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# Late Carboniferous Tectonostratigraphy in the Avalon Terrane of Southern New Brunswick

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Development of the basement-involved, fold-thrust belt in coastal southern New Brunswick is attributed to dextral transpression associated with regional, Carboniferous strike-slip displacements. In the vicinity of Saint John, deformation strongly influenced Westphalian sedimentation in the penecontemporaneous Lancaster and Balls Lake Formations and reflects sustained NW-SE shortening that coincides with a major compressive bend in the E-W, Cobequid-Chedabucto fault system which records significant, right-lateral Pennsylvanian displacement.

Purple conglomerates and lithic wackes of the Balls Lake Formation record syntectonic, NW-progradation of an alluvial fan in response to the uplift of a source to the SE and display facies depicting proximal to mid-fan, mid-fan, and distal settings. Locally interfingering and laterally equivalent, grey lithic arenites of the Westphalian Lancaster Formation are the product of major, NE- flowing, meandering streams partially influenced by the prograding distal fan.

Initial deformation ($D_1$) produced NW-directed, basement-involved thrusts that structurally invert regional stratigraphy. Associated lower greenschist facies metamorphism accompanied development of a widespread, SE-dipping fabric ($S_1$), variably expressed as a slaty cleavage, protomylonitic solution cleavage and orthomylonitic foliation. The fabric locally bears a strong but variably oriented mineral lineation ($L_1$) and is axial planar to NW-vergent, isoclinal microfolds and regional overturned structures ($F_1$) that plunge gently NE and SW. Renewed thrusting ($D_2$) and backthrusting ($D_3$) produced conjugate fold sets coaxial with $F_1$ that verge both NW ($F_2$) and SE ($F_3$). Associated axial planar crenulation cleavages ($S_2$ and $S_3$) overprint $S_1$ and dip SE and NW respectively.

On-strike variations in deformational style and timing, coupled with the presence of steeply dipping, en echelon zones of intense deformation, suggest the fold-thrust belt is segmented by right-stepping, convergent wrench faults synthetic to the deeply listric, Cobequid-Chedabucto system. These faults may shallow into thrusts to form positive flower structures, and locally terminate in thrusts associated with anomalous NW-SE trends in $D_1$ and $D_2$. Thrust uplift in response to transpression on locally downward-steepening, en echelon faults subparallel to the Fundy shore is proposed to account for the source area of the syntectonic Balls Lake fan. Further displacement and telescoping resulted in structural inversion of regional stratigraphy and deposition of the Balls Lake and Lancaster Formations in advance of an overriding allochthon to the south.

On impute le développement d'une zone orogénique chevauchante solidaire du socle au littoral du Nouveau-Brunswick méridional à une transpression dextre accompagnée de décrochements régionaux carbonifères. Près de Saint John, la déformation, qui a fortement marqué la sédimentation westphalienne dans les formations synchrones de Lancaster et de Balls Lake, provient d'un raccourcissement soutenu NW-SE ayant coïncidé avec un important coude en compression dans le système de failles E-W de Cobequid-Chedabucto. Ce dernier représente un coulissage à droite de grande valeur d'âge pennsylvanien.

Les poudingues pourpres et les wackes lithiques de la Formation de Balls Lake soulignent la progradation syntectonique NW d'un cône de déjection et traduisent la

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proximité de reliefs émergés au SE; les faciès témoignent de régimes proximaux à milieux de cône, de milieux de cône, et distaux. Les arénites lithiques grises de la Formation de Lancaster, du Westphalien, en sont l'équivalent latéral et s'y interdigitent par endroits. Elles sont, pour leur part, le produit de grands cours d'eau à méandres coulant vers le NE sous l'influence partielle du cône distal progradant.

Des nappes de socle de direction NW inversent structuralement la stratigraphie régionale et témoignent d'une déformation initiale ($D_1$). Le développement largement répandu d'une fabrique ($S_1$), pentée SE et prenant l'aspect variable d'un clivage ardoisier, d'un clivage sous solution protomylonitique et d'une foliation orthomylonitique, fut accompagné d'un métamorphisme dans le faciès schistes verts inférieur. Localement, la fabrique acquiert une linéation ($L_1$) forte mais variable, soulignée par l'orientation de minéraux dans le plan axial de microplis isoclinaux à vergence NW et de structures régionales retournées ($F_1$) qui plongent gentiment vers le NE et le SW. S'y associent des clivages de crénulation de plan axial ($S_2$ et $S_3$), pentés respectivement SE et NW, qui se superposent sur $S_1$.

Des variations longitudinales dans le style et l'époque de la déformation, couplées à la présence de zones intensément déformées, en échelon et fortement pentées, suggèrent que la zone orogénique chevauchante est scindée par des décrochements verticaux décalés à droite, qui convergent et sont, eux-mêmes, synthétiques du système fortement listrique de Cobequid-Chedabucto. Ces failles se couchent vers la surface pour devenir des chevauchements qui engendrent des structures en fleur positives; elles s'estompent par endroits en des chevauchements associés aux orientations anormales NW-SE dans $D_1$ et $D_2$. On explique la source du cône syntectonique de Balls Lake par la surrection des paquets chevauchants sous le jeu en transpression de failles en échelon subparallèles à la côte de Fundy et dont les pendages se redressent localement vers le bas. Un déplacement et un télescopage supplémentaires résultèrent en une inversion structurale de la stratigraphie régionale et en la déposition des formations de Balls Lake et de Lancaster en avant du terrain charrié plus au Sud. [Traduit par le journal]

## INTRODUCTION

The southeastern margin of the Avalon terrane in southern New Brunswick forms a narrow, basement-involved, fold-thrust belt that trends east-northeast and broadly parallels the northern shore of the Bay of Fundy (Fig. 1). Variously termed the "Maritime Disturbance" (Poole 1967), the "Fundy Cataclastic Zone" (Ruitenberg *et al.* 1973) and the "Variscan Front" (Rast and Grant 1973), the thrust belt is the product of Carboniferous compressive deformation in contrast with the regional strike-slip faulting that is the dominant late Paleozoic structural style in Maritime Canada. Carboniferous deformation in much of the Maritimes reflects mainly dextral movements on major wrench structures (Keppie 1982; Rast 1984), and resulted in the development of pull-apart basins recorded in penecontemporaneous sedimentation (Bradley 1982; Yeo and Ruixing 1986). However, in southern New Brunswick the relationship of sedimentation to Carboniferous tectonics is less clear as the region has been interpreted as a major overthrust terrain in which Carboniferous sedimentary rocks formed entirely allochthonous members of the overriding plate (Rast *et al.* 1978). The tectonostratigraphy of the fold-thrust belt and its relationship to regional strike-slip faulting have consequently remained uncertain.

However, Plint and van de Poll (1982, 1984) and Currie and Nance (1983) have recently shown that late Carboniferous sedimentary rocks within the fold-thrust belt are, in part, autochthonous and have proposed they record syntectonic alluvial fan and fluvial sedimentation, developed in response to the uplift and late Carboniferous emplacement of thrust sheets. Mosher and Rast (1984) have further suggested that development of the overthrust terrain reflects termination of the Cobequid-Chedabucto fault system of Nova Scotia, on which some 165 km of dextral displacement was accommodated in the mid-Pennsylvanian and Permian (Keppie 1982).

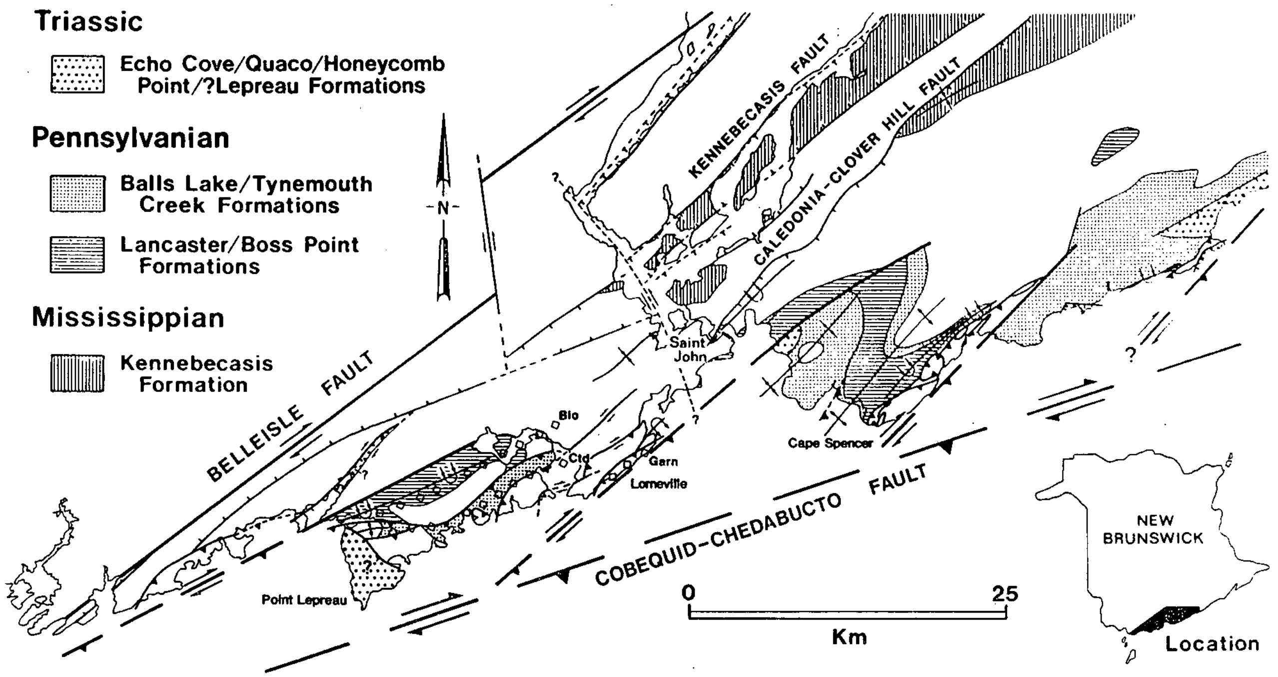

Fig. 1. Geologic sketch map of late Carboniferous fold-thrust belt in southern New Brunswick (modified after Hayes and Howell 1937; Alcock 1938; Rast *et al.* 1978; Wardle 1978; Ruitenberg *et al.* 1979; Plint and van de Poll 1982,1984; Currie and Nance 1983; Currie 1984, 1986; McCutcheon 1984; McCutcheon and Ruitenberg 1984; Mosher and Rast 1984; Parker 1984; Ruitenberg 1984; Nance and Warner 1986; and others). Biotite (Bio), chloritoid (Ctd) and garnet (Garn) isograds from Mosher and Rast (1984).

A detailed history of late Carboniferous deposition and deformation is recorded in Pennsylvanian sedimentary rocks within the fold-thrust belt. Southeast of Saint John (Fig. 1), these straddle a major structural front along which mildly deformed and essentially autochthonous units to the north are overthrust by their polydeformed stratigraphic equivalents to the south. The depositional record preserved within the autochthon (Caudill and Nance 1986), coupled with the structural history recorded in the allochthon (Nance and Warner 1986), support a syntectonic, alluvial fan to fluvial setting that developed in response to tectonic uplift along the present Fundy shore during a Westphalian phase of transpression on the offshore Cobequid-Chedabucto fault system (Nance 1986).

## STRATIGRAPHY AND GEOLOGIC SETTING

Carboniferous sedimentary rocks in the vicinity of Saint John are traditionally subdivided into two distinct packages (Fig. 1). Late Devonian to Mississippian redbeds of the Kennebecasis Formation pre-date, and are largely unaffected by, late Carboniferous deformation and record local, graben-fill alluvial sedimentation developed in response to normal movements on major, through-going faults. In contrast, clastic rocks of the Pennsylvanian Lancaster and Balls Lake Formations, and the lithologically correlative Boss Point and Tynemouth Creek Formations to the northeast (Plint and van de Poll 1982, 1984), were deposited penecontemporaneously with the development of the fold-thrust belt and are locally intensely deformed.

Within the mildly deformed autochthon (Caudill and Nance 1986) southeast of Saint John (Fig. 2), the Balls Lake Formation comprises greyish purple lithic wackes containing subrounded pebbles and thin conglomeratic horizons; similarly coloured, moderately sorted, bimodal and polymict orthocon-

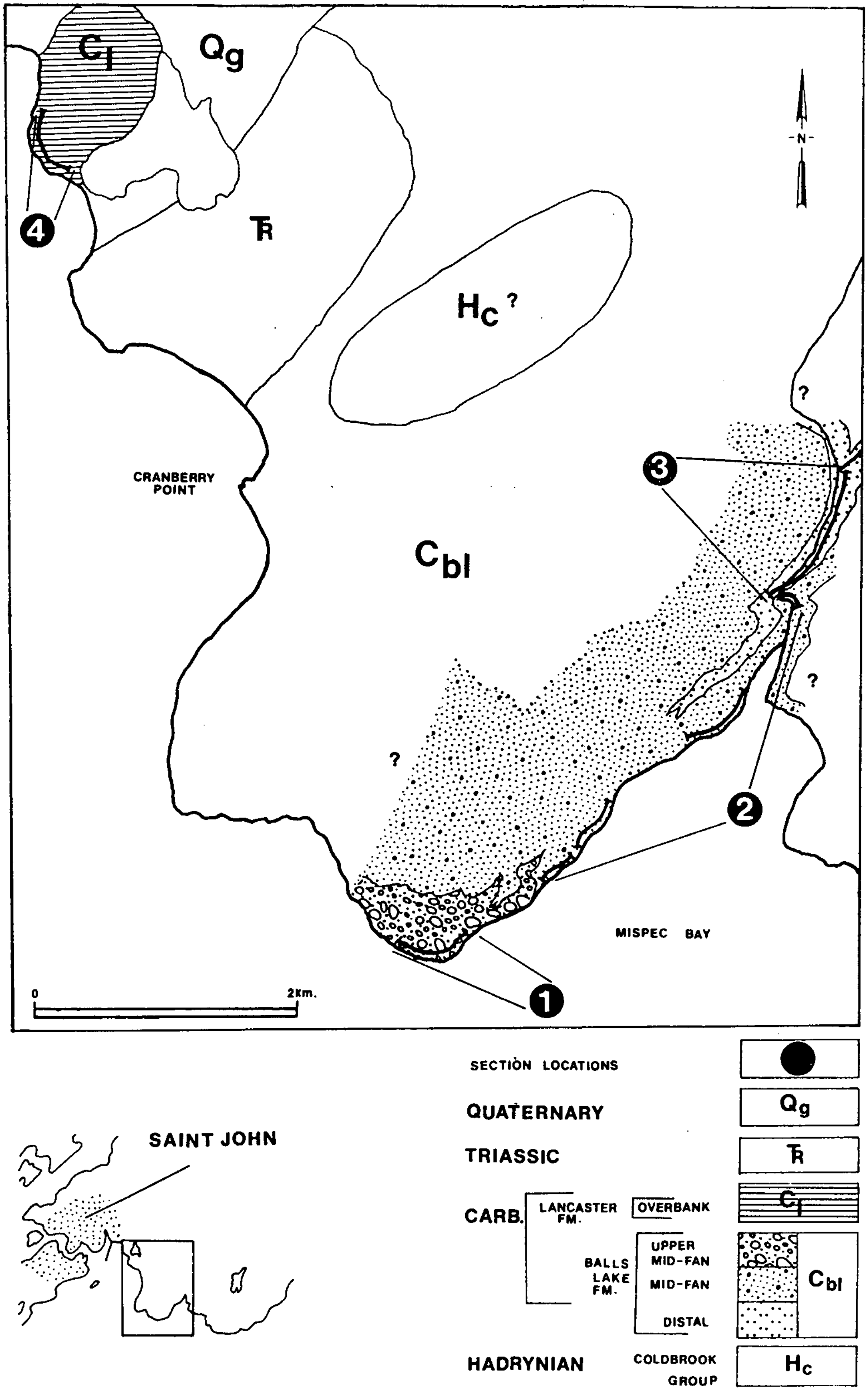

Fig. 2. Simplified geological map of autochthonous Lancaster and Balls Lake Formations southeast of Saint John illustrating facies distribution and field location of synoptic stratigraphic sections shown in Figure 4 (after Caudill and Nance 1986).

glomerates; red to greyish red, unsorted, polymict and polymodal paraconglomerates; and occasional red siltstones. The formation attains a maximum estimated thickness of 200 m but thins northwestward to a few metres near Saint John (Currie and Nance 1983). In contrast, the Lancaster Formation, which attains a maximum thickness in excess of 400 m, consists of grey to greyish brown, lithic arenites with occasional thin conglomeratic pebble lags; common grey-green siltstones; and grey to dark grey shales. Poorly preserved plant fragments within the shales have been locally assigned to the Westphalian B (Stopes 1914) and Westphalian C (N. Rast, pers. comm. 1985) and probably span the interval Westphalian A-C. The Lancaster Formation conformably overlies and, locally, may underlie the Balls Lake Formation while vertical and lateral transitions from typical Balls Lake lithologies to grey-green units similar to those of the Lancaster Formation suggest lateral equivalence of the two units in some areas. An early Westphalian age for the unfossiliferous Balls Lake Formation therefore seems probable. Locally, both formations rest unconformably on Eocambrian feldspathic sandstones, volcanogenic conglomerates, felsic tuffs and basalt flows that overlie the late Precambrian Coldbrook Group (Currie 1984; Tanoli *et al.* 1985).

Further south, late Carboniferous deformation in parautochthonous units of the Balls Lake and Lancaster Formations progressively intensifies towards Cape Spencer (Fig. 3) where they are overthrust by allochthonous volcano-sedimentary units and the Cape Spencer granite (Nance and Warner 1986). Variably deformed, purple to green polymict conglomerates, lithic wackes, siltstones and shales, traditionally assigned to the Balls Lake Formation, closely resemble the mid-fan facies of the autochthon described by Caudill and Nance (1986) and are associated with pale green calcareous siltstones similar to their distal fan facies. Stratigraphically and/or structurally overlying grey to tan, cross-bedded lithic and quartz arenites, thin pebble conglomerates, and locally plant-bearing black shales are assigned to the Lancaster Formation.

At Ploughshare Rock (Fig. 3), the Lancaster Formation is itself overthrust by strongly deformed, clastic and volcanogenic sedimentary rocks that are tectonically overlain by metavolcanic rocks. The sedimentary unit comprises green calcareous siltstones, purple sandstones and green to pink, volcanogenic chlorite-calcite schists. The predominantly volcanic succession includes grey-green volcanogenic sandstones and siltstones, epidotized intermediate to basic volcanics, fragmental pyroclastics and occasional green laharic conglomerates. Although clearly older than the Balls Lake Formation, to which they contribute clasts, the age of these units is uncertain. The volcanic succession has traditionally been assigned to the West Beach Formation of presumed Carboniferous age (Hayes and Howell 1937; Alcock 1938), whereas the sedimentary unit has been assigned to both the West Beach (Hayes and Howell 1937) and Balls Lake Formations (Alcock 1937; Ruitenberg *et al.* 1979; Parker 1984). However, both units most closely resemble the Eocambrian succession and late Hadrynian Coldbrook Group (Currie and Nance 1983; Ruitenberg 1984) which unconformably underlie the Balls Lake and Lancaster Formations further north (Currie 1984; Tanoli *et al.* 1985).

Extending northeastward from Cape Spencer (Fig. 3) are a series of orthomylonitic granitoid and quartz dioritic klippen that occupy the structurally highest position within the allochthon and collectively constitute the Cape Spencer granite. A late Hadrynian age for this granite, which is separated from the tectonically underlying volcano-sedimentary assemblage by a prominent mylonitic thrust surface, is supported by textural and compositional similarities to Hadrynian plutons north of the fold-thrust belt (Wardle 1978;

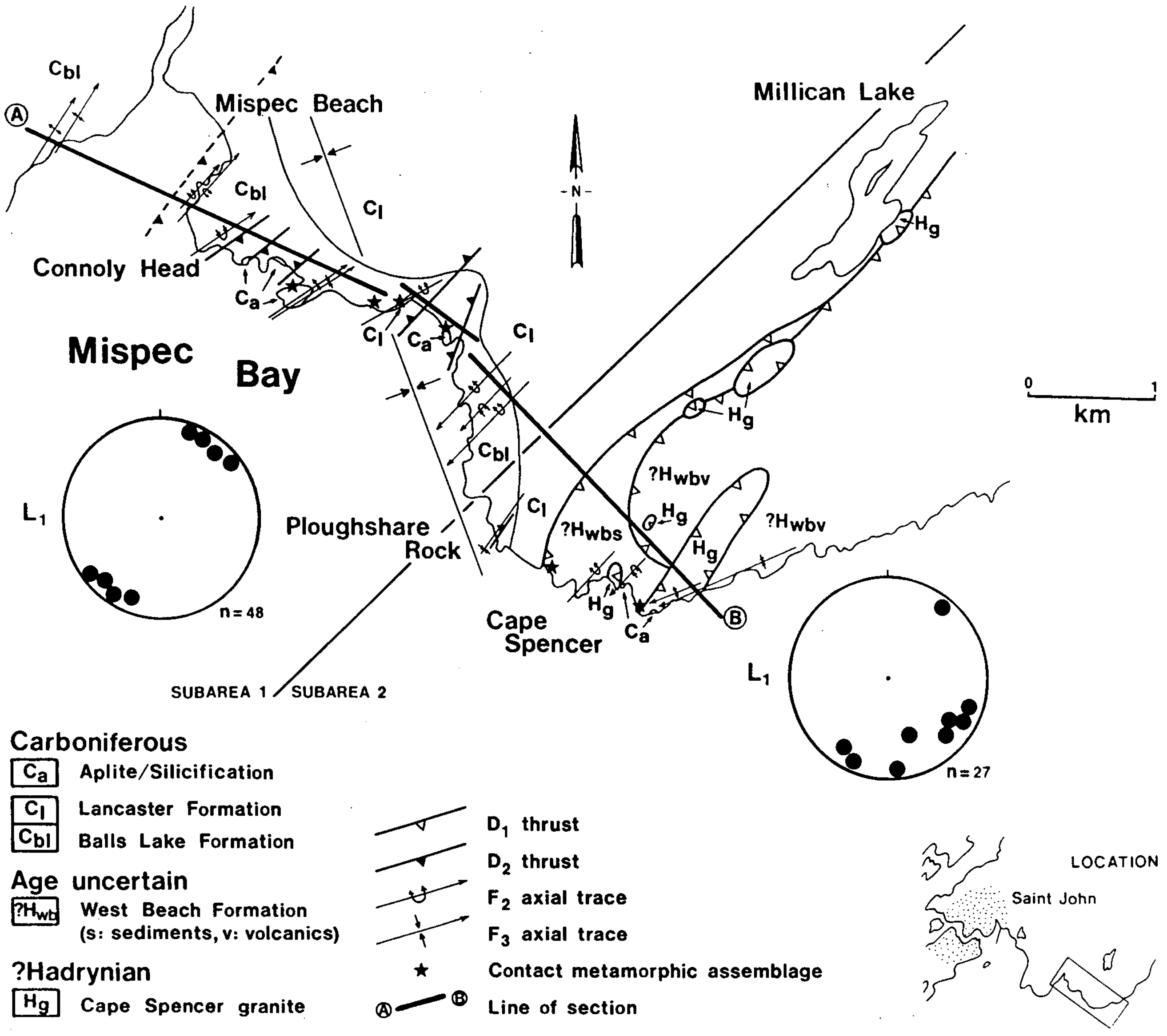

Fig. 3. Structural sketch map of parautochthonous and allochthonous units and $L_1$ lineation orientations on the eastern shore of Mispec Bay (after Nance and Warner 1986).

Currie *et al.* 1981).

The Cape Spencer granite and sedimentary rocks of the volcano-sedimentary unit and the Balls Lake Formation are locally invaded by small, sill-like masses of ?aplite and minor felsic dikes that appear to be associated with retrogressed chlorite-?andalusite spots which also occur within the Lancaster Formation. Development of these enigmatic bodies is associated with intense wall-rock silicification and is demonstrably syntectonic with respect to Carboniferous deformation as both aplites and their possible contact metamorphic or metasomatic assemblages cross-cut the principal ($S_1$) deformational fabric of their host rocks, but are themselves folded by later ($D_2$ and $D_3$) stages of deformation (Warner 1985).

## SEDIMENTOLOGY AND DEPOSITIONAL SETTING

### Balls Lake Formation

North of Mispec Bay (Fig. 2) mildly deformed and essentially autochthonous units of the Balls Lake Formation have been interpreted to be the product of a northwestward-prograding alluvial fan (Caudill and Nance 1986). More proximal portions of the fan (Section 1; Fig. 4) display braided stream deposits interbedded with subaerial debris flows. Braided sequences comprise erosively based, channel-fill deposits in which clast-supported pebble conglomerates fine upwards into coarse, large-scale, trough-cross-bedded sandstones. In contrast, debris flows form unusually coarse, unsorted and matrix-supported, polymict conglomerates of broadly tabular geometry. They are ungraded, devoid of current stratification, and exhibit textural inversion whereby contained pebbles display a significantly greater degree of rounding than larger cobbles and boulder-sized clasts. These larger clasts are predominantly calcareous, cross-bedded sandstones lithologically similar to interbeds of fluvial origin and suggest that the debris flows originated on the contemporary fan surface. Despite the lack of current stratification, these intraclasts further display a strong cleavage-parallel alignment that is absent in pebbles of older lithologies. As features indicative of intraclast rotation are absent, alignment of the flattened clasts occurred prior to conglomerate lithification and hence provides evidence that Carboniferous deformation was broadly syndepositional (Caudill and Nance 1986).

In the mid-fan region (Section 2; Fig. 4), bed thickness decreases, debris flows are absent, and the succession is dominated by braided fluvial deposits similar to, but thinner than, those of more proximal settings. Fluvial conglomerates interbedded with thin fining-upward sequences display horizontal to very low angle stratification and are associated with peripheral sandstone wedges resembling modern bar deposits (Rust 1972). Laterally extensive and parallel-laminated sandstones recording sheet-flood deposition predominate down section.

As distal reaches of the fan are approached (Section 3; Fig. 4), bed thicknesses further decrease, the proportion of siltstone and shale increases, and the succession becomes dominated by laterally extensive, grey-green sandstones interbedded with finer-grained overbank deposits. The tabular and low-relief, erosively based sandstones are attributed to channel deposition within a small meandering stream network draining the fan toe. Here stream-bank stability and floodplain development was fostered by the baffling effect of plant growth and resulted in more sinuous channels than those typical of braided river systems (Caudill and Nance 1986).

Paleocurrent directions within the Balls Lake Formation, based on foreset inclination of trough cross-beds, display a radial dispersal pattern typical of alluvial fans (Bull 1972) and indicate northwestward paleoflow consistent with a source area to the southeast (Caudill and Nance 1986).

## Lancaster Formation

The Lancaster Formation is largely the product of a major, northeasterly flowing, meandering stream system (van de Poll 1970) that drained the basin into which the Balls Lake fan prograded. However, in the vicinity of the fan toe, overbank sediments of the Lancaster Formation are influenced by the distal stream network of the Balls Lake fan. Adjacent to the fan (Section 4; Fig. 4), small meandering channel-fill deposits, comprising pebble conglomerates with shale rip-ups that fine upwards to parallel-laminated and trough cross-bedded sandstones, are incised into floodplain shales containing mud cracks and Westphalian plant fragments. However, paleocurrent directions showing a somewhat greater dispersion than those of the Balls Lake Formation are predominantly westward for these channel deposits (Caudill and Nance 1986) suggesting that they are the product of small meandering streams that drained the Balls Lake fan onto the floodplain of the Lancaster fluvial

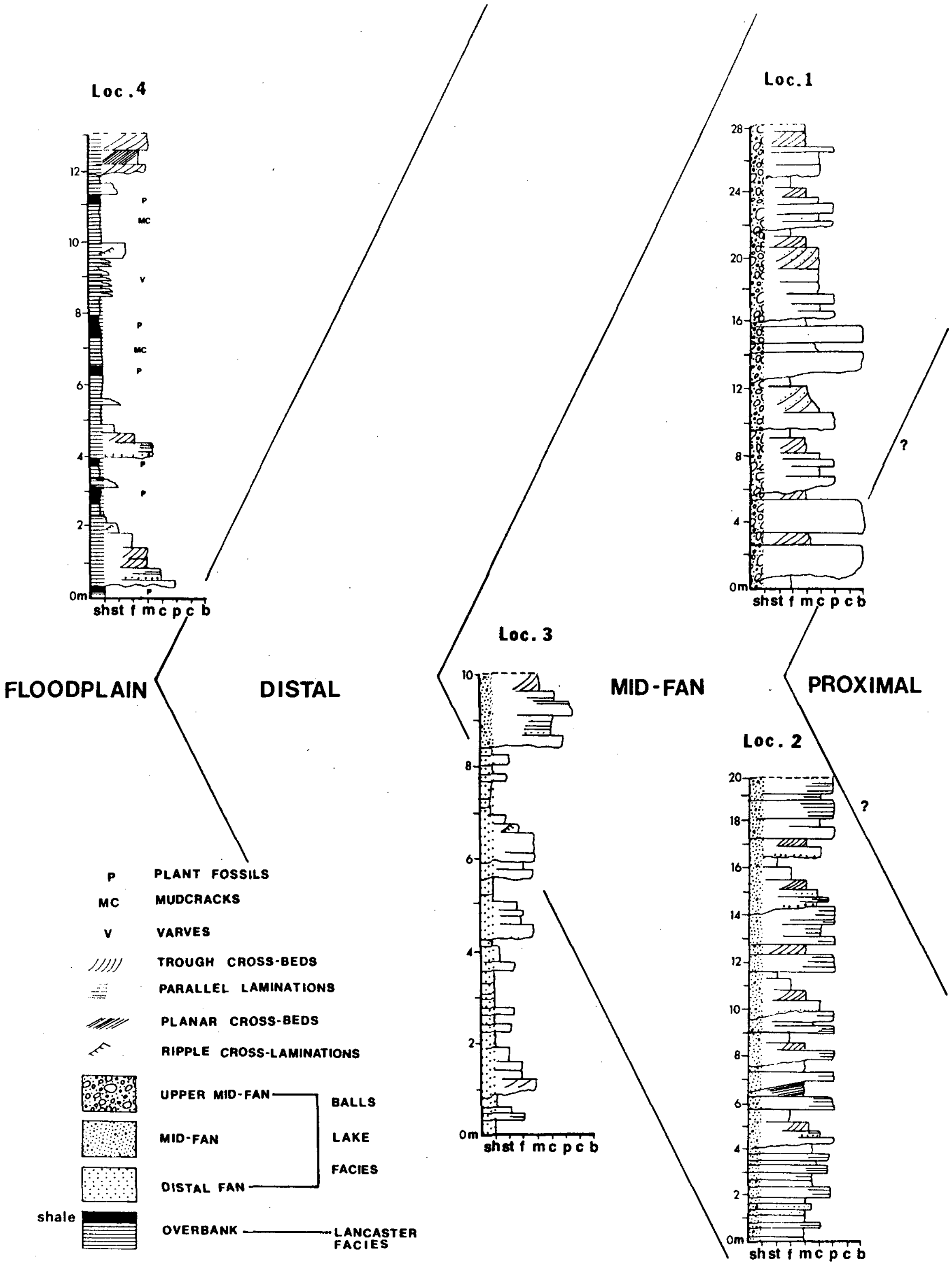

Fig. 4. Correlation of synoptic stratigraphic sections for the Balls Lake and Lancaster Formations showing vertical facies distribution suggesting fan progradation. See Figure 2 for section locations (after Caudill and Nance 1986).

system. Distinctly finer, parallel-laminated, trough and planar cross-bedded sandstones toward the top of the section are attributed to stream deposition on an encroaching Lancaster floodplain at progressively greater distances from the receding fan toe.

## Depositional Model

Caudill and Nance (1986) have interpreted the Balls Lake Formation in terms of a simple alluvial fan model (Fig. 5) in which braided streams of the mid fan are associated with debris flows derived from steeper portions of the proximal fan and give way distally to rapidly migrating streams. These distal streams eventually meander across the floodplain of the Lancaster fluvial system where they locally influence sedimentation that was primarily controlled by flooding of major, northeast-flowing streams. Fluctua-

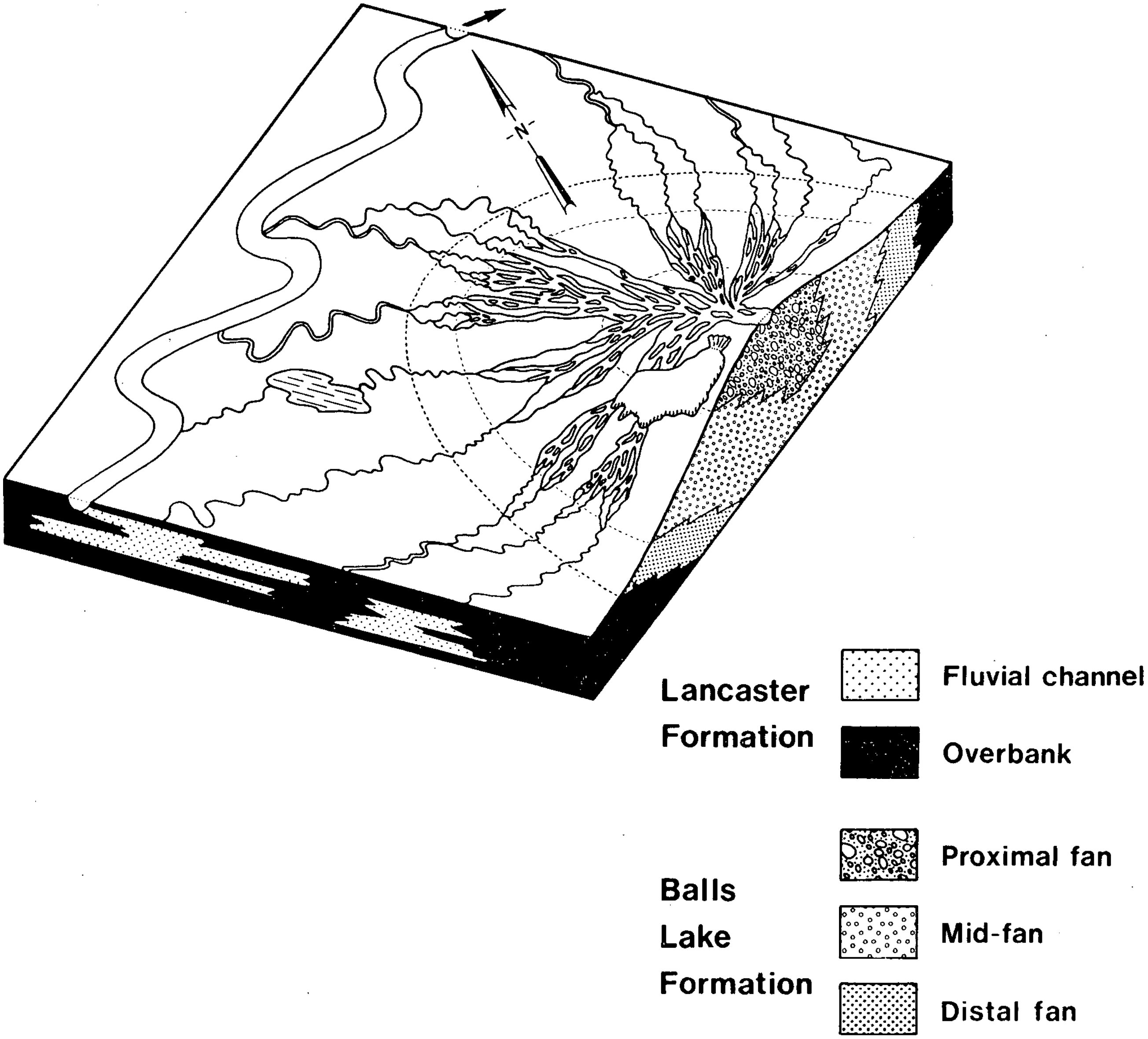

Fig. 5. Schematic alluvial fan model illustrating depositional setting and spatial distribution of Lancaster and Balls Lake Formation facies (modified after Caudill and Nance 1986).

tions of the rate of sedimentation in the respective depositional systems produced an interfingering of the Balls Lake and Lancaster Formations as the fan prograded northwestward. Within the Balls Lake Formation, the encroachment of mid-fan facies into areas initially and finally occupied by the distal fan (Fig. 4) suggests a progradation-retreat response of the fan to changing local relief and erosion rates within a southeasterly source area and is, hence, consistent with the paleocurrent data. Fan progradation requires marked relief to the southeast while intraclast alignment within debris flow conglomerates of the Balls Lake Formation suggest sedimentation was syndeformational. The model is therefore consistent with development of the fan ahead of an actively advancing allochthon as proposed by Currie and Nance (1983).

A closely analogous depositional model has been presented by Plint and van de Poll (1984) for Pennsylvanian sediments at the northeastern end of the fold-thrust belt (Fig. 1). Here, Westphalian redbeds of the Tynemouth Creek Formation are interpreted as the product of alluvial fans which, in response to the tectonic uplift and thrust emplacement of a source area to the southeast, prograded northwestward into a basin previously drained by a major northeasterly flowing fluvial system (Boss Point Formation). Further thrusting subsequently caused both formations to be tectonically overridden and was followed by early Mesozoic extensional reactivation associated with opening of the offshore Fundy Basin during initial rifting of the present Atlantic Ocean (Nadon and Middleton 1984).

## STRUCTURAL GEOMETRY AND DEFORMATIONAL HISTORY

The tectonic development of the Balls Lake fan (Nance and Warner 1986) is recorded southeast of Mispec Bay (Fig. 3) where the regional stratigraphy has been structurally inverted. In this area, three major, coaxial fabric-forming events affect both the parautochthonous Balls Lake and Lancaster Formations and the structurally overlying allochthonous units. In the following discussion, these are designated $D_1$ to $D_3$, although their regional development is likely to have been diachronous and, in part, conjugate.

### $D_1$ Structures

The earliest phase of Carboniferous deformation ($D_1$) records the northwest-directed thrusting that emplaced the Cape Spencer allochthons on surfaces now represented by the mylonitic basal contacts of the Cape Spencer granite and both units of the underlying volcano-sedimentary section. Associated lower greenschist (chlorite zone) metamorphism accompanied the development of a pervasive, broadly southeast-dipping but variably expressed planar fabric ($S_1$) that locally contains a strong but variably oriented extensional lineation ($L_1$). Southeast of Saint John, $S_1$ is axial planar to rare, isoclinal microfolds ($F_1$) that plunge gently northeast and southwest. To the west of the city (Fig. 1), however, $S_1$ is associated with northwest-verging overturned structures of regional extent (Rast *et al*. 1978; Parker 1984; Nance 1986).

Within the parautochthonous Balls Lake and Lancaster Formations of subzone 1 (Fig. 3), $S_1$ ranges from a well-spaced, protomylonitic solution cleavage in competent conglomerates and sandstones, to a closely spaced, chlorite-muscovite slaty cleavage in finer lithologies. Elongate sedimentary porphyroclasts, mica beards and conglomerate pebbles locally define an $L_1$ lineation that parallels $F_1$ axes and plunges gently northeast and southwest (Fig. 3). The lineation has been attributed to both tectonic and sedimentary influences (Bradley 1984), the latter being supported by its perpendicular orientation with respect to paleoflow within the host Balls Lake and Lancaster Formations such that alignment of elongate pebbles may partly reflect depositional processes (Caudill and Nance 1986). Based on the shape of conglomerate pebbles, the XY plane of strain in subzone 1 lies within a broadly flat-lying $S_1$ cleavage while the principal axis (X) parallels $L_1$ and $F_1$. Qualitative strain estimates (Warner 1985) plot in both the constrictional and flattening fields and show orientations relative to minor structures that suggest flattening during thrust emplacement coupled with extension parallel to contemporary fold axes.

In the allochthonous units of subzone 2 (Fig. 3), deformation is markedly more intense. $S_1$ is commonly mylonitic and reflects substantial ductile shearing, thrust-related flattening and post-tectonic annealing in addition to pressure solution. $L_1$, defined by mylonitic quartz ribbons, elongate porphyroclasts and mica beards, is variable in orientation (Fig. 3) with an east-southeast-plunging maxima taken to indicate the stretching direction during thrust transport. In klippen of the Cape Spencer granite, protomylonitic fabrics preserving primary granitic textures progressively give way to orthomylonites and ultramylonitic muscovite schists within discrete shear zones and towards basal thrust contacts. Isolated sigmoidal porphyroclasts indicate top-to-northwest shear according to the criteria of Simpson and Schmid (1983). In the tectonically underlying volcano-sedimentary section, $S_1$ is variably expressed as a closely spaced slaty cleavage, protomylonitic solution cleavage and orthomylonitic foliation. In the latter, sigmoidal, solution-modified detrital porphyroclasts again indicate top-to-northwest shear and may be associated with optically continuous quartz ribbons produced through crystallographic slip, and core-and-mantle structures reflecting pronounced, post-tectonic annealing. Qualitative strain estimates again plot in both the constrictional and flattening fields (Warner 1985) with predominantly south-southeast-plunging axes of maximum elongation (X). However, observed strain in subzone 2 is complex and probably reflects the temporal and spatial overlap of various thrust-related processes such as shearing, flattening and pressure solution. Shearing during initial northwestward thrusting produced east-southeast-plunging prolate ellipsoids, and was followed by a component of flattening that became increasingly important as thrust imbrication progressed. In addition, deformation involved significant mass transfer, particularly in the Cape Spencer granite where the conversion of a quartzo-feldspathic protolith to a muscovite-rich mylonite requires net loss of silica, part of which is represented by ubiquitous $S_1$-parallel quartz veins that locally achieve thicknesses of over 5 metres (Alcock 1938).

### $D_2$ and $D_3$ Structures

Subsequent Carboniferous deformation ($D_2$ and $D_3$) was broadly coaxial with $D_1$ and produced trains of asymmetric folds that verge both northwest ($F_2$) and, more commonly, southeast ($F_3$). Associated axial planar crenulation cleavages range from barely perceptible to intense fabrics dipping southeast and northwest respectively. The resultant fold belt (Fig. 6) is superimposed on the $D_1$ thrust terrain at Cape Spencer, is geometrically conjugate in profile, and is quite narrow since correlative fold closures rapidly become less frequent and more gentle north of Mispec Bay (Nance 1985). Associated $D_2$ and $D_3$ thrusts are marked by an intensification of their respective cleavages and folding but do not appear to juxtapose significantly different units and are likely to be of modest displacement relative to those of $D_1$. $F_2$ folds, distinguished only by their northwest vergence, plunge gently northeast and southwest and are largely confined to the northern portion of subzone 1. Coaxial but southeast-

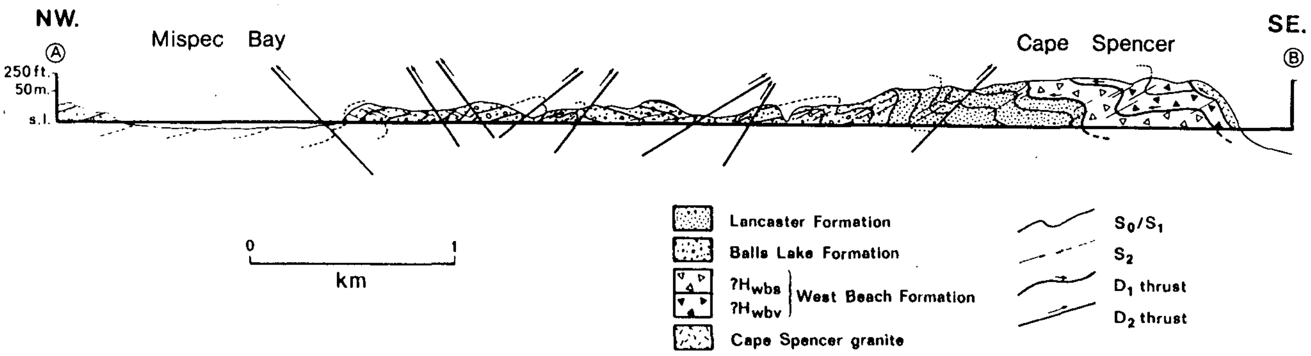

Fig. 6. Schematic cross section, Mispec Bay to Cape Spencer. See Figure 3 for section location (after Nance and Warner 1986).

verging $F_3$ folds are rare in areas of $F_2$ folding but become more abundant to the southeast. As both fold sets show similar structural style and texturally identical crenulation cleavages, they probably represent a conjugate folding/backfolding response to renewed or continued northwest-southeast compression that earlier produced $D_1$. Asymmetric, conjugate kink sets with gently northwest and southeast plunging axes locally overprint $D_2$ and $D_3$ and are equally dispersed across the entire area (Nance and Warner 1986).

## DISCUSSION AND INTERPRETATION

Major phases of Carboniferous deformation recorded in Westphalian sedimentary rocks southeast of Saint John reflect sustained northwest-southeast compression that was initially responsible for structural inversion of the regional stratigraphy during basement-involved, northwest-directed thrusting, and was later accommodated by conjugate folding and backthrusting (Nance and Warner 1986). The event strongly influenced deposition of the Balls Lake Formation as shown by facies relationships, pebble lithologies that match allochthonous units to the southeast, and northwest vectors of paleoflow that are perpendicular to fold axes (Caudill and Nance 1986). The Balls Lake Formation therefore provides both a deformational and depositional record of the event as suggested by Currie and Nance (1983). Syndepositional tectonic fabrics within the Balls Lake Formation, coupled with its lateral equivalence to part of the Lancaster Formation (Caudill and Nance 1986), constrains the onset of deformation to the early Westphalian. Its duration, however, is less certain. Folding clearly affects Lancaster sedimentary rocks as young as Westphalian C (N. Rast, pers. comm. 1985) and may have intermittently continued to the Permian (Rast 1983). Deformed redbeds of the Lepreau Formation, assigned to the Triassic on the basis of reptile tracks (Sarjeant and Stringer 1978), might have provided an upper time limit for the event as they possess a southeast-dipping fracture cleavage and are folded about northeast- southwest axes (Stringer and Lajtai 1979). However, Lepreau Formation siltstones have subsequently yielded Mississippian (late Visean) spores so that the age of the formation is currently uncertain (Stringer and Burke 1985). Triassic redbeds elsewhere are undeformed.

Carboniferous sedimentation for much of Maritime Canada has been successfully modeled in terms of pull-apart basin development adjacent to major strike-slip faults that record significant syndepositional displacements (Bradley 1982; Yeo and Ruixing 1986). Although this is potentially consistent with the calc-alkaline assemblage of the enigmatic West Beach Formation (Strong *et al.* 1979), assuming that the latter is of Carboniferous age, this is clearly inconsistent with the demonstrably Carboniferous Balls Lake and Lancaster Formations where sedimentation accompanied strong compressive deformation. Furthermore, the spatial coincidence of the fold-thrust belt with a major convergent bend in the Cobequid-Chedabucto fault system (Fig. 7), which is known to record significant, right-lateral Westphalian movement (Keppie 1982), stongly suggests that shortening in southern New Brunswick reflects late Carboniferous transpression at the western terminus of the Cobequid system where the vector of strike slip is compressionally oblique to the fault trace. As illustrated by the regional strain ellipse (insert, Fig. 7), dextral transpression under these conditions would be accompanied by a northwest-southeast component of compression capable of producing fold-thrust orientations closely matching those of southern New Brunswick.

Support for transpression as the underlying mechanism for deformation in southern New Brunswick is also evident within the fold-thrust belt itself. In the absence of megascopic $F_1$ structures southeast of Saint John, the widespread development of flattened conglomerate pebbles and a pervasive, subhorizontal, bedding-parallel $S_1$ cleavage within the parautochthon of subzone 1 (Fig. 3) suggest that the granitic and volcano-sedimentary allochthon, presently preserved on moderate to steeply dipping thrusts at Cape Spencer, was formerly more extensive. Hence the implied geometry of thrusting, in addition to being basement-involved, is downward-steepening to the south. Furthermore, while mylonitic porphyroclasts within the allochthon of subzone 2 (Fig. 3) consistently yield up-dip, top-to-northwest shear sense, stretching lineations taken to indicate transport direction predominantly plunge east-southeast and are, hence, right-laterally oblique to their associated, southeast-dipping thrust surfaces.

A transpressional origin for the fold-thrust belt would also account for the regional, on-strike variations in its deformational style, orientation and intensity. Regional northwest-verging $D_1$ structures (Rast *et al.* 1978; Parker 1984) and post-tectonic greenschist facies metamorphism that culminates in the occurrence of garnet at Lorneville (Mosher and Rast 1984) southwest of Saint John (Fig. 1), are absent southeast of the city where megascopic $D_1$ folds are unknown and metamorphism is syntectonic and lies entirely within the chlorite zone (Nance and Warner 1986). Furthermore major allochthonous zones within the fold-thrust belt are not laterally persistent but rather show en echelon trends. Thus the intensely deformed zone of the Lorneville peninsula (Currie 1984) does not extend east of Saint John but instead appears to side-step to that of Cape Spencer where it terminates to the northeast and may again side-step seawards (Fig. 1). Similarly, the highly deformed zone west of Lepreau also terminates to the northeast and may side-step to that of Lorneville. Such closely spaced, on-strike discontinuities in deformational geometry, timing and intensity are not readily resolved within a simple overthrust system but rather suggest differing degrees of convergence on separate, right-stepping wrench faults. These faults segment the fold-thrust belt (Fig. 1), are synthetic with respect to the offshore Cobequid-Chedabucto system, and shallow into thrusts to form positive flower structures. Evidence that this may be the case can be found at Musquash Harbour (Fig. 8) where the thrust termination of one such dextral shear would provide an explanation for otherwise anomalous, northwest-southeast fold trends at the western end of the Lorneville belt (Parker 1984; Nance 1986).

Carboniferous deformation on Western Head (Fig. 8) mimics that described by Rast *et al.* (1978) with major recumbent $D_1$ folds cut by two sets of younger cleavages. However, whereas the third deformational phase ($D_3$) corresponds in style and orientation with the $D_3$ backthrusting event south-

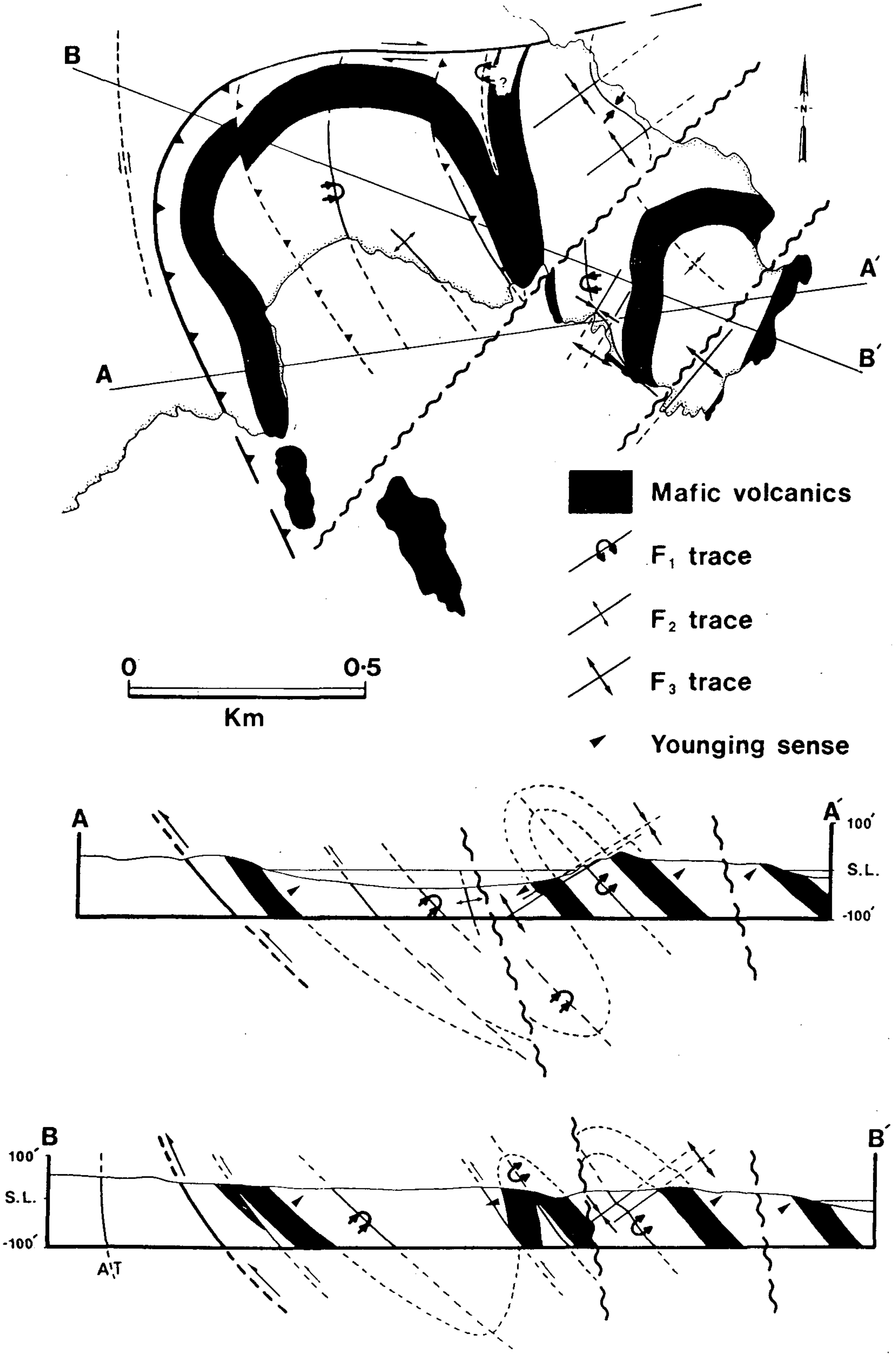

Fig. 7. Geologic sketch map and interpretive cross sections of Western Head (see Figure 8 for location).

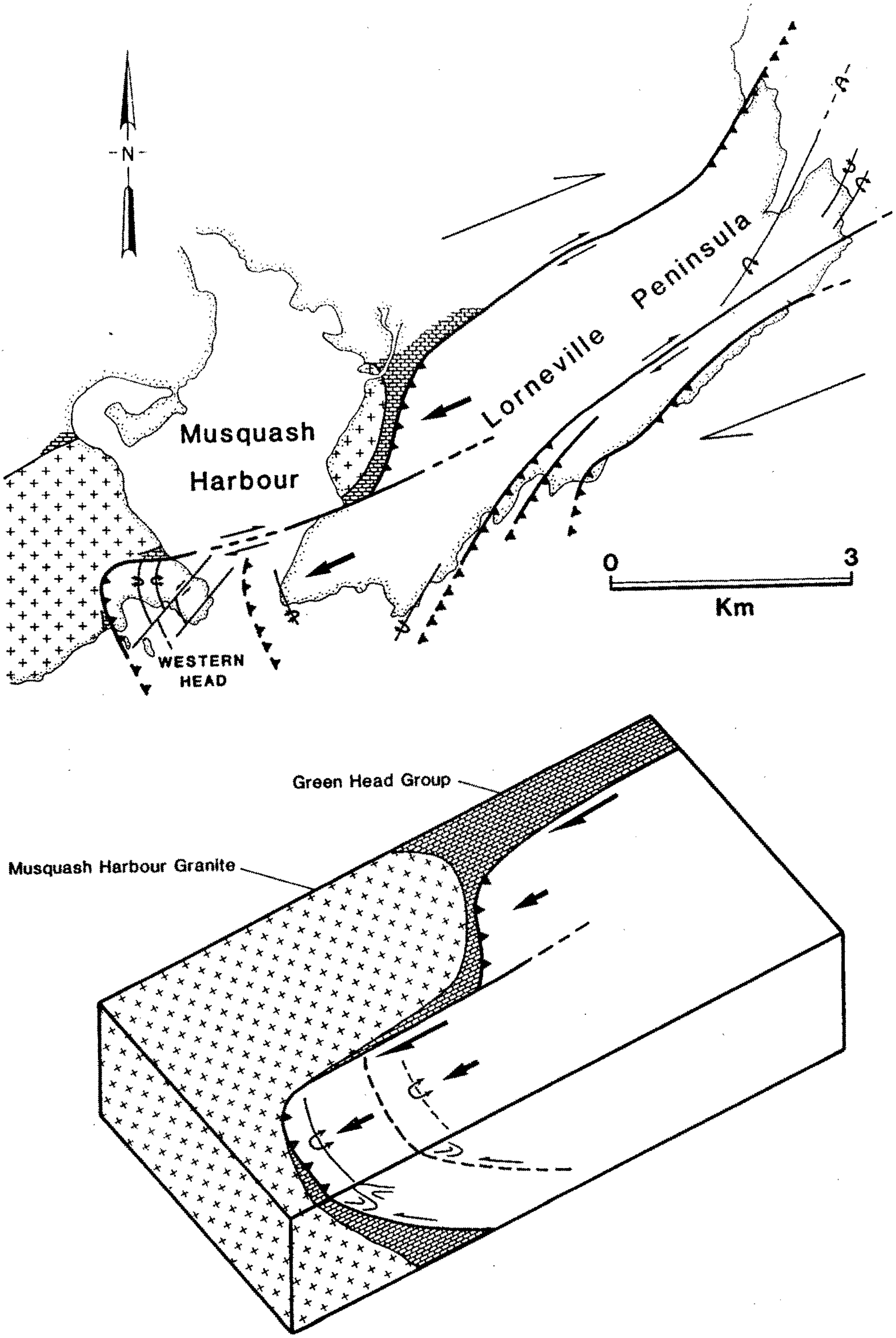

Fig. 8. Interpretation of anomalous cross-folds at the western end of the Lorneville belt as thrust termination of dextral shear buttressed against a major granitoid and detached on carbonates of the Green Head Group.

east of Saint John, the earlier two phases ($D_1$ and $D_2$), although broadly coaxial and coplanar, are perpendicular to their equivalent folds southeast of Saint John and trend northwest-southeast. In this area $D_1$, which records the regional early thrusting event, occurred in response to southwest-directed transport and produced major, southwest-vergent overturned structures ($F_1$) and a pervasive, bedding-subparallel $S_1$ cleavage (Fig. 8). Renewed or continued thrusting ($D_2$) produced coaxial folds ($F_2$) overturned to the southwest and a pervasive $S_2$ cleavage that is inclined at a shallow angle to $S_1$. $D_3$, however, records regional backthrusting with the development of southeast-vergent, overturned folds ($F_3$) and a strong, northwest-dipping, axial planar crenulation. The distribution of the anomalous northwest-southeast folds at the western end of the Lorneville belt (Fig. 9) suggests that dextral movement on synthetic wrench faults was here buttressed against a major, ?Hadrynian granitoid and terminated in southwest-directed thrusting detached on carbonates of the ?Helikian Green Head Group (Nance 1986).

Nance and Warner (1986) have therefore proposed a tectonic model for late Carboniferous deposition and deformation of the Balls Lake and Lancaster Formations southeast of Saint John in which thrusting is attributed to transpression rather than simple convergence (Fig. 10). In character with convergent wrench settings (Harding and Lowell 1979), individual upward-splaying faults shallow outwards into near-surface thrusts to define a positive flower structure over a synthetic, convergent wrench fault subparallel to the present Fundy shore. Uplift and structural inversion over the wrench fault provides the southeasterly source area for the Ball Lake alluvial fan which then fed the meandering stream system of the Lancaster Formation further north. However, with continued displacement on the wrench system, thrusting progressively overrode the Balls Lake and Lancaster Formations and produced the area's present structural geometry in which floodplain facies of the Lancaster Formation and fan facies of the Balls Lake Formation are overthrust, in turn, by their deformed equivalents, units of the ?Eocambrian volcano-sedimentary assemblage and, finally, by the Cape Spencer granite.

On a regional scale, a model involving the development of positive flower structures over en echelon, convergent wrench faults synthetic to a

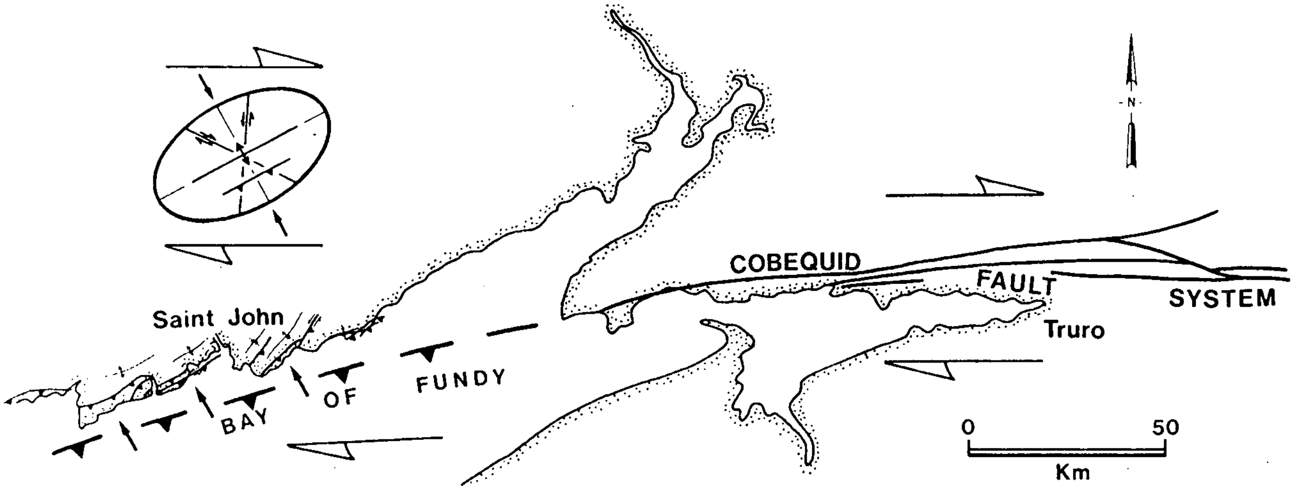

Fig. 9. Simplified structural map of the Bay of Fundy illustrating the coincidence of thrusting in the Saint John region with a major compressive bend in the Cobequid-Chedabucto fault system (after Nance and Warner 1986). Composite strain ellipse (Harding 1974) indicates predicted fold-thrust orientations during dextral shear (Saint John structures modified after Mosher and Rast 1984).

deeply listric, Cobequid-Chedabucto system (Fig. 11) might also account for significant differences in source area indicated by the conglomerate pebbles of individual fan complexes. In contrast to the Balls Lake fan where conglomerate pebbles can be largely matched to rocks of the New Brunswick Avalon terrane, those of the Tynemouth Creek Formation contain possible contributions from both the Meguma Terrane and the, then closer, Cobequid terrane (Plint and van de Poll 1982). The on-strike segmentation of individual fan

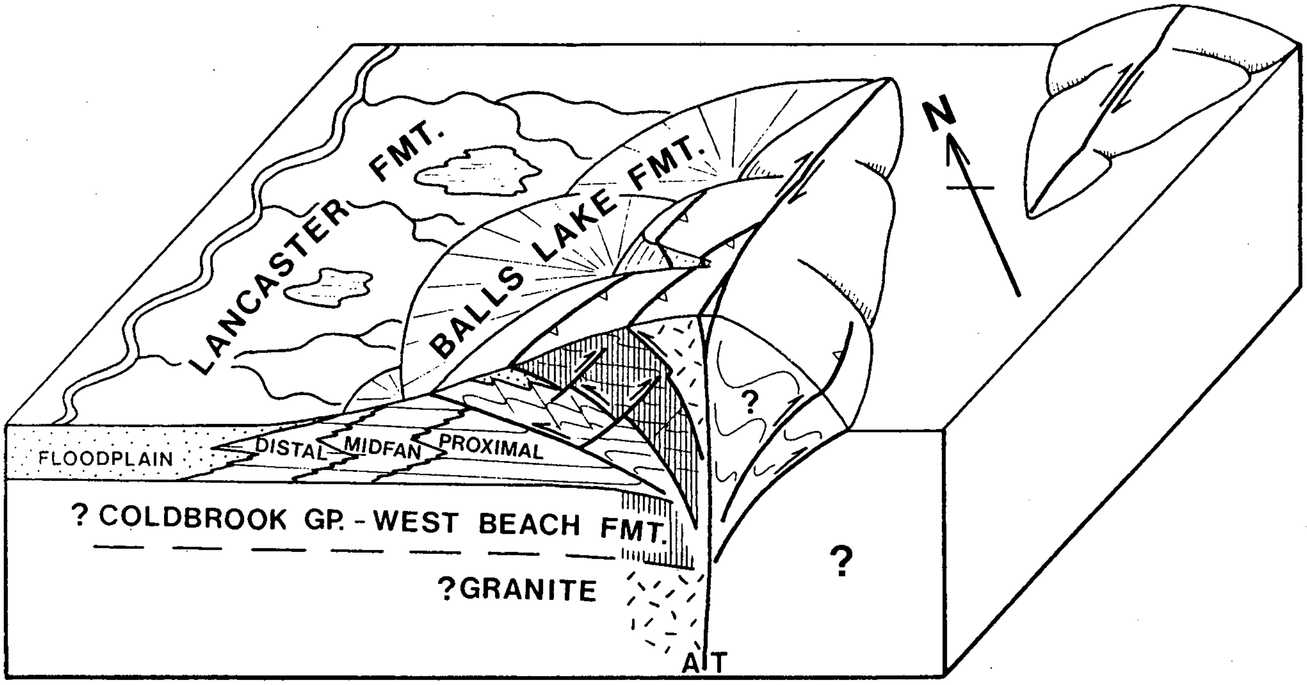

Fig. 10. Conceptual model for late Carboniferous deposition and deformation of the Lancaster and Balls Lake Formations through syndepositional thrusting and the development of a positive flower structure during regional dextral transpression (after Nance and Warner 1986).

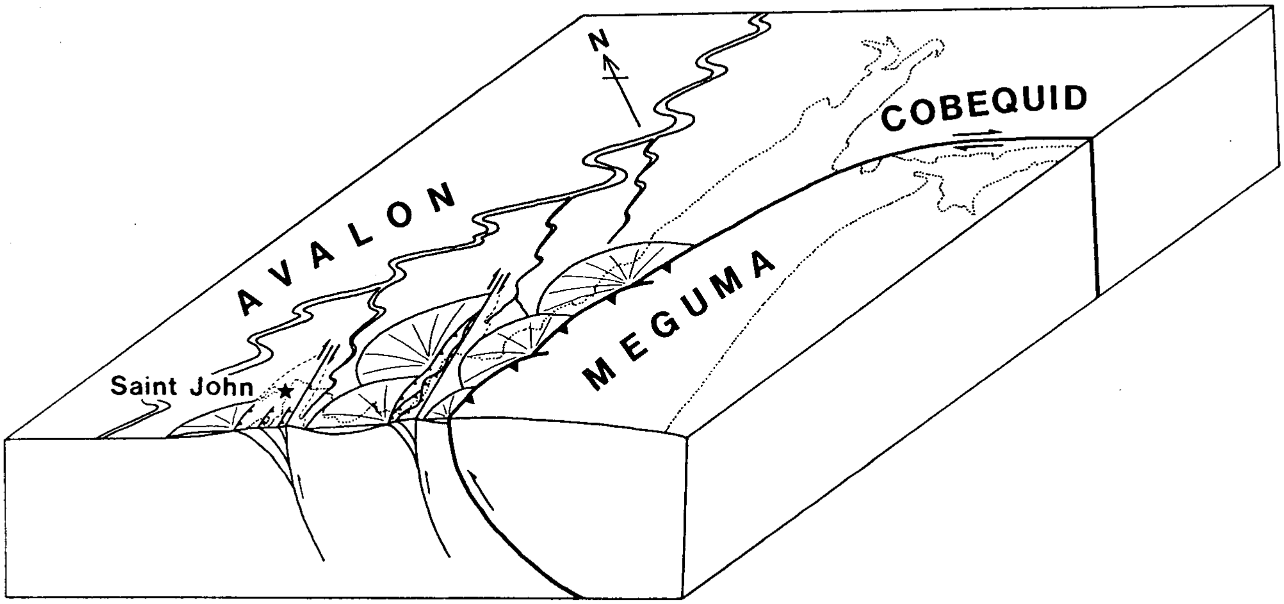

Fig. 11. Regional development of positive flower structures over en echelon, convergent wrench faults synthetic to the deeply listric Cobequid-Chedabucto fault system as an explanation for provenance variation within Westphalian alluvial fan complexes.

basins suggested by these variations in provenance, while counter to that expected for simple overthrust systems, is the predicted pattern of convergent wrench settings.

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