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FACIES AND STRUCTURAL CONTRASTS ACROSS BONNE BAY CROSS-STRIKE DISCONTINUITY, WESTERN NEWFOUNDLAND

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ABSTRACT. The Bonne Bay cross-strike discontinuity of western Newfoundland corresponds with major along-strike changes in depositional facies and structural styles of rock units overlying Grenville basement. Facies associations in time-equivalent Lower Ordovician rock units of the Humber Arm Allochthon change abruptly in character at Bonne Bay. Redeposited shelf carbonates are absent from the allochthonous Upper Tremadocian to Arenig sediments south of the bay but present in time equivalent sediments to the north. The influx of synorogenic foreland-basin flysch commences at least one graptolite zone earlier to the south of the cross-strike discontinuity than to the north. South of Bonne Bay, the complete structural succession of the Humber Arm Allochthon is preserved, whereas to the north only the lower structural slices of the allochthon are present. The cross-strike discontinuity corresponds with the southern limit of the Acadian uplift of the Grenville Long Range Inlier and also marks a reversal in Acadian structural vergence from west-directed folds and thrust in the north to east-directed folds and thrusts in the south.

The Bonne Bay cross-strike discontinuity is inferred to represent a transfer fault formed during continental rifting at the inception of the Appalachian cycle that was reactivated during the subsequent history of the orogen. Additional cross-strike discontinuities, inferred on the basis of along-strike changes in the style of Taconian and Acadian orogenesis, probably occur near the southern boundary of the Humber Arm Allochthon and at the northern and southern boundaries of the Hare Bay Allochthon. These zones, like the Bonne Bay structure, appear to mark the boundaries of small-scale (second-order) promontories and reentrants in the Humber Zone margin, which controlled allochthon emplacement and subsequent Acadian orogenic deformation.

INTRODUCTION

Orogenic belts are characterized by a linear distribution of rock units and structural elements aligned approximately parallel to the belt. Locally however, these trends are disrupted and terminated or offset by cross-strike discontinuities (Coleman, 1986; Morley, 1987). Such structures may represent cross-faults initiated during orogenesis, perhaps through differential movement in a thrust sheet, or they may also represent the reactivation of an earlier crustal suture formed either during the early phase of the orogenic cycle or as a basement structure predating the current orogenic cycle. Differentiating between a single and multiphase origin for a discontinuity requires a detailed analysis of facies and structural contrasts across the fracture. The southern end of the Grenvillian Long Range Inlier, west Newfoundland is marked by a major cross-strike discontinuity affecting both sedimentary facies distribution and orogenic structure. This paper outlines lithologic and structural changes across the zone and discusses the origin of this structure with respect to the Appalachian orogenic cycle.

REGIONAL SETTING

The Appalachian Orogen records a cycle of Late Precambrian to mid-Paleozoic ocean opening and closing (Wilson, 1966). The western margin of the orogen, termed the Humber Zone (Williams, 1978, 1979), constitutes the ancient continental margin of eastern North America. The zone consists of a Precambrian crystalline basement, which was formed before and modified during the earlier Grenville orogenic cycle, stratigraphically overlaid by an uppermost Precambrian to mid-Ordovician cover sequence of mainly sedimentary rocks, which are in turn structurally overlain by an allochthonous sequence of uppermost Precambrian to lower Ordovician sedimentary and igneous thrust slices (fig. 1; Stevens, 1970; Williams and Stevens, 1974; Cawood and others, 1988).

The evolution of the Humber Zone involved initial rifting of Grenville basement during the latest Precambrian with associated rift-facies sedimentation and volcanism, followed in the Early Cambrian by the establishment of a passive continental-margin shelf, slope, and basin sequence (Williams and Stevens, 1974; Williams and Hiscott, 1987). In situ shelf-edge and slope sequences are not preserved in Newfoundland but must have lain east of White Bay (fig. 1), where the most easterly outcrops of platformal carbonates are preserved. Recent deep seismic reflection studies suggest Grenville basement may extend at least 70 km east of the Baie Verte Line, the eastern surface limit of the Humber Zone (Keen and others, 1986; Marillier and others, 1989).

Passive continental-margin sedimentation was terminated at the end of the Early Ordovician by the emplacement of a imbricate thrust stack (Taconian allochthons) over the shelf (Williams and Stevens, 1974). This event caused drowning of the shelf and the establishment of a deep-water foreland basin which was infilled by sediment derived from the advancing thrust sheets (Stevens, 1970; González-Bonorino, 1990; Stenzel, Knight, and James, 1990). The lower slices of the thrust stack consist of rocks from the nearby continental margin. The highest slices of the allochthons consist of ophiolite suites, which represent oceanic crust and mantle (Church and Stevens, 1971). They are the farthest traveled of the slices within the thrust stack and represent fragments of the Dunnage Zone that have been thrust over the miogeocline (Cawood and others,

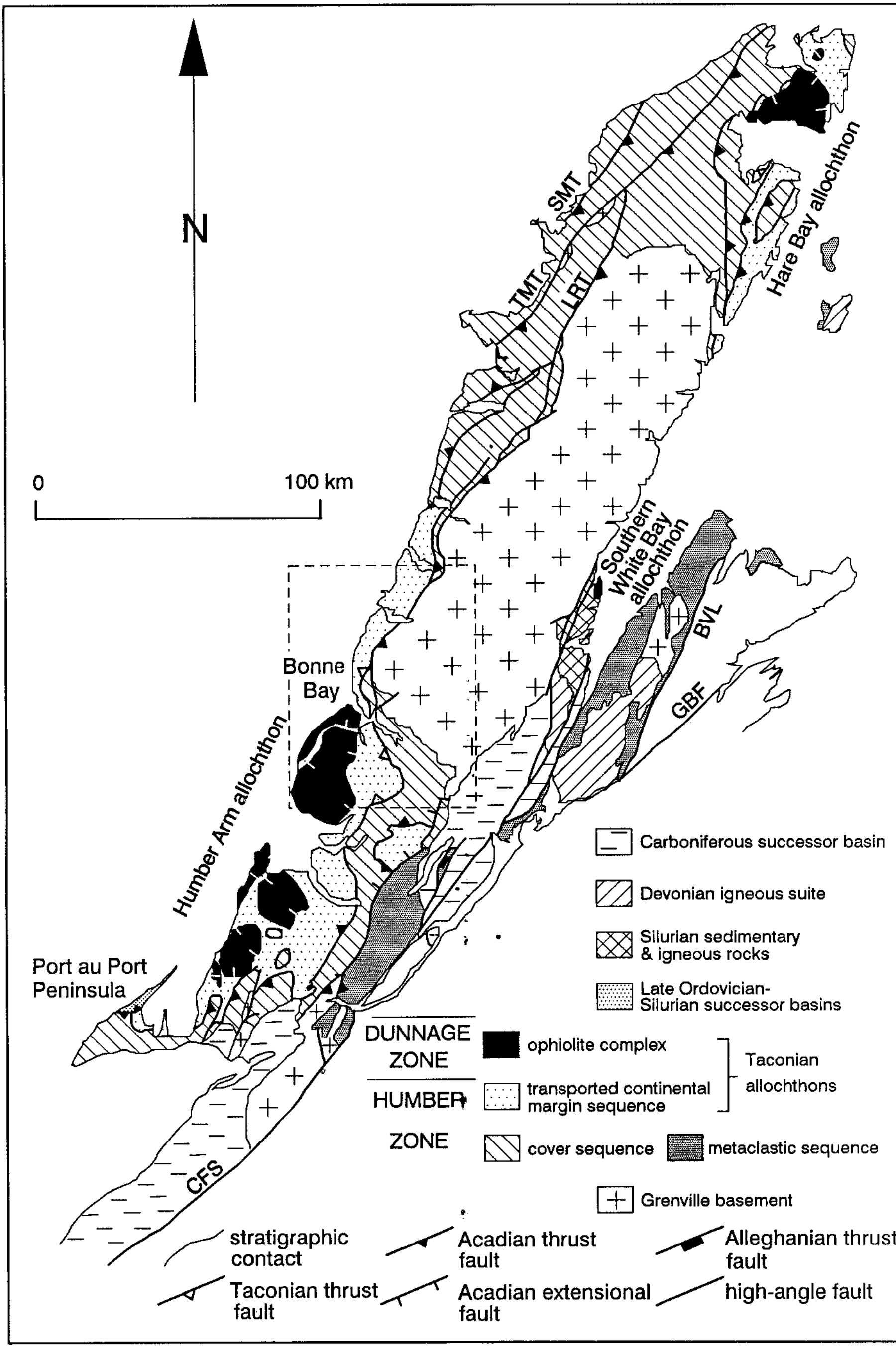

Fig. 1. Simplified geologic map of the Humber Zone, western Newfoundland. Abbreviations: LRT—Long Range Thrust; TMT—Ten Mile Lake Thrust; SMT—St. Margaret Bay Thrust; BVL—Baie Verte Lineament; CFS—Cabot Fault System; GBF—Green Bay Fault. Dashed line outlines area of figure 2.

1988; Colman-Sadd, Hayes, and Knight, 1990). In Newfoundland, the transported rocks are composed of the Humber Arm, Hare Bay, and Southern White Bay allochthons (fig. 1; Smyth and Schillereff, 1982; Williams and Smyth, 1983; Williams and Cawood, 1989).

Throughout the Appalachians, the Humber Zone follows an overall sinuous course determined, at least in part, by an original orthogonal geometry of promontories and reentrants along the ancient continental margin (Thomas, 1977, 1983, 1991; Williams, 1978; Hatcher and others, 1990). The swing from a promontory into a reentrant marks a major along-strike change in the character of the orogen, and Thomas (1977, 1991) related this to offset of the Late Precambrian rift system by transform faults. Reentrants are characterized by rift-related volcanic rocks, thick accumulations of both rift-facies clastics and syn-orogenic clastic wedges, wide zones of thin-skinned deformation, and are the locus for the emplacement of Taconian allochthons. These features tend to be less pronounced around the promontories, which are characterized by the occurrence of Grenville basement inliers (Rankin, 1976; Thomas, 1977; Williams and Doolan, 1979).

The Long Range Inlier of western Newfoundland (fig 1.) constitutes one of the major basement inliers within the Appalachian Orogen (Williams, 1978). The inlier separates the Humber Arm and Hare Bay allochthons (fig. 1). Along the northern, eastern, and southern margins of the inlier, Grenville basement is unconformably overlain by upper Precambrian to middle Ordovician rocks of the cover sequence. The western margin of the inlier is marked by the Long Range Thrust (Johnson, 1941; Cawood and Williams, 1986; Grenier and Cawood, 1988; Grenier, 1990) which brings basement up over the cover sequence and locally, in the south, over the Humber Arm Allochthon (fig. 1).

BONNE BAY CROSS-STRIKE DISCONTINUITY

The southern termination of the Long Range Inlier is exposed in the Bonne Bay region (fig. 2) and corresponds with major along-strike changes in the depositional facies and structural style of the rock units overlying basement. This structure is herein termed the Bonne Bay cross-strike discontinuity.

Facies Contrasts

Time-equivalent strata are preserved on either side of the Bonne Bay cross-strike discontinuity within both the cover sequence and the Humber Arm Allochthon. Stratal disruption and relatively high-grade metamorphism, both probably associated with Acadian deformation, prevent a detailed facies analysis of the cover sequence within this region. North of the cross-strike discontinuity, the cover sequence is preserved only in a thin, steeply-dipping and disrupted band sandwiched between the Humber Arm Allochthon and the Long Range Thrust (fig. 2; Williams and others, 1986; Cawood, Williams, and Grenier, 1987). South of the cross-strike discontinuity, the cover sequence is commonly penetratively

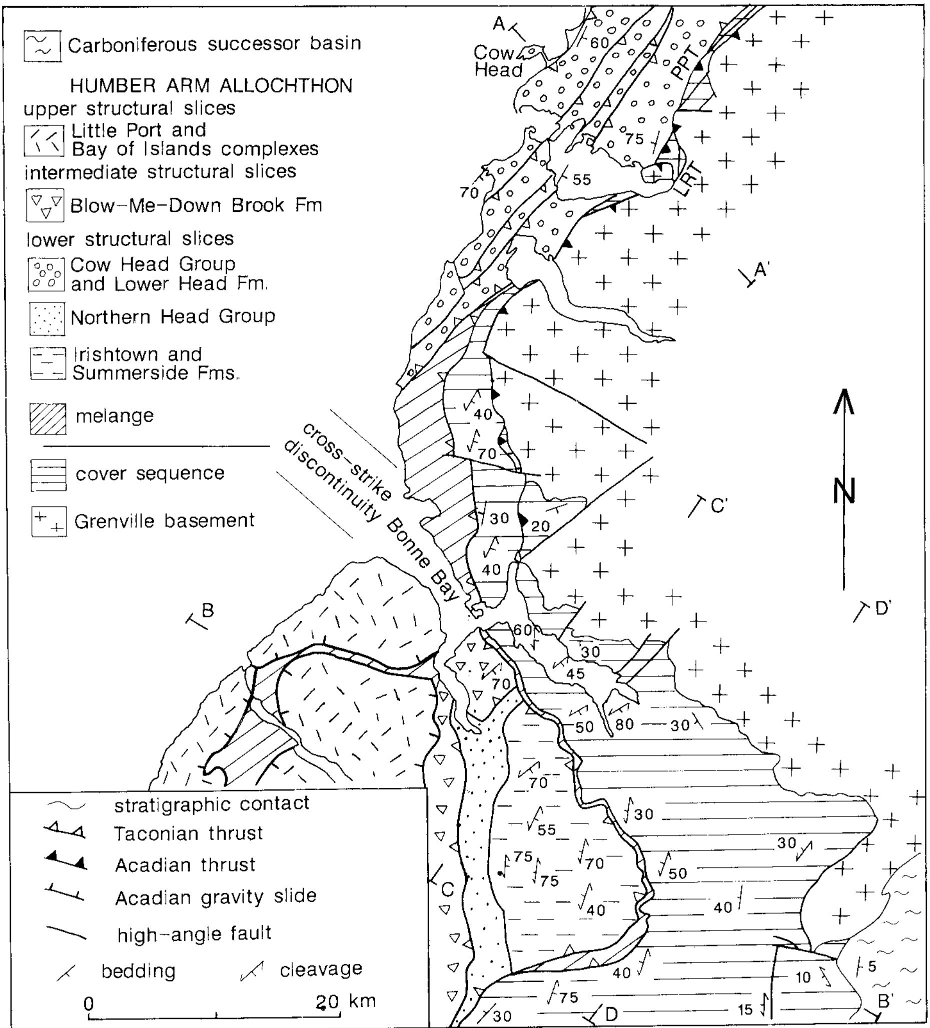

Fig. 2. Geologic map of the Bonne Bay region. Abbreviations: LRT—Long Range Thrust; PPT—Parsons Pond Thrust.

deformed and strongly recrystallized, particularly in the more eastern sections (Williams, Gillespie, and Knapp, 1983; Williams and others, 1984). In addition, rift-facies strata within the cover sequence are only exposed to the north of the cross-strike discontinuity. In this region, they form a thin (5–10 m) drape on Grenville basement. South of the cross-strike discontinuity, neither Grenville basement nor rift facies clastic rocks are exposed in stratigraphic continuity with the platform carbonates. Basement re-emerges in the Indian Head Inlier, located some 100 km farther south, just to the east of the Port au Port Peninsula (fig. 1). Like the southern Long Range Inlier, the rift-facies sequence on the Indian Head basement is only on the order of a few meters thick. A relatively thick sequence of rift-facies sedimentary and igneous rocks does, however, occur within the metaclastic sequence located to the south and east of the Long Range Inlier (fig. 1; Williams and others, 1983). This sequence is in tectonic contact with the main cover sequence to the west, and on the Baie Verte Peninsula, east of White Bay (fig. 1), it is also separated from the western cover sequence by strike-slip faults (Cabot Fault System), so that its original relationship with the western sequence is no longer preserved. Analysis of facies contrasts across the Bonne Bay cross-strike discontinuity is restricted to the strata of the Humber Arm Allochthon.

Humber Arm allochthon.—Although the strata within the Humber Arm Allochthon were structurally transported and broken into thrust slices during the Ordovician (fig. 2), they are generally preserved in relatively intact and little metamorphosed sequences amenable to facies analysis. Middle Cambrian to Lower Ordovician strata within the lower sheets of the Humber Arm Allochthon outcrop on either side of the Bonne Bay cross-strike discontinuity and form part of the Humber Arm Supergroup (Stevens, 1970). Rock units to the north of Bonne Bay belong to the Cow Head Group and overlying Lower Head Formation (fig. 3; James and Stevens, 1986). Time-equivalent strata to the south of Bonne Bay constitute the Northern Head Group and Eagle Island Formation (Botsford, 1988). The Northern Head Group is divisible into the Middle Cambrian to Lower Ordovician (Tremadoc) Cooks Brook Formation and the conformably overlying upper Tremadoc to Arenig Middle Arm Point Formation (fig. 3; Stevens, 1970; Botsford, 1988).

Both the Cow Head and Northern Head groups represent base-of-slope sediment apron deposits which accumulated to the east-southeast of the now structurally underlying shelf sequence (Williams and Stevens, 1974). Detailed facies analysis of the two groups reveal strong similarities in the depositional history of the Cooks Brook portion of the Northern Head Group and the comparable upper mid-Cambrian to upper Tremadoc portion of the Cow Head Group (fig. 4; James and Stevens, 1986; Botsford, 1988; Botsford and James, 1988). Both groups were formed by extensive movement of shelf-derived sediment gravity flow deposits (debris flows and turbidites) into a basinal setting that contained little bioturbated pelagic carbonate and clay (fig. 4). The strong parallelism in the depositional history of the two regions indicates that these units accumulated along a similar slope and responded in the same manner to regional events controlling the nature of the carbonate platform upslope.

The depositional history of the Cow Head and Northern Head groups diverges dramatically in the late Tremadoc when the supply of carbonate decreases from upslope of the Northern Head Group (fig. 4; Botsford and James, 1988). The top of the Cooks Brooks Formation

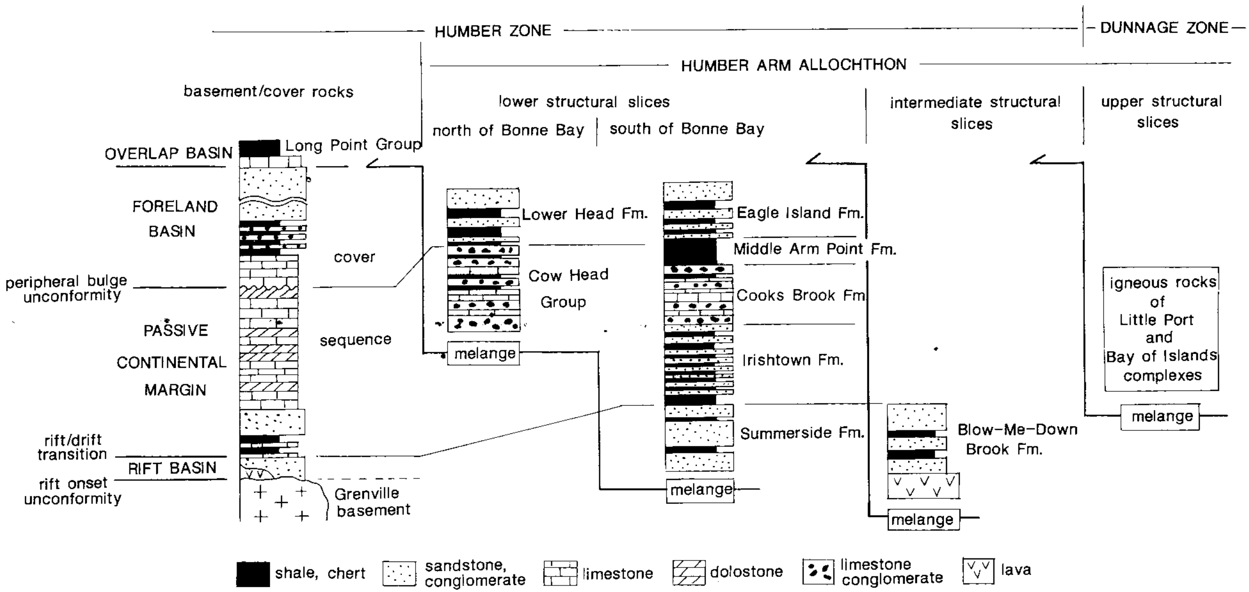

Fig. 3. Geologic columns correlating the major stratigraphic units of the Humber Arm Allochthon with the basement/cover sequence. The Middle Arm Point and Cooks Brook formations constitute the Northern Head Group and are time equivalent to the Cow Head Group.

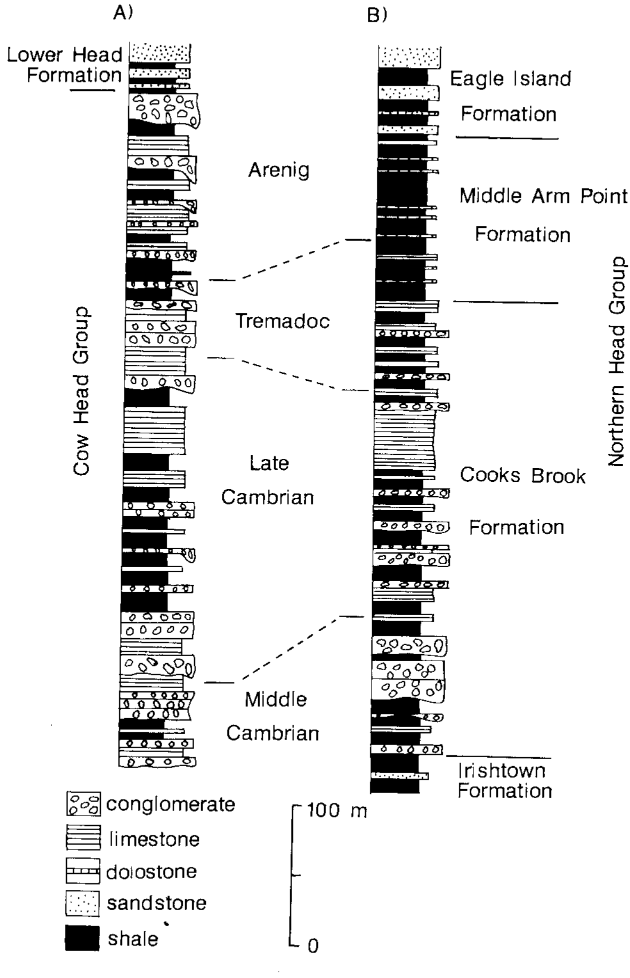

Fig. 4. Schematic sections through Middle Cambrian and younger rock units in the lower structural slices of the Humber Arm Allochthon. (A) Section to the north of Bonne Bay through the Cow Head Group and Lower Head Formation; (B) section to the south of Bonne Bay through the Cooks Brook, Middle Arm Point, and Eagle Island formations.

(Tremadoc La 2 zone) is marked by a distinctive interval of black organic carbon-rich shale and thin-bedded lime mudstone, which is in turn overlain by the shale-dominated Middle Arm Point Formation. Unlike the Middle Arm Point Formation, equivalent mid-Tremadoc to Arenig strata within the Cow Head Group provide a record for continued input of shelf-derived carbonate debris (fig. 4; James and Stevens, 1986).

The Cow Head and Northern Head Groups are conformably overlain by a coarsening upward succession of deep-water sandstone and shale of the Lower Head and Eagle Island Formations, respectively (figs. 3 and 4; James and Stevens, 1986; Botsford, 1988; Williams and Cawood, 1989). These units accumulated in a foreland basin in front of the advancing thrust nappes of the Humber Arm Allochthon (Williams and Stevens, 1974; Cawood and others, 1988). They herald the foundering and subsidence of the continental margin associated with allochthon emplacement. Paleocurrent indicators are from the northeast to the southwest, in contrast to the northwest source of detritus in the Cow Head and Northern Head groups. The sandstones were derived from a mixed-source terrane which included silicic intrusions, portions of an ophiolite suite, and sedimentary sequences. The influx of the Eagle Island Formation began in the mid-Arenig during the *Isograptus victoriae victoriae* graptolite zone in a regime of tectonic instability characterized by slumping and associated clastic-dike injection (Botsford, 1988). Deposition of the Lower Head Formation commenced during the Arenig *Undulograptus austrodentatus* zone (Williams and Stevens, 1987, 1988) which is at least one graptolite zone later than the Eagle Island Formation.

Interpretation.—Deep-water carbonate sediments are derived from and thus provide a history of the adjacent platform margin (James and Mountjoy, 1983). Similarities in the sedimentary record of the Cooks Brook Formation of the Northern Head Group and equivalent Middle Cambrian to upper Tremadocian strata in the Cow Head Group indicate they were deposited along a similar slope and responded in a similar way to regional events controlling the nature of the carbonate platform upslope. Strata in both groups accumulated at a relatively high-relief by-pass type margin with extensive movement of shelf-derived gravity flows into a base-of-slope sediment apron. This depositional setting continued in the Cow Head region until the mid-Arenig and the initiation of deposition of the Lower Head Formation. In contrast, the influx of continental margin carbonate debris decreases abruptly in the Northern Head region in the late Tremadoc, indicating a drowning of the platform upslope and establishment of a low-relief margin (Botsford, 1988; Botsford and James, 1988). Platform carbonate systems are remarkably resilient and able to keep pace with increasing water depth resulting from normal margin subsidence and eustatic events (Schlager, 1981). The abrupt and localized cessation of carbonate sedimentation in the upper Northern Head Group together with the internal coherence of the sedimentary record in this group and the sharp contrast with the equally coherent record in the upper Cow Head Group suggests a tectonic control we ascribe to cross-faulting and margin differentiation.

The Lobster Cove Head area provides additional evidence of platform differentiation and a complex margin configuration at the boundary between the Northern Head and Cow Head groups in the Early Ordovician (James, Botsford, and Williams, 1987). Lobster Cove Head lies on the north side of Bonne Bay and constitutes the southernmost outcrop of the Cow Head Group. It is composed of a large intact raft of

Arenig sediments lying in a shale mélange at the base of the Humber Arm Allochthon (Williams and Cawood, 1989). Strata within the raft belong to the upper part of the Cow Head Group and the overlying Lower Head Formation. The Cow Head strata are divisible into two discrete packages (James, Botsford, and Williams, 1987). The lower sequence, deposited through the *T. approximatus* to *D. bifidus* graptolite zones of Williams and Stevens (1987, 1988), is similar to the proximal facies of the Cow Head Group and contains redeposited shelf carbonate debris interstratified with black and green shale. The upper sequence spans the *I. v. victoriae* and *I. v. maximus* graptolite zones and is distinct from contemporaneous Cow Head Group strata (James, Botsford, and Williams, 1987). This unit, termed the Lobster Cove Head Member by James, Botsford, and Williams (1987), is composed of thick beds of silty dolostone and black and green shale deposited by weak turbidity currents. The contact between the two sequences is marked by a faunal break and represents an abrupt cessation of carbonate sedimentation. This indicates that the margin upslope from the Lobster Cove Head region was removed from the zone of active carbonate production, probably through drowning. James, Botsford, and Williams (1987) proposed that the abrupt differentiation of the Lobster Cove Head region from the remainder of the Cow Head Group is the result of cross-faulting farther upslope on the margin. As additional support for this model, they pointed out that time-equivalent strata on the platform are disrupted by syn-sedimentary faulting and that the polymict megaconglomerates (olistostromes) at the top of the main Cow Head Group sequence were probably derived by faulting at the platform margin. The platform-drowning event recorded in the Lobster Cove Head sequence is similar to that recorded at the base of the Middle Arm Point Formation of the Northern Head Group, except that it look place in the mid-Arenig rather than in the late Tremadoc and thus requires further differentiation and subdivision of a margin that up until mid-Tremadoc times was characterized by a relatively uniform along-strike sedimentary package.

Structural Contrasts

Structural styles within the Newfoundland segment of the Humber Zone reflect the combined effects of deformational events associated with emplacement of the Taconian allochthons in the mid-Ordovician and renewed contraction of the region during the Devonian Acadian Orogeny (Cawood and Williams, 1988). The Bonne Bay region corresponds with abrupt along-strike changes in the styles of both these orogenic events.

Taconian orogeny.—Taconian deformation is largely restricted to the allocthonous thrust sheets, and the structurally underlying shelf and crystalline basement are largely undeformed. This relationship is well displayed in the Humber Arm and Hare Bay allochthons. The base of the Humber Arm Allochthon north of the isthmus of Port au Port Peninsula is a sharp planar contact separating basal mélange of the allochthon from the underlying, essentiallly undeformed foreland basin sequence at the stratigraphic top of the shelf carbonates. Shearing in the mélange and bedding in the underlying succession, are subparallel to the basal contact, indicating that the allochthon was emplaced along a more or less flat surface (Cawood and others 1988; Cawood, 1991a). A gradation between mélange and underlying shale marks the same boundary at the northern end of the Humber Arm Allochthon, north of Bonne Bay, and at the base of the Hare Bay Allochthon (Williams and Smyth, 1983). Folds associated with Taconian thrusts are west-directed recumbent structures.

Structural characteristics of the Humber Arm Allochthon differ to the north and south of Bonne Bay. South of the bay, the complete structural succession of the allochthon is preserved. This succession consists of lower structural slices of predominantly sedimentary rock, termed the Humber Arm Supergroup, and upper structural slices of mainly igneous rock (Stevens, 1970; Williams, 1975). The highest igneous slices include ophiolitic rocks of the Bay of Islands and Little Port complexes (fig. 2 and 3) which represent displaced fragments of the Dunnage Zone (fig. 1). The lower sedimentary slices of the allochthon preserve a relatively complete continental-margin sequence which includes upper Precambrian to Lower Cambrian rift-facies clastic rocks (Summerside and Blow-Me-Down Brook formations) as well as a deep-water, passive continental margin sequence and overlying foreland basin strata (fig. 3).

North of Bonne Bay, only the lower sedimentary slices of the allochthon are represented (figs. 2 and 3). Igneous rocks from the upper igneous slices are absent. Within the sedimentary slices only the upper part of the deep-water continental-margin sequence, the Cow Head Group, and overlying foreland-basin clastic rocks of the Lower Head Formation are exposed. Correlatives of the rift-facies and deep-water continental-margin siliciclastic rock sequences present within the transported slices south of Bonne Bay are absent (fig. 2). Strata are exposed in a series of narrow, laterally continuous and east-younging, fault-bounded sequences which form a well developed east-dipping thrust stack (Cawood and Williams, 1986; Williams and Cawood, 1989). In contrast, thrusts with equivalent strata to the south of Bonne Bay form a less coherent package with broad zones of mélange developed between slices (Williams and Cawood, 1989).

Acadian orogeny.—Acadian deformation affects Precambrian Grenville basement and its cover sequence, as well as overprinting Taconian deformational fabrics in the allochthonous rocks (Cawood and Williams, 1988; Cawood 1991a). This has resulted in the allochthon lying in a structural depression surrounded to the northeast, east, and south by uplifted blocks of basement and platformal carbonates (figs. 1 and 2). Acadian deformational and metamorphic features in west Newfoundland are bracketed by their overprinting of Ordovician Taconian structural elements associated with allochthon emplacement, the presence of sub-Carboniferous unconformities, post-tectonic Devonian granites cutting deformed rocks of Silurian and older age, and Siluro-Devonian K-Ar and $^{40}Ar/^{39}Ar$ cooling ages (Cawood, 1991a).

Age of Acadian deformation is best constrained by relations on the Port au Port Peninsula and in the southern White Bay region (fig. 1). At the former, Pridoli-age strata (Berry and Boucot, 1970; F. O'Brien, personal communication, 1990) of the Clam Bank Group lies in a footwall syncline, structurally overlain along the Round Head thrust by Ordovician shelf carbonates (Cawood and Williams, 1988; Williams and Cawood, 1989; Stockmal and Waldron 1990). Nearby Carboniferous strata are undeformed and unconformably overlie the deformed Silurian and older sequence. In southern White Bay, deformed and metamorphosed rocks of the upper Silurian Sops Arm Group (Lock, 1969, 1972) are intruded by the undeformed and post-tectonic granite of the Gull Lake Intrusive Suite which has yielded a U-Pb zircon age of around 390 Ma (Baadsgaard, Erdmer, and Owen, unpublished data). Lower Carboniferous rocks of the Deer Lake Basin unconformably overlie both the Gull Lake Intrusive Suite and the Sops Arm Group.

The character of the mid-Paleozoic deformational fabric changes abruptly at the position of the Bonne Bay cross-strike discontinuity. North of Bonne Bay, west-directed thrusts and associated west-verging folds are the dominant structural elements (Cawood and Williams, 1986; Grenier and Cawood, 1988; Grenier, 1990). South of Bonne Bay, in eastern localities, structural vergence is reversed, and east-directed thrusts and folds characterize the Acadian structural fabric (Bosworth, 1985; Waldron, 1985; Williams and Cawood, 1986).

North of Bonne Bay, deformation is concentrated along the Long Range Thrust (fig. 2; Johnson, 1941) which delineates the western margin of the Long Range Inlier and brings Grenville basement up over the shelf carbonates and the Humber Arm Allochthon. The Grenville basement within the hangingwall forms a single large and internally coherent block. The footwall sequence is deformed into a major asymmetric, west-verging footwall syncline (fig. 5). Platformal carbonates in the steeply dipping eastern limb of the syncline are locally cleaved and recrystallized to marble. The cleavage parallels the plane of the Long Range Thrust and is axial planar to rare mesoscopic west-verging folds. The Parsons Pond Thrust, a splay off the Long Range Thrust, disrupts the footwall sequence and thrusts shelf carbonates westward over the allochthon (fig. 2; Grenier and Cawood, 1988). Warping within the footwall syncline may be related to blind thrusts at depth.

South of Bonne Bay, the Acadian deformation is dominated by a downward converging cleavage fan. The axis of the cleavage fan trends south-southwest from the head of Bonne Bay (fig. 2), and folds, to which the cleavage is axial planar, vary from west-verging in the west to upright, symmetrical structures around the axis of the fan to east-verging in the east. Cleavage decreases in intensity westward and dies out around the eastern margin of the Bay of Islands Complex. No contractional deformational features are observed in rocks farther west. However, seismic

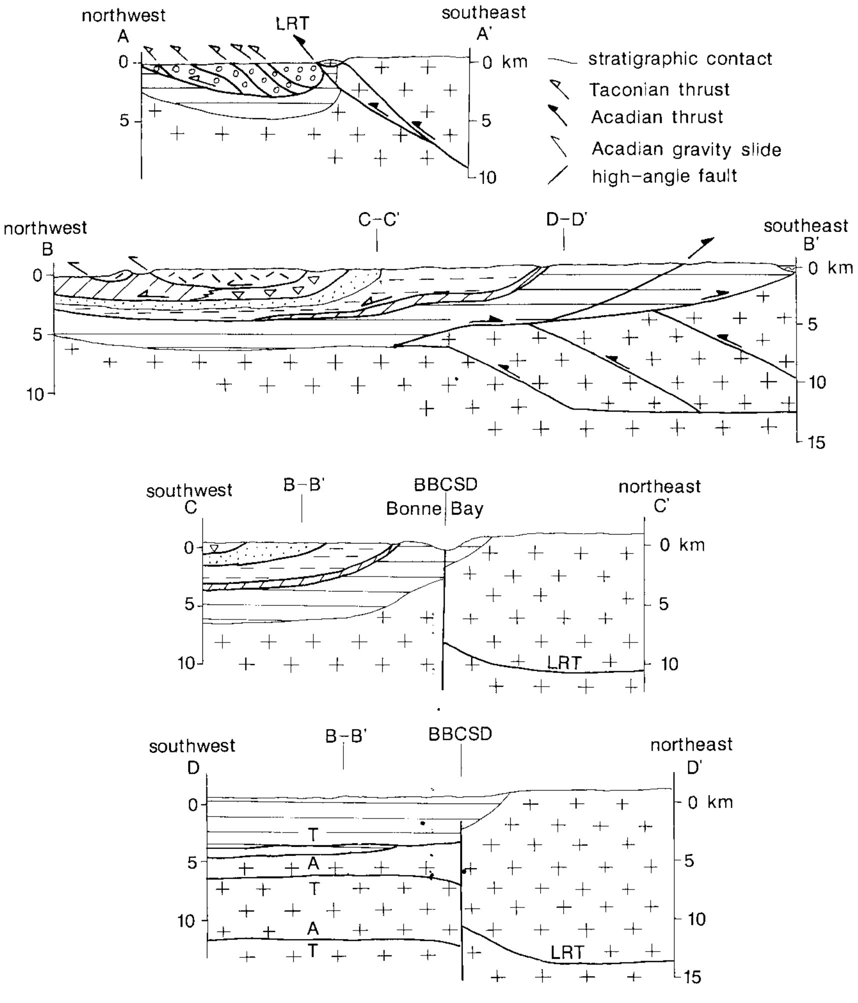

Fig. 5. Cross sections through the Humber Arm Allochthon and underlying basement/cover rocks in the vicinity of the Bonne Bay cross-strike discontinuity. Location of sections shown on figure 2. Abbreviations: LRT—Long Range Trust; BBCSD—Bonne Bay cross-strike discontinuity; letters A and T refer to direction of thrusting being either into (away) or out of (toward) the plane of the page. Sections B-B′, C-C′, and D-D′ show the location of cross cutting sections C-C′, B-B′, and B-B′, respectively. In all sections V = H. Symbols as on figure 2.

reflection data suggest some Acadian-age thrusting and associated folding immediately offshore of the Bay of Islands Complex (Stockmal and Waldron, 1990; Cawood and others, 1991). The western limb of the cleavage fan is a relatively narrow zone, up to 10 km wide, in which cleavage is weakly developed and has a steep to moderate dip. The eastern limb is a broad zone, up to 30 km wide, in which cleavage is well developed and has a moderate to shallow dip. East-directed thrusts, aligned approximately parallel to cleavage, are developed along the eastern side of the cleavage fan (Williams and Cawood, 1986, 1989). Farther east, cleavage again steepens and east of Deer Lake becomes west-dipping.

Interpretation.—At Bonne Bay, west-verging structures on the west limb of the Acadian cleavage fan merge with west-directed structures developed in the footwall of the Long Range Thrust. This suggests that overthrusting of the Long Range Inlier was synchronous with development of the cleavage fan and east-directed folding and thrusting along the eastern margin of the allochthon. Thus, along-strike variations in vergence reflect changes in the response of rock units to the same deformational event, rather than to separate, unrelated events, and the along-strike and across-strike changes in Acadian structural vergence developed in response to a regime of regional west-directed contraction (Williams and Cawood, 1986; Cawood and Williams, 1988). To account for these changes, Cawood and Williams (1988) proposed that north of Bonne Bay west-directed thrusting took place throughout the crustal section (fig. 5, section A-A′: basement, cover, and allochthon), whereas to the south, basement and cover were delaminated with basement stacked in a west-directed duplex wedge below the cover sequence (fig. 5, section B-B′). Such a model explains the presence of east-directed thrusts and east-verging folds developed in the eastern parts of the allochthon and the absence of Grenville basement from the region south of Bonne Bay, but its presence to the north (Long Range Inlier).

The change in structural vergence at Bonne Bay must be accommodated by a cross fault in Grenville basement which links the west-directed Long Range Thrust to the north with the conjugate backthrust developed above the presumed Grenville duplex to the south (fig. 5, cross sections C-C′ and D-D′; compare Butler, 1987, fig. 19). The East Arm of Bonne Bay probably marks the trace of the cross-fault extending from the southern termination of the Long Range Inlier. East of the head of Bonne Bay the fracture is confined to basement and concealed under the drape of cover lithologies (fig. 5, cross section D-D′). The cross-fault at the southeast margin of the inlier may mark the re-emergence of this structure (fig. 2). Termination of the southern Long Range Inlier by a cross-fault has also been postulated by Waldron (1988) and Waldron and Milne (in press).

DISCUSSION

To establish that a cross-strike discontinuity has been active at multiple phases throughout an orogenic cycle, rather than just initiated as a cross-fault during late-stage orogenic activity, it is necessary to demonstrate a prolonged history of lithological and structural contrasts across the inferred discontinuity. The lithological and structural contrasts across the southern end of the Long Range Inlier suggest a prolonged history of activity on the Bonne Bay discontinuity extending from at least the Ordovician until the Devonian. However, the restriction of contrasts in Ordovician-age lithologies and structures to the transported thrust slices of the Humber Arm Allochthon require that for these differences to be controlled by the Bonne Bay discontinuity, emplacement of the allochthon was approximately parallel to the northwest trend of the discontinuity.

Data on the direction of emplacement of the Humber Arm Allochthon, derived from asymmetric folds developed within, and at the base of, the allochthon, minor tear faults within thrust sheets, and rare lineations within the transported slices consistently indicate a mean vector of transport to the northwest (Waldron, 1985). This indicates that the Northern Head and Cow Head Groups, as well as other continental-margin thrust slices within the allochthon, overlie those portions of the shelf that were originally located orthogonally upslope. The cross-fault(s) responsible for foundering and drowning of the platform edge upslope from the Northern Head Group may well coincide with the position of the cross-fault bounding the southern termination of the Long Range Inlier.

Correlation of the temporally discrete periods of faulting to the same basement fracture implies that the later Acadian cross-fault was not a new structure initiated in massive, undisrupted Grenvillian basement, but rather a rejuvenated, pre-existing structural discontinuity. Similarly, the late Tremadocian fault movement upslope from the boundary between the Northern Head and Cow Head Groups probably also nucleated along a pre-existing zone of weakness. The termination of carbonate production upslope from the Northern Head Group requires major differential subsidence and drowning of this platform segment relative to the region upslope from the Cow Head Group. The late Temadocian age of margin differentiation probably marks the time of initial loading of the margin associated with ophiolite obduction (Williams and Stevens, 1974; Cawood, 1991b). It is unlikely that subsequent facies and structural contrast within the allochthon reflect a simple differential loading of the margin to the north and south of Bonne Bay as the wave-length over which such loading would be effective is of the order of 10's to possibly 100's of kilometers, not the 10 km or less required for the abrupt change from the Northern Head Group to the Cow Head Group. The abrupt change in along-strike conditions of the shelf recorded by the Cow Head and Northern Head groups imply margin differentiation through either initiation or reactivation of a cross-fault in response to uniform loading of the margin. We favor reactivation of a pre-existing basement discontinuity, for although differentiation occurred at the beginning of the Taconian orogenic event, the platform margin was still well to the west of the deformation front at this time. Thus, the continuous late Tremadoc sedimentary record and the lack of any penetrative deformation fabric of this age in nearby strata suggest that margin differentiation took place through movement of pre-existing basement blocks rather than through the initiation and propagation of new structures.

Origin of Cross-Strike Discontinuity

Although the stratigraphic and structural relations suggest the Bonne Bay discontinuity is at least pre-late Tremodocian in age, data are not yet available to place a lower age limit on initiation of this structure. The lack of evidence for any tectonic activity during the Lower Cambrian to Ordovician phase of passive-margin sedimentation suggests that the discontinuity must have either developed at the initiation of the Appalachian orogenic cycle during rift facies sedimentation or perhaps during the earlier Grenville orogenic phase. Because the Bonne Bay discontinuity is roughly orthogonal to the northeast-southwest Appalachian trend but shows no set relationship to the older Grenvillian north-northwest trends, we believe the discontinuity developed during stretching of the Grenville crust at the initiation of the Appalachian orogenic cycle and was then reactivated during the Taconian and Acadian orogenic events.

During orogenic deformation the stretched and attenuated continental basement of a rifted margin is contracted and vertically thickened (Dewey and others, 1986). Under stress fields of appropriate orientation, contractional structures generated during orogenesis will nucleate along pre-existing zones of weakness (Helwig, 1976; Jackson, 1980; Dewey, 1982). Thus, shortening in continental-margin basement blocks can be taken up through reactivation of extensional systems formed during initial continental rifting: listric normal faults are reactivated as thrusts (Helwig, 1976; Jackson, 1980), and rift-related transfer faults become strike-slip faults (Etheridge, 1986). Transfer faults accommodate along-strike differences in the geometry of normal fault systems. They have steep to vertical dips and strike perpendicular to the associated normal fault system (Lister, Etheridge, and Symonds, 1986). The Bonne Bay discontinuity could represent a transfer fault reactivated during accretion onto the ancient continental margin of eastern North America.

The contrasting Taconian structural styles within the Humber Arm Allochthon may be related to margin differentiation during the earliest stages of platform loading. South of Bonne Bay, late Tremadocian margin subsidence and drowning may have led to a margin with a less pronounced shelf edge than in the region north of Bonne Bay (fig. 6). This subsequently provided an overall gentler and smoother glide path for the advancing allochthon thrust stack in the region south of Bonne Bay and may account for the presence of the large flat thrust sheet found in this region. North of Bonne Bay the Grenville basement of the Long Range Inlier formed a steep buttressing ramp over which the allochthon thrust stack had to be emplaced. This would have required the building up of the thrust wedge and its critical taper and may account for the well developed imbricate thrust stack in the Cow Head and Lower Head rock units.

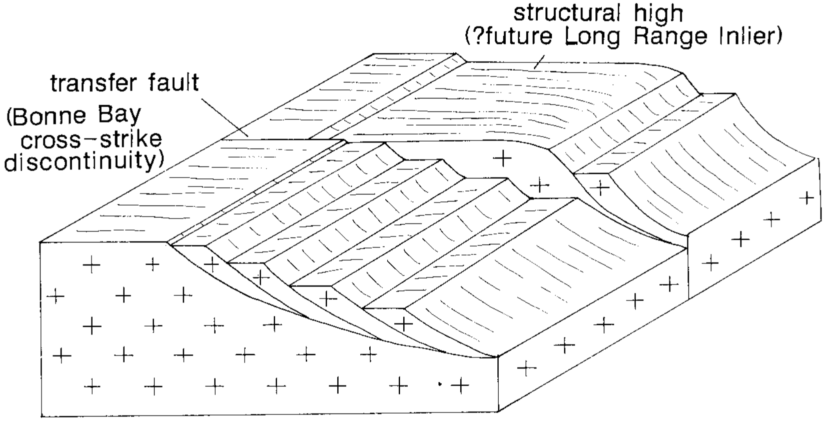

Fig. 6. Reconstruction showing inferred initiation of the Bonne Bay cross-strike discontinuity as a transfer fault associated with initial Precambrian rifting of Grenville basement.

REGIONAL RELATIONS

Along-strike variations in distribuion of stratigraphic units and structural style in the other areas of the west Newfoundland Humber Zone, apart from the Bonne Bay region, may also correspond to cross-strike discontinuities. From south to north these additional structures are termed Serpentine Lake cross-strike discontinuity, Canada Bay cross-strike discontinuity, and Belle Isle cross-strike discontinuity (fig. 7).

The Serpentine Lake cross-strike discontinuity corresponds with the southern limit of the downward-converging Acadian cleavage fan and associated east-directed folds and thrusts developed to the south of the Bonne Bay cross-strike discontinuity (Cawood and Williams, 1988). South of this structure the platform carbonates and Grenville basement are deformed into a series of west-verging box-folds, in part disrupted and breached along their western margin by a linked system of west-directed thrusts. The Humber Arm Allochthon occupies the intervening synclines. The presence of Grenville basement in the core of the anticlines constrains the level of the sole thrust to basement depths. The change in structural vergence at Serpentine Lake corresponds with the southern limit of coherent sections in the Northern Head Group. Farther south the sedimentary sequence of the allochthon is disrupted into tectonic mélange which on the Port au Port Peninsula and at Bear Cove, near the mouth of the Serpentine River, contains large blocks lithologically similar to the Cow Head Group (Schuchert and Dunbar, 1934; Kindle and Whittington, 1965). The blocks contain upper Cambrian and lower Ordovician sequences of thick-bedded grainstone, limestone conglomerate, and thin-bedded limestone and shale. The thickness of the grainstones at the Port au Port locality, which reach up to 1 m, and the

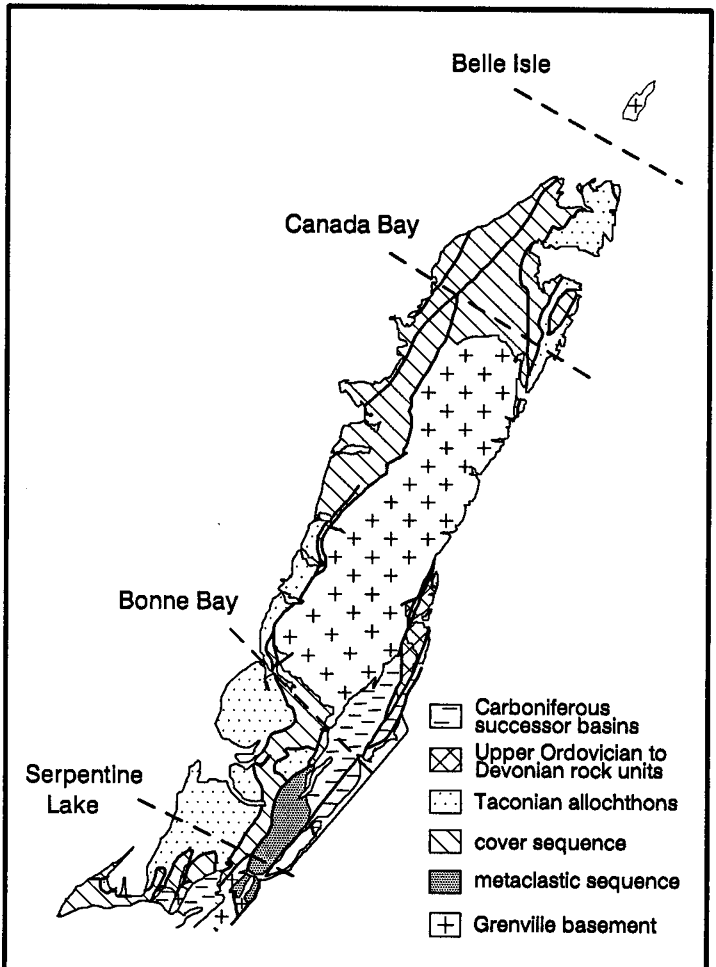

Fig. 7. Simplified geologic map of western Newfoundland showing location of Serpentine Lake, Bonne Bay, Canada Bay, and Belle Isle cross-strike discontinuities.

coarseness of the conglomerate beds at Bear Cove, which contain blocks up to 1 m across, distinguish these sequences from the nearby Cooks Brook Formation and suggest correlation with the Cow Head Group. The change from Cooks Brook Formation to Cow Head Group type lithologies across the Serpentine Lake cross-strike discontinuity suggests that, like the Bonne Bay cross-strike discontinuity, this structure marks a change in margin morphology.

The Canada Bay and Belle Isle cross-strike discontinuities correspond with the approximate southern and northern limits respectively of the Taconian Hare Bay Allochthon. In addition, the Canada Bay structure approximates the northern limit of exposure of the Grenvillian Long Range Inlier, and the Belle Isle structure marks the re-emergence of this basement to the north (fig. 7).

The late Tremadoc subsidence and drowning of the shelf edge upslope from the Northern Head Group and the similar drowning of the shelf edge upslope from the Lobster Cove segment of the Cow Head Group in the mid-Arenig immediately preceded the complete destruction of the continental margin associated with ophiolite obduction and emplacement of the Taconian allochthons. Thus, the cessation of carbonate input into the upper Northern Head Group and parts of the Cow Head Group represents the first evidence for impingement of the obducted ophiolite with the continental margin (James, Botsford, and Williams, 1987; Botsford and James, 1988). Dallmeyer (1977) previously suggested that the age of ophiolite obduction in western Newfoundland is diachronous, taking place originally in northern Newfoundland during the Tremadoc and not extending into the Humber Arm region until the Arenig. This model was based on significant differences in the age of the metamorphic sole to the ophiolitic complexes of the Hare Bay and Humber Arm allochthons. The metamorphic sole to the St. Anthony Complex of the Hare Bay Allochthon has yielded an $^{40}Ar/^{39}Ar$ age on hornblende of 489 ± 5 Ma (Dallmeyer, 1977; new decay constant), whereas hornblende from the Bay of Islands metamorphic sole has given an $^{40}Ar/^{39}Ar$ age of 469 ± 5 Ma (Dallmeyer and Williams, 1975; new decay constant), Stratigraphic relationships, outlined above, for a Late Tremadoc age for earliest phases of the Taconian Orogeny in the Humber Arm Allochthon correspond to an absolute age of around 490 Ma on most geologic time scales (Harland and others, 1982; Haq and van Eysinga, 1987; Tucker and others, 1990). Thus, ophiolite obduction and allochthon emplacement probably commenced in a similar time frame in both the Humber Arm and Hare Bay regions. These relationships suggest that obduction of the Bay of Islands ophiolite only commenced after initial foundering of the ancient North American continental margin had already started to collapse.

CONCLUSIONS

Depositional facies and structural styles within the Humber Arm Allochthon differ markedly to the north and south of Bonne Bay. Similarly, the character of the Acadian thrust front changes abruptly across strike in the Bonne Bay region. We believe that these relationships are not fortuitous but represent multiple reactivation of a long-lived structural discontinuity within the crust, herein termed the Bonne Bay cross-strike discontinuity. Similar structural discontinuities are postulated in the vicinity of Serpentine Lake, Canada Bay, and Belle Isle (fig. 7).

Although the cross-strike discontinuities are most easily delineated by along-strike variations in structural style, the variations in both the distribution of rock units and sedimentation patterns indicate that they predate orogenesis and probably formed transfer faults associated with initiation of the Applalachian cycle during rifting of the Laurentian shield. The discontinuities in western Newfoundland may have defined the boundaries of a series of small-scale promontories and reentrants which subsequently controlled margin morphology during orogenesis. These represent second-order features superimposed on the first-order promontories and reentrants that define the overall sinuous course of the Appalachian Humber Zone (Thomas, 1977; Williams, 1978).

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