cm in diameter are surrounded by shaly rocks, defining large-scale sigma structures that apparently indicate reverse sense movement. However, weak C–S fabrics present in another west-dipping mylonitic zone imply normal-sense movement. A quarry face oriented approximately north–south exposes two folds with strongly curved hinges, each about 3 m across (Fig. 5*e*). The S_2 cleavage appears axial planar to these structures.

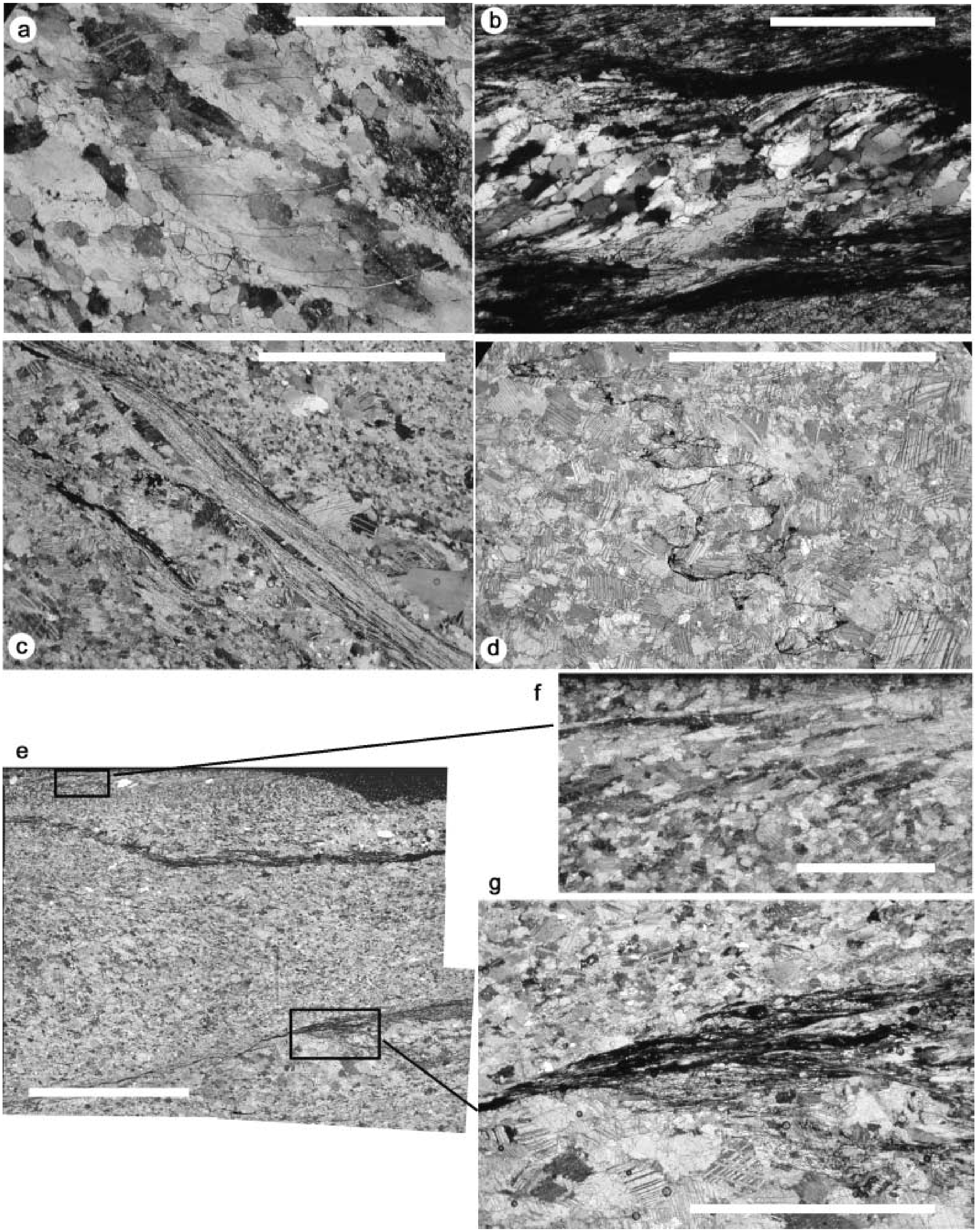
In thin sections cut parallel to the stretching lineation, indicators of deformation are numerous and varied. Abundant deformed calcite crystals exhibit strain twinning, undulose extinction, subgrains, and dynamic recrystallization (see Fig. 10*a*). In some cases, early calcite veins show internal deformation of the calcite crystals, indicating that ductile deformation followed brittle fracturing. Effects of pressure solution can also be seen, in the form of microscopic stylolites.

Areas of stretched quartz grains are visible, displaying an oblique foliation pattern (Fig. 10*b*). Within these domains, the quartz grains closer to the edges appear more elongate and have more undulose extinction than the crystals closer to the centre, suggesting that shearing was concentrated at the edges of the quartz-rich domains. In one section, zones of highly deformed “ribbon quartz” (see Fig. 10*b*) define an extension direction consistent with normal-sense shearing, as do muscovite-rich zones showing anastomosing foliations including shear bands (Fig. 10*c*). A moderately clear C–S fabric is developed, most evidently in the calcite-rich zones of these rocks, again indicating normal-sense (top to the west) shearing.

The shear sense indicators found at location B (Fig. 6) show evidence for two opposing senses of movement. All the ductile deformation seen in thin sections, and the outcrop scale C–S fabric indicate top-to-the-west (normal-sense) motion on the northwest-dipping shear surfaces. The sigma structures seen in outcrop suggest a top-to-the-east interpretation. The relative timing of these two opposing senses of deformation cannot be determined.

At locality C (Fig. 6), on the Trans-Canada highway, Pinchgut Lake group rocks display evidence for both ductile and brittle deformation at mesoscopic as well as microscopic scales. At outcrop scale, ductile indicators include small sigma structures found within moderately west-dipping mylonite zones, C–S fabrics in the shaly sections, and abundant stretching lineations trending generally west to northwest. Reclined folds occur in thinly bedded nodular limestones; strong stretching lineations defined by deformed nodules and clasts in limestone conglomerate plunge westward, raking steeply on the foliation surfaces.

At thin-section scale, ductile kinematic indicators are also diverse. As with the rocks from the locality B, most of the calcite crystals in the sampled rocks have sheared, elongate shapes and display distinct undulose extinction patterns,



subgrains, and dynamic recrystallization features. These rocks also display abundant evidence of pressure solution in the form of stylolites (see Fig. 10*d*). Foliated zones that are muscovite and chlorite rich represent original argillaceous layers.

At outcrop scale, all the ductile indicators found in the

Pinchgut Lake group display normal-sense, top-to-the-west movement. In thin sections cut parallel to the lineation, kinematic indicators are found to show opposing senses of movement, sometimes in the same thin section (Fig. 10*e*). Stretched calcite crystals indicate thrust-sense motion (Fig. 10*f*), whereas the shear bands visible in the muscovite and chlorite zones of these rocks clearly show top-to-the-west, normal displacement (Fig. 10*g*).

Structures showing brittle deformation are also abundant. Pervasive fault planes display steeply raking calcite slickenfibres. The majority show thrust movement, but in one example normal-sense slip was recorded. In some cases, brittle thrust planes follow and reactivate mylonitic normal-sense shear zones; the lack of ductile deformation in the fibres clearly shows that thrust-sense brittle fracturing postdated ductile shearing. In addition to the faults, east-dipping zones of en echelon tension gashes were observed, with sense indicating reverse-sense motion (see Fig. 5*f*).

The repeated overprinting of brittle and ductile structures in these rocks indicates that they passed through the brittle–ductile transition several times. This was most likely because of variations in fluid pressure during deformation. The simplest history that can explain the array of structures involves an early episode of mainly ductile normal-sense shearing on west-dipping surfaces. Subsequently, thrust-sense shearing occurred in response to horizontal shortening. This generated some ductile structures, but later reactivated the mylonitic surfaces as brittle fractures.

In general, both the mylonitic surfaces and the brittle fractures are close in orientation to the S_2 cleavage seen in adjoining rocks. In contrast to outcrops in the Blue Ponds thrust stack to the south (Knight 1996*b*; Ferguson 1998), mylonitic foliation surfaces are not visibly folded by F_2 folds. Instead, F_2 folds appear to be tightened and rotated into reclined orientations in the mylonitic zones. We infer, therefore, that the normal-sense ductile shearing in this area postdated F_2, and that reverse-sense shearing and faulting were later still.

Later folding and fabric development

Crenulation lineations on S_2 surfaces are sporadically developed in the Corner Brook, Summerside, and Irishtown areas. In some cases, multiple crenulation lineations are seen on the same surface. The heterogeneous distribution of these fabrics makes it difficult to definitively establish a sequence of events. A steep crenulation cleavage strikes west-northwest. Locally, this crenulation is axial planar to upright folds that refold the S_2 cleavage. In previous mapping (Waldron 1985), these folds were labelled F_3; culminations and depressions on F_2 folds were attributed to F_3 folding. However, the discovery of significant shear zones and sheath folds (earlier in the text) casts doubt on both these interpretations. There is no clear indication of the relative timing of the shear zones and the crenulation; and shearing produced sheath-like fold geometries that could account for the map pattern without appealing to fold interference. Based on relationships to the east at Old Man's Pond, where normal-sense shear zones are refolded by northwest-trending folds, the shear zones are tentatively interpreted as D_3 structures, the crenulation cleavage is labelled S_4.

In the Corner Brook and Irishtown areas, two lineations can be seen on S_2 surfaces, and overprinting relations can locally be discerned. The second, steep, crenulation cleavage (S_5) strikes south-southwest, crenulating both S_2 and S_4 and distorting the L_4 crenulation lineations. It may reasonably be correlated with the episode of thrust-sense motion late in the history of the shear zones described earlier in the text.

Discussion

Stacking of slices

Although the Humber Arm Allochthon and adjoining units were clearly thrust onto the continental margin of Laurentia, the characteristics of the units differ from those of typical foreland thrust belts; for example, structures that extend bedding are common and resemble structures found in accretionary terrains at trenches. Waldron et al. (1988) attributed this to the development of high fluid pressures during Taconian D_1 deformation of relatively wet sediments. Despite the abundance of extensional structures at outcrop scale, it is clear that on a regional basis, slices in the Humber Arm Allochthon and adjoining units are bounded by thrust faults, because at most tectonic contacts, older units are superimposed upon younger units (Fig. 9), as in typical thrust belts (e.g., Dahlstrom 1969; Boyer and Elliot 1982). There are some extensional structures at map scale. For example, on the west limb of the Rattler antiform, both on the north and south shores of Humber Arm, the Cooks Brook and Middle Arm Point formations are strongly reduced in thickness and locally absent; this is provisionally attributed to bed-parallel extension during D_1 deformation, though other explanations are possible: for example, the units in question are located in the steeply dipping "forelimb" of a fold, where attenuation is typically recorded even in more conventional thrust belts.

The kinematics of incorporation of lava blocks into mélange zones is poorly understood. Comparable lavas are known in the Woods Island succession, which lies high in the structural stack, and we suspect that a sheet of mélange was initially spread across all the lower units as the Woods Island sheet was thrust over the margin. This material was then incorporated between slices as individual sheets were shortened as duplexes.

Transport distances

Minimum distances of transport for the various sheets and slices may be determined by matching footwall and hanging wall cutoffs of stratigraphy. However, in many cases the D_1 transport direction is not precisely known and the three-dimensional exposure is insufficient to determine whether cutoffs represent frontal or lateral ramps. In addition, any distances so determined will not take into account the shortening because of F_2 and later folding and faulting. Original distances of D_1 transport may have been much larger. With these caveats, the minimum displacement on various thrusts are estimated as follows.

The Watsons Brook thrust must have been sufficient to bring the Pinchgut Lake group entirely across the area of exposed shelf carbonates to the east, or at least 10 km, but probably much more, given the folded and thrusted configuration of the platform succession. The slice boundary within the Watsons Brook sheet accounts for an additional 5 km.

The Corner Brook sheet was transported over the Watsons Brook sheet by at least 20 km, and the transport distance on the Crow Hill Thrust within the Corner Brook sheet was at least 6 km. The upper slice exposed at Snooks Pond must have been emplaced at least the across-strike width of the belt of Cooks Brook and Middle Arm Point formation that lies to the east, another 6 km.

The Woods Island sheet must have been transported by at least the across-strike width of the underlying Corner Brook sheet or at least 26 km, based on the area mapped in Fig. 2, but probably much more, depending on the extent of the Blow Me Down Brook formation in the area to the west. A close similarity in provenance (Cawood and Nemchin 2001) between clastics of the Blow Me Down Brook formation and the metamorphic Fleur de Lys Supergroup (Fig. 1) to the east suggests a correlation of the Woods Island sheet with that unit.

Origin and timing of later structures

The geometry of S_2 has long been a puzzle in the geometry of the allochthon. Cleavage axial planar to F_2 folds varies from generally upright and east-dipping in the vicinity of the Cooks Brook synform, where it is sporadically developed and weak, to west-dipping in the Corner Brook area, where it is more penetrative and locally phyllitic. These relationships would be consistent with its development in association with shortening above an east-vergent detachment, but such a scenario is difficult to reconcile with the overall geometry of the allochthon, which at its western margin is inserted into a tectonic wedge in the foreland basin (Stockmal and Waldron 1990; Stockmal et al. 1998). Thus there is no obvious location for a “root zone” for a basal detachment associated with D_2 deformation. However, Waldron et al. (1998) noted that the Acadian tectonic wedge geometry at the thrust front almost certainly postdates the development of S_2 fabrics within the allochthon; hence, at the time of S_2 fabric development, the allochthon may have been located significantly east of its present location, providing room for an east-vergent thrust to have been located within the underlying basement, possibly at the time of east-vergent thrusting and accretion in central Newfoundland (van Staal and de Roo 1996; van Staal et al. 1998).

We have no direct stratigraphic or isotopic evidence for the timing of D_2 deformation. However, isotopic results from the internal Humber Zone, immediately east of the area of our mapping, allow some inferences to be made. Cawood et al. (1994) determined a U/Pb age of 436^{+2}_{-3} Ma for a pegmatite affected by a regional foliation (their S_1, possibly correlative with our S_2), and interpreted to be syntectonic. A monazite age of 430 ± 2 Ma records peak metamorphic conditions; it overgrew the regional foliation but was overprinted by later regional fabrics. These correlations suggest a Silurian (Salinian) age for our D_2 structures.

Shear zones along the eastern edge of the Watsons Brook sheet record normal-sense motion that postdates D_2, followed by later shortening. Normal-sense motion late in the sequence of structures appears widespread in the area east of Corner Brook (Waldron and Milne 1991; Cawood and van Gool 1998) and is attributed to “extensional collapse” of the orogen following Salinian (Silurian) shortening. Later shortening, recorded by thrust-sense brittle shear zones and tension gashes, can reasonably be related to shortening at the thrust front that postdates the Devonian Red Island Road formation but predates the Mississippian Codroy Group (Stockmal et al. 1998). However, in the absence of isotopic dates, these correlations remain speculative.

Conclusions

The region around Humber Arm, traditionally mapped as Humber Arm Allochthon, includes rocks of several distinct stratigraphic successions, emplaced above platform carbonates during D_1 thrusting. Each succession is interpreted to represent a major thrust sheet, derived from a distinct environment on the Laurentian margin. Although relationships at outcrop scale show widespread evidence of extension, major tectonic contacts typically show thrust geometries.

All the thrust sheets were subsequently folded by F_2 folds that show culminations and depressions with local development of sheath-like geometries related to modification during D_3 shearing, associated with widespread extension of the Humber Zone. Still later in the tectonic history, renewed shortening was probably associated with Devonian or younger thrusting.

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