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A MAPPER'S GUIDE TO NOTRE DAME BAY'S FOLDED THRUST FAULTS: EVOLUTION AND REGIONAL DEVELOPMENT

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ABSTRACT

Major faults accompanied by several generations of coeval folds and foliations are mappable throughout large parts of the Dunnage Zone in Notre Dame Bay, where they affect rocks ranging in age from Tremadoc to Ludlow. Four superposed phases of regional deformation (D1 to D4) developed tectonic structures that are distinquished by individual geometric properties and which occur in a consistent temporal sequence. Fault displacement was largely by thrusting during the D1 and D2 deformations, but was apparently related to wrench movements during the D3 and D4 deformations.

Northwest- and northeast-trending structural domains, typified by conjugate folds and cleavage fans, were established and then enhanced during D1 to D4 deformation. Flower structure patterns recurred as deformation proceeded within these domains. Each regional deformation contributed to the evolution of the Z-shaped oroclinal flexure of central Notre Dame Bay, as newly formed features were inhomogeneously developed and overprinted structures were variably reworked.

Fault-rimmed domes and basins, from which incompetent Caradocian slates were preferentially excised, originated by open F2 folding of D1 faults, and were further modified by isoclinal F3 folding of D2 faults. Isolated belts of tectonic mélange were produced during D1 and D2 deformations as the terrestrial and marine strata of the northeastern Dunnage Zone were regionally imbricated. In this low-grade part of the Appalachian hinterland, the variable orientations and ages of folded faults are interpreted to have been ultimately controlled by the reactivation of ancestral structures in arc, ophiolite, or mélange units underlying closed back-arc and fore-arc basins.

INTRODUCTION

In the hinterland of the Newfoundland Appalachians, rocks of the Dunnage, Gander and Avalon zones occur in mantled gneissic, periclinal phyllitic and fault-rimmed domes, each of which is elongate and disposed about regional oroclinal flexures (e.g., Williams *et al.*, 1988). Where the Ordovician and Silurian rocks of the Dunnage Zone are regionally metamorphosed at sub-greenschist and low-greenschist grades, the regional structure of the hinterland is predominantly characterized by folded thrust faults (Dean and Strong, 1977) that comprise imbricate fans and duplexes, best developed in the hinge zones of Z-shaped flexures (Figure 1).

In the northeastern part of the Dunnage Zone, mapping of individual major faults demonstrates a regional pattern of fault coalescence adjacent to a relatively thin, laterally extensive, stratigraphic unit composed largely of incompetent black shale. From a regional structural perspective, these Caradocian-aged shales are preferentially excised and, where preserved, are typically fault-bounded and tectonically duplicated. In stratigraphically underlying and overlying rocks, Jura-type boxfolds (Laubscher, 1977; Suppe, 1983) are developed, particularly where Llanvirn–Llandeilo and Ashgill–Llandovery units are well-stratified. In geometric contrast, upright, cuspate, pinch-type folds of thrusts (e.g., the isoclinal lift-off folds of Mitra and Namson, 1989) occur exclusively within this incompetent unit.

Although a regional décollement surface is evidently not present within the Middle–Upper Ordovician succession, these structural features point to an incomplete mechanical decoupling of the black shales from older and younger rocks, as the fissile Caradocian beds were selectively and persistently utilized by thrust faults. This shaly horizon appears to be especially prone to decoupling where it overlies an Early Ordovician basement of crystalline arc and ophiolitic rocks, or an Early–Middle Ordovician substrate of olistostromal Dunnage Mélange. However, this phenomenom also occurs where the black shale substrate is represented by dominantly arc-volcanic packages that are locally devoid of a substantial thickness of well-bedded sediments (e.g., the lower Tea Arm or lower New Bay Pond volcanics of Dec *et al.*, 1992 and of Swinden and Jenner, 1992, respectively).

The outcrop pattern of the major folds and faults in the Exploits and Notre Dame subzones of the Dunnage Zone in

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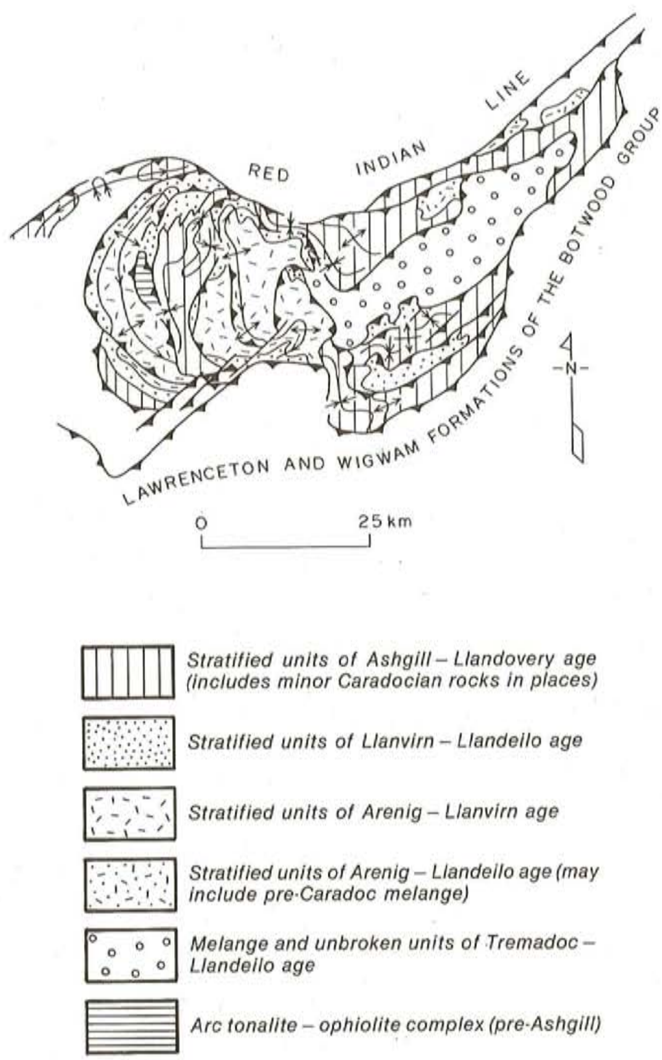

Figure 1. *Regional structural map of the Z-shaped oroclinal fold of central and eastern Notre Dame Bay with its constituent dome-and-basin structures illustrated. The lithostratigraphic unit most commonly excised by faulting is the Lawrence Harbour Formation of Caradocian black shale.*

central Notre Dame Bay generally reflects regional strain variation in a slate belt that is transitional to a mélange belt and thick-skinned, fold-and-thrust belt. Areas of small total strain in the multilayered Mid Ordovician to Late Silurian sequence contain vertical to inclined, dip-lineated slaty cleavages and large wavelength, gently doubly plunging folds. Major fold structures vary from types that are round-hinged and parallel to those that are angular-hinged and straight-limbed. Conjugate folds having steeply to moderately inclined axial surfaces are common; related cleavage fans are strikingly convergent in anticlines and divergent in synclines.

In areas of large total strain, small wavelength, asymmetric folds, displaying a variable but strong sense of vergence, have complex geometric relationships with slaty cleavage. Shallowly plunging folds in such zones are gently inclined (overturned), normal (upright) or reclined (neutral), and pass continuously along their axial trace from one into the other fold orientation. As a result, the cleavage associated with these folds typically forms a primary half-fan. In areas affected by the largest total strain, axial surface inclinations of minor folds lie parallel to the foliation in the hanging wall and footwall and to the intervening reverse fault, regardless of whether these structures are steeply or gently dipping. Together, these observations suggest that, not only do the major faults have both steep and flat segments, but that their listric shape was an original feature.

Imbrication of the rock units and folding of thrust faults on mesoscopic scale are most common where strata are ductilely attenuated in response to a tectonic straightening process related to mélange formation.

SUPERPOSED REGIONAL DEFORMATIONS

Regional (post-Caradoc) deformation of the northeastern part of the Dunnage Zone is generally considered as having been tectonically driven, in part, by renewed subduction and/or transform movements as an Early Ordovician-accreted arc complex converged obliquely on an Iapetan trench, north of Avalonia (Kay, 1976; McKerrow and Cocks, 1978; Arnott, 1983; van der Pluijm, 1987; Pickering *et al.*, 1988). Continued widespread deformation is also postulated to have occurred when this arc and its back-arc basin terminally collided with the sialic margins of, or the microcontinents off, the ancient landmasses of Gondwana and Laurentia (Pajari *et al.*, 1979; Colman-Sadd *et al.*, 1992; van Staal and Williams, 1992; Quinlan *et al.*, 1992).

Numerous studies documenting the detailed structural analysis of various parts of the Dunnage Zone in Notre Dame Bay have recently established complex sequences of overprinted tectonic structures that attest to superposed polyphase deformation of low-grade Ordovician and Silurian strata (e.g., Nelson, 1981; Karlstrom *et al.*, 1982; van der Pluijm, 1986; van der Pluijm *et al.*, 1987; Blewett and Pickering, 1988; Elliott and Williams, 1988; Elliott *et al.*, 1989). The interrelationships and precise chronological development of faults, folds and foliations vary with each deformation phase and from one area to another. However, several of these deformation episodes produced regionally developed structures that display characteristic geometric and kinematic properties. Such structures, which may be broadly coeval, can be identified and mapped throughout large parts of Notre Dame Bay (Figure 1).

As first proposed by Kay and Williams (1963) and regionally extended by Karlstrom *et al.* (1982), Tremadoc- to Ludlow-aged rocks in northeastern Newfoundland are structurally repeated by reverse faults. These bound panels of simply folded strata which, for the most part, are overturned and possess an inclined slaty cleavage. Although some faulted panels have been reported to contain regional anticlinoria and synclinoria, most have been deemed to be composed of either northwest- or southeast-younging successions, alternating in a complex imbricate arrangement. The predominant dip of the reverse faults is southeastward, and the predominant direction of overturning of asymmetrical folds is northwestward. Such structures have generally been assigned to the main episode of regional deformation, which most workers, including the writer, ascribe to a second phase of tectonic deformation.

Faults and allied ductile structures also originated during several, superposed, later deformations. Blewett (1991) and van der Pluijm (1986), in particular, have provided an analysis of these and earlier structures, which seems to be regionally applicable. Both workers commented on the localization of post-main-phase deformation in major thrust zones, which were complicated by later strike-slip movements. The northeast-trending, brittle transcurrent faults of Notre Dame Bay (e.g., Kusky *et al.*, 1987) postdate all of the deformation phases described herein.

The earliest recognizable episode of tectonic deformation in Notre Dame Bay is of crucial importance to the structural evolution of the major fault zones, and also of considerable bearing on the regional disposition of the rock units. Most workers have described minor structures of the first regional deformation where they have been locally preserved within superposed structures; accordingly, their origin has been considered enigmatic. However, a commonly quoted exception, where early structures of various types and scales are apparently well exposed, is stated to occur within several of the faulted panels of Notre Dame Subzone rocks, north and west of the Red Indian Line. There, and throughout the Exploits Subzone, the first tectonic deformation has been tentatively related to a regional thrusting event that produced either gently inclined or bedding-parallel faults (and folds) in a horizontal multilayer. Various workers have either included or excuded the Lawrenceton and Wigwam formations of the Silurian Botwood Group (Figure 1) from the rock groups affected by this phase of deformation.

The concept of southeast-directed tectonic transport during the earliest phase of regional deformation, followed by predominantly northwest-directed movements during the main deformation, was initially developed as a consequence of large scale tectonic–stratigraphic considerations. Early-stage major faults that presently dip gently northwestward have not been identified or regionally mapped out. Synsedimentary slump folds in Ashgillian strata (Pickering, 1987) were generally interpreted as having been triggered by hard-rock structures, now observed as early-phase tectonic features in the Lower–Middle Ordovician rocks of the Notre Dame Subzone (the hanging-wall sequence of Nelson, 1981) or in the pre-Caradoc substrate of the Exploits Subzone (the Taconian basement of Helwig, 1970).

Specific faults, folds and foliations generated during pre-main-phase deformation have been recently identified by Kusky (1985), LaFrance (1989) and Blewett (1991), the first two of whom are in stated agreement with the concept of early southeast- or southwest-directed tectonic transport. These structures, which are purported to have formed intermittantly (?) between the late Caradoc and the late Llandovery, are reported as having developed on minor, mesoscopic and megascopic scales in various parts of central Notre Dame Bay. However, overfolding during superposed deformations has resulted in these earliest phase structures: (1) dipping to the southeast or southwest, (2) displaying an apparent normal (as opposed to primary reverse) sense of shear, (3) being obscured in later tectonic mélanges, and (4) being overprinted by ductile strike-slip structures.

FAULTS AND FOLDS: NATURE AND SEQUENCE

For descriptive purposes, regional deformations during which major faults were formed, or were modified by folding and further faulting, are referenced as D1 to D4 in the figures and text that follow. Penetrative foliations and variably sized folds were also inhomogeneously developed during each of the D1 to D4 deformations; however, their dynamic relation to kindred faults (i.e., products of the same deformation episodes) are not fully understood.

The D1 to D4 structural sequence in Notre Dame Bay is typical of hinterland fold-and-thrust belts in that recumbent-upright cycles of deformation are recognizable in both time and space (Bell and Johnson, 1989). Furthermore, structural development is distinctly domainal, and structures that distinguish a domain (by its particular orientation) are generated during several deformation episodes (O'Brien, 1985). Thus, D1 and D4 structures trend northwest, whereas D2 and D3 structures trend northeast. Significantly, structures of D1 to D3 age each vary from steeply to gently inclined and, with the possible exception of D3, conjugate folds formed during every deformation phase. Figure 2 illustrates a boundary zone separating a northwest- and a northeast-

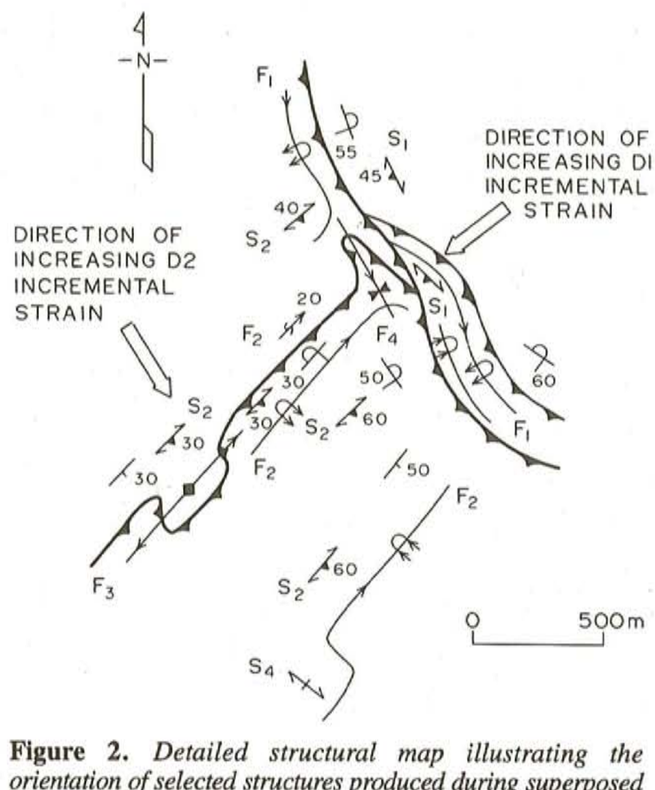

Figure 2. *Detailed structural map illustrating the orientation of selected structures produced during superposed D1 to D4 deformations, and their interference patterns near a typical boundary separating northeast- and northwest-trending structural domains. Note the scale of this example taken from Upper Black Island (NTS 2E/6).*

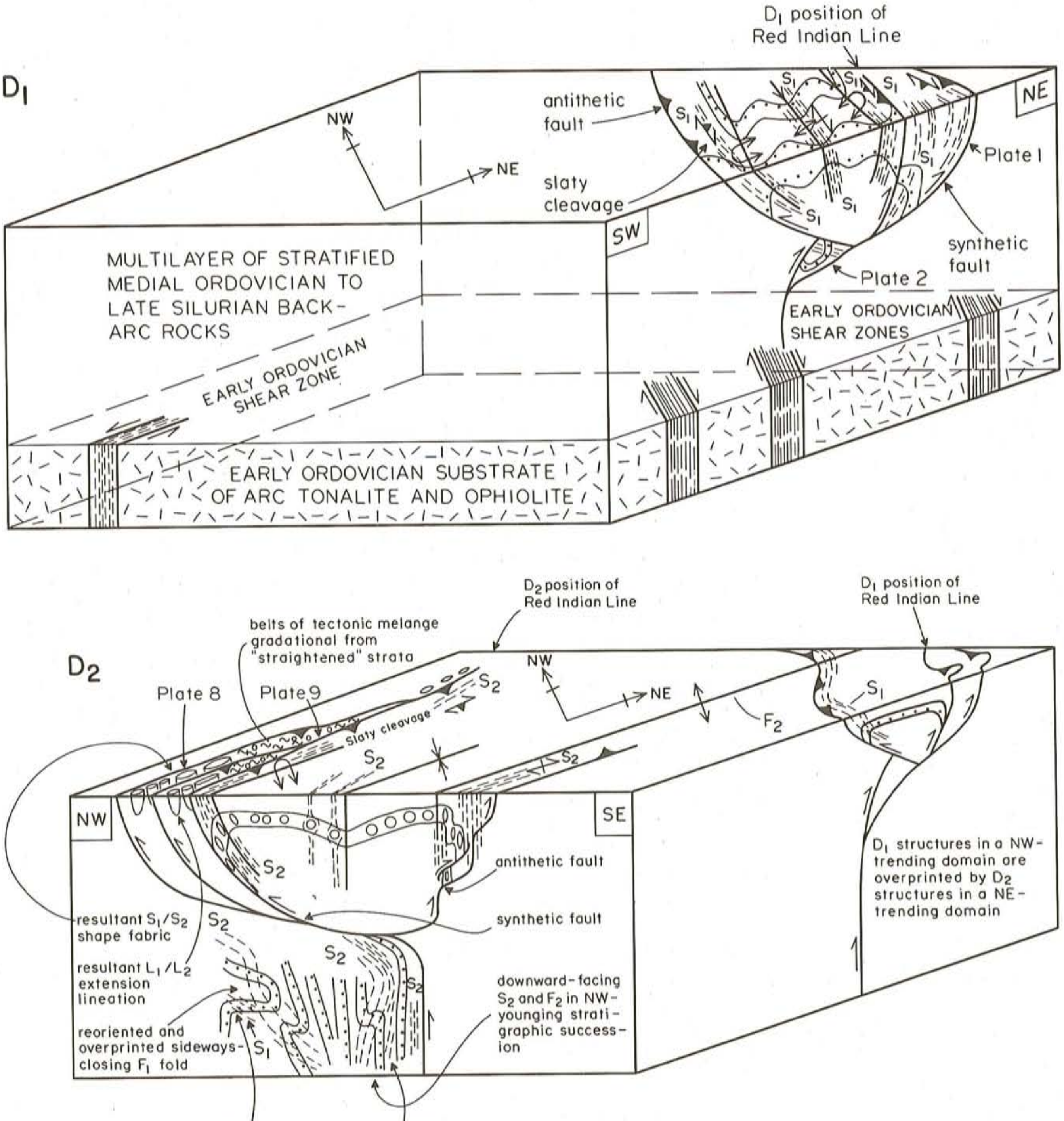

Figure 3. *Synoptic block diagrams illustrating the variable nature and orientation of faults, folds and foliations formed during the D1, D2, D3 and D4 phases of regional deformation. The characteristic features of each deformation episode are noted on the diagrams. Plate numbers relate to field photographs of particular structures depicted on the line drawings.*

trending structural domain in plan view, and shows the characteristic geometry and typical interference patterns of faults, folds and foliations of D1 to D4 age near the margins of these domains.

D1 Deformation

The D1 structures that are inclined gently to moderately southwestward are those most commonly encountered,

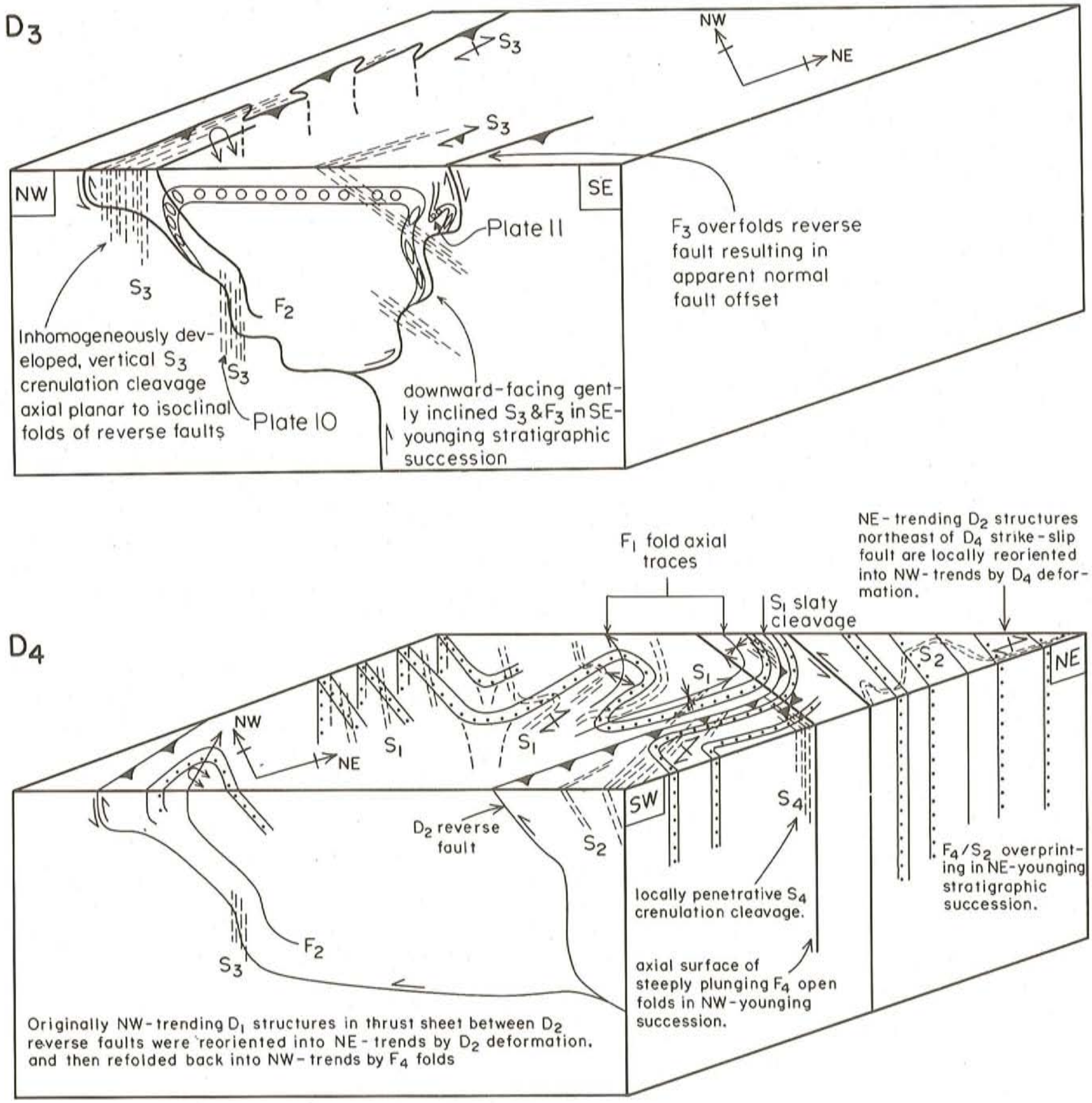

Figure 3. *Continued.*

although vertical and northeast-dipping D1 structures are observed (Figure 3). Northwest-trending S1 slaty cleavage is associated with plunging F1 folds that are overturned northeastward and, more rarely, southwestward. In places, however, second-order F1 folds within major anticlines and synclines have upright axial surfaces. Because F1 folds and S1 cleavage displayed their distinctive but variable orientations prior to D2 overprinting, these tectonic elements are presumed to have defined primary fans or D1 flower structures.

Asymmetrical F1 folds display progressively smaller interlimb angles and develop a stronger sense of vergence as S1 foliation intensifies in country rocks adjacent to D1 faults, regardless of the D1 rake of fault surfaces. Because variations in D1 incremental strain are reflected by folds, foliations and fault-rocks, it is assumed that D1 contraction faults had their listric shape governed by the geometry of the D1 flower structure and their particular position in the structural fan. Therefore, high-angle reverse faults are believed to pass up-dip and down-dip into thrusts.

Plate 1. *Typical example of a southwest-dipping Dl reverse fault, viewed looking to the southeast. An inverted succession of northeast-younging pillow lavas in the Fortune Harbour Formation (Llanvirn ?) of the Cottrells Cove Group develop a relatively strong, southwest-dipping Sl foliation in a narrow, northeast-directed, reverse shear zone. The locality pictured is located north of the Red Indian Line of Figure 1. See Figure 3 for regional structural setting. UTM grid reference is Zone 21U/XE E62275 N548825 (NTS 2E/11).*

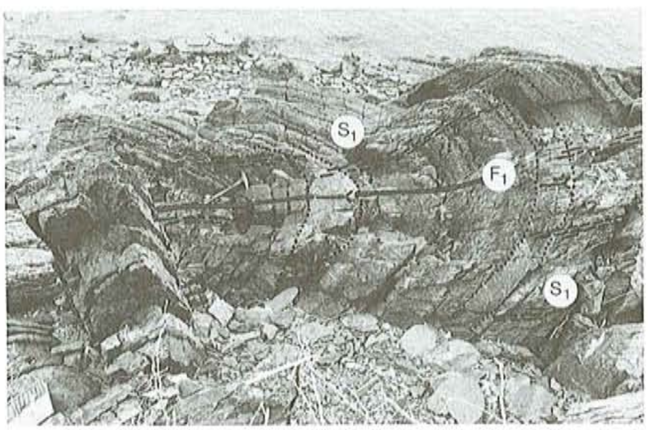

Plate 2. *Reclined Fl fold in the Moores Cove Formation (Llanvirn ?) of the Cottrells Cove Group, north of Red Indian Line. Viewed looking northeastward, the axis of this fold plunges moderately, pitching down the northeast dip of the Fl axial surface and the attendant Sl slaty cleavage. In this sideways-closing syncline in the footwall of a southwest-directed reverse fault (see Figure 3), the sedimentary succession is younging to the northwest (from right to left). UTM grid reference is Zone 21U/XE E62320 N548295 (NTS 2E/11).*

Thrusts and high-angle reverse faults of Dl age are interpreted as conjugate structures. Based solely on relative abundance, it seems that the synthetic faults were northeast-directed and that the antithetic faults were southwest-directed. Some major southwest-dipping faults associated with northeastward tectonic transport, however, display younger-over-older thrust relationships. Poorly developed L1 extension lineations pitch moderately to steeply on Sl foliations in shear

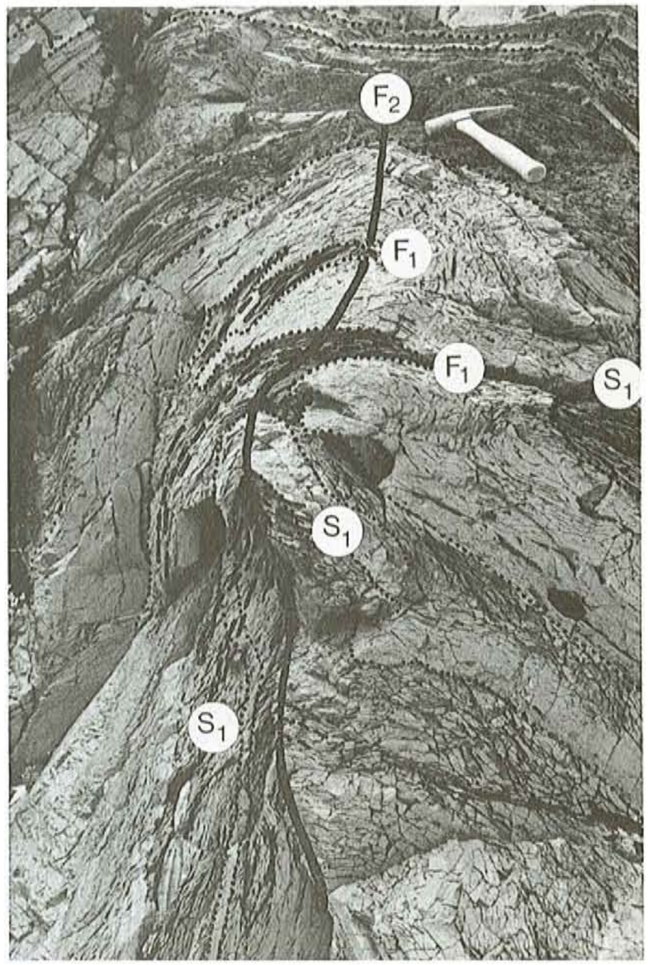

Plate 3. *Bedding, Sl slaty cleavage and the axial surfaces of minor Fl folds are folded about a shallowly plunging F2 anticline in the New Bay Formation (Arenig–Llanvirn) of the Exploits Group. As a result of D2 deformation, these Dl structures have contrasting structural facing relationships either side of the F2 axial surface on opposing F2 fold limbs. Viewed looking west-southwest down the F2 plunge. UTM grid reference is Zone 21U/XE E62810 N546485 (NTS 2E/6).*

zones near major Dl faults, probably suggesting oblique dip-slip movements on at least some reverse faults and back thrusts.

In some extensive regions of small total strain, the absence of Sl slaty cleavage, combined with the sporadic presence of S2 slaty cleavage, could be interpreted to mean that Dl deformation was areally restricted in comparison to D2 deformation.

D2 Deformation

The main D2 phase of regional deformation in Notre Dame Bay caused the widespread northeast-trending structures that predominate within the oroclinal flexure. D2 deformation produced regional anticlinoria and synclinoria, major thrust-sense fault zones and a widely developed slaty

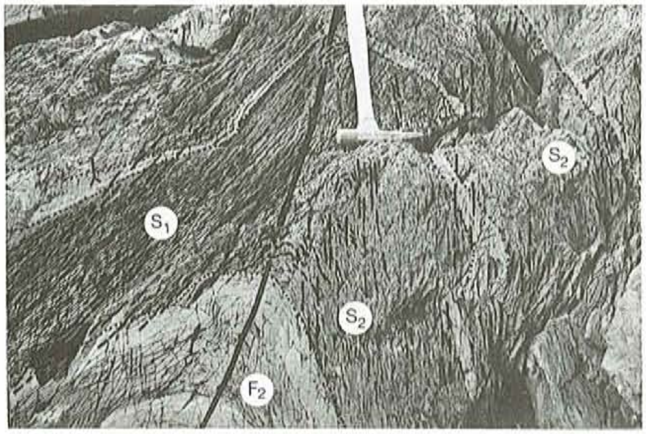

Plate 4. *Shallowly plunging F2 anticline in the New Bay Formation displaying vertical, upward-facing S2 slaty cleavage on its steeply dipping limb, and preserving moderately inclined, upward-facing S1 slaty cleavage on its gently dipping limb (see Figure 3 for setting of an analogous structure). S2 crenulation of variably facing S1 cleavage is observed in the crest of the F2 fold. Viewed looking west-southwest down the F2 plunge. UTM grid reference is Zone 21U/XE E62810 N546485 (NTS 2E/6).*

cleavage. The attitudes of all scales of D2 structures characteristically vary from vertical to southeast-, or more rarely, northwest-inclined.

The D2 faults are interpreted to have formed as conjugate structures. This is because the orientations of fault-related F2 folds and S2 foliations change systematically, giving rise to regional structural fans, which display opposing directions of overfolding either side of a vertical axial zone (Figure 3). However, despite the presence of these D2 zones of structural facing confrontation, mapping of major F2 folds demonstrates that most of these structures are northwesterly overturned and are gently doubly to locally steeply plunging. Inverted or right-way-up strata adjacent to such folds occur within the thrust sheets of major D2 fault zones, which typically dip moderately to gently southeastward. Based solely on their abundance relative to northwest-dipping D2 faults, these listric-shaped imbricate structures are interpreted as synthetic faults. Significantly, near certain southeast-dipping D2 faults, S2 cleavage overprints F1 folds and transects F2 folds, suggesting complex temporal and spatial relationships between the conjugate fault sets and developing regional folds (Figure 3).

Southeast-directed, antithetic faults developed along with the northwest-directed thrusts during D2 deformation. These D2 back 'thrusts' dip steeply northwestward, do not comprise extensive imbricate fans, and are apparently restricted to areas where regional anticlinoria or synclinoria are contained within fault-bounded panels.

Throughout the Z-shaped flexure in Notre Dame Bay, and particularly on its northeast-trending limbs, D2 overprinting caused regionally significant modification and

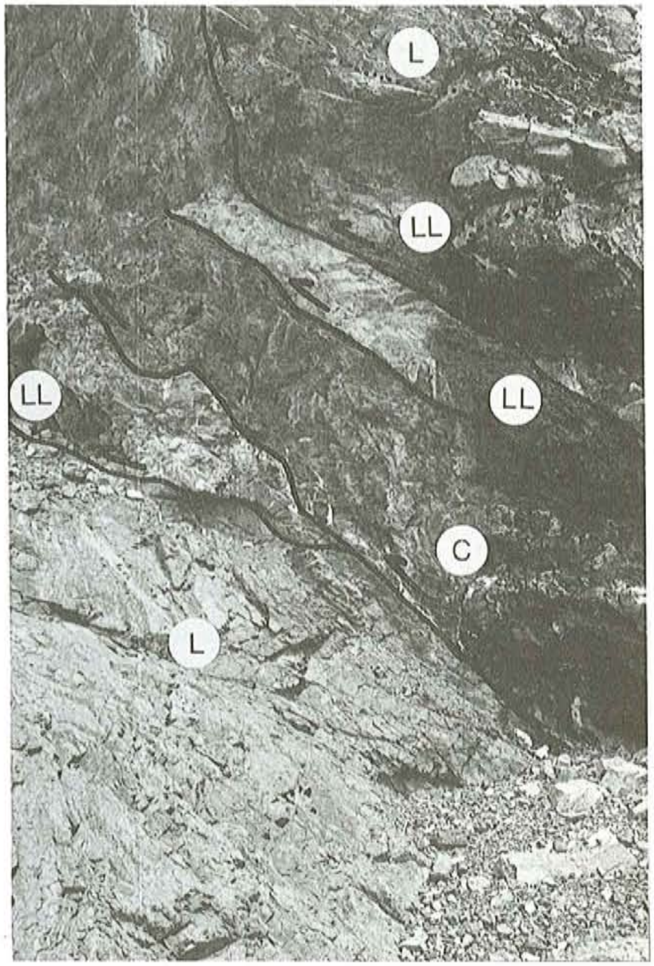

Plate 5. *Mesoscopic scale example of fault imbrication in a D2 thrust stack of Ordovician lithostratigraphic units. Viewed looking northeast, this 5-m-high exposure contains five thrust sheets separated by four southeast-dipping thrust faults. From its structural base to its top, the schuppen structure is composed of mylonitic Lawrence Head basalt (Llanvirn=L), Cobbs Arm-equivalent marble (Llanvirn-Llandeilo=LL), Lawrence Harbour black shale (Caradoc=C), Cobbs Arm-equivalent limestone, and Lawrence Head basalt with infolded Cobbs Arm-equivalent limestone. UTM grid reference is 21U/XE E63760 N547755 (NTS 2E/6).*

reorientation of originally northwest-trending D1 structures. In areas of small D2 incremental strain, D2 structures locally face downwards in stratigraphically continuous successions because of the strata's position on overprinted D1 structures. Where large-scale F2 folds refold D1 folds, foliations or faults in strata affected by variable D1 incremental strain (Figure 3), D2 and D1 structures gradually become coaxial as the D2 structures change from open to tight. As the regional D2 strain increases, northeast-trending imbricate fans of small D2 faults develop over narrow tracts of ground marked by ductile rotations or rigid body translations of D1 structures. Where syn-S2 recrystallization intensifies or where S2 completely transposes S1 foliation, D1 and D2 faults with similar displacement sense become coplanar (Figure 4).

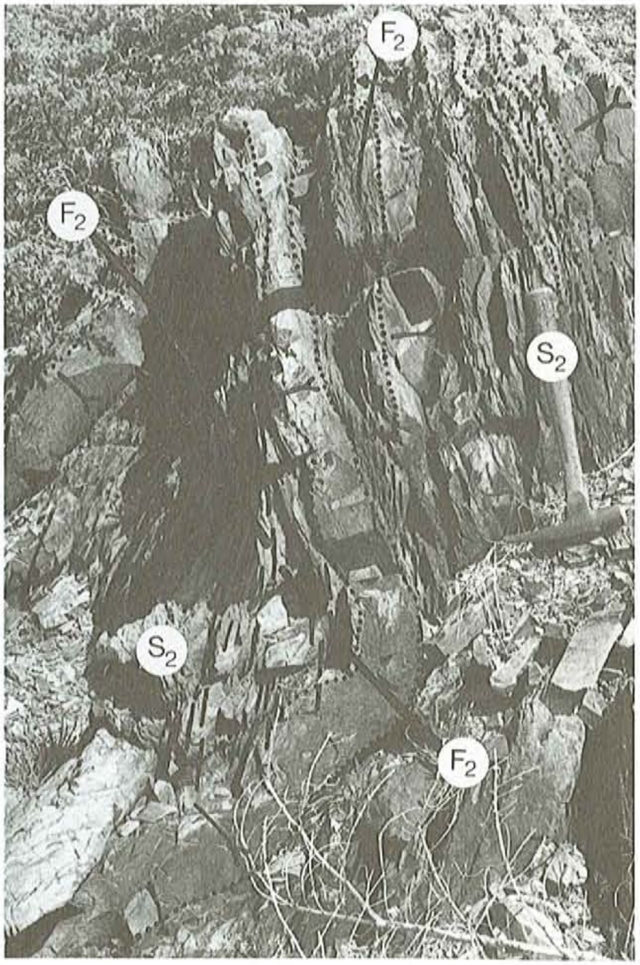

Plate 6. *Gently plunging F2 asymmetrical syncline with non-axial-planar S2 slaty cleavage. Note that S2 faces downwards on the steeply dipping inverted limb, faces upwards on the right-way-up, gently dipping limb, and crosscuts the hinge zone of this upward-facing F2 fold. However, S2 cleavage is axial planar to the downward-facing F2 minor fold illustrated in the top right-hand corner of the photograph (see Figure 3 for structural framework). Viewed looking northeastward. UTM grid reference is 21U/XE E61770 N546830 (NTS 2E/6).*

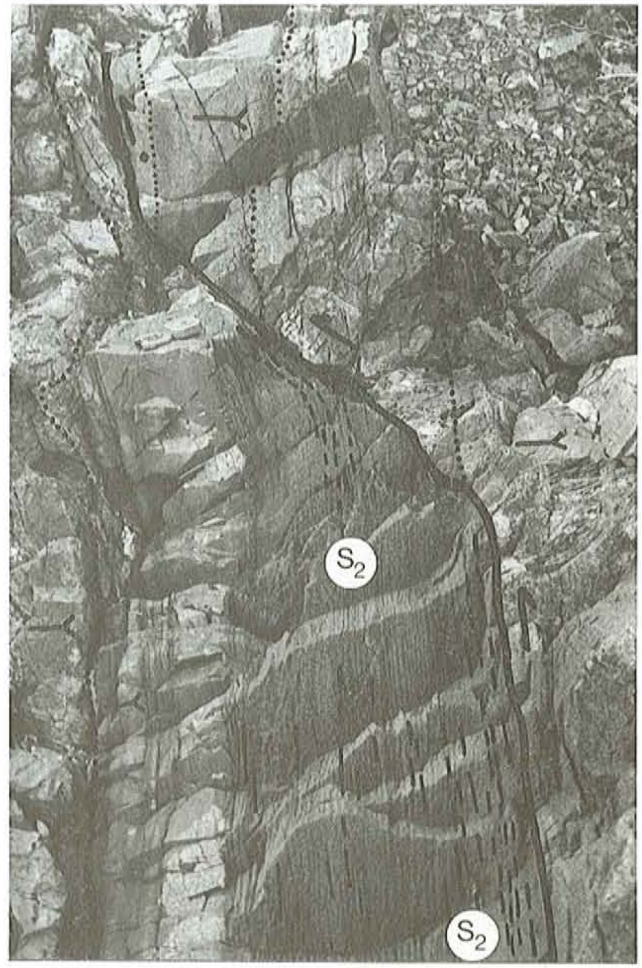

Plate 7. *Bedding-parallel D2 fault with an inclined thrust ramp in a subvertical succession of Strong Island chert and wacke (Llanvirn). See Figure 3 for structural setting of this type of fault. Note that strata become younger from the viewer's right to the left, and that bedding planes are truncated only on the right-hand side of the fault. In contrast, beds are ductilely attenuated in the footwall (the left hand side of the fault). Bedding-parallel S2 pressure solution cleavage intensifies adjacent to the vertical portions of the fault, and is rotated to lie parallel to the hanging-wall ramp. Viewed looking northeastward; field of view is about 8 m^2. UTM grid reference is 21U/XE E62095 N547450 (NTS 2E/6).*

Reverse faults of D1 and D2 age are mapped to locally coalesce near, or are obscured within, D2 mylonite belts, which are common adjacent to major faults bounding northeast-trending structural domains.

D2 thrust-imbricated zones of tectonically straightened rocks display resultant D2 shape fabrics (Figure 3). The S1–S2-shape fabric dips southeastward near synthetic faults and subvertically near antithetic faults. The resultant extension lineation pitches steeply down the dip of the straightened S-fabric; however, an independent measure of the L2 extension direction is not available. Where the total D1–D2 strain is large in schuppen structures, ductilely straightened rocks are observed to pass laterally and gradationally into tectonic mélange (Figure 3).

The D2 deformation style was possibly inherited from D1 deformation and/or controlled by suitably oriented older structures in underlying basement. However, during D2 deformation, flower structure patterns were developed on a larger scale than in D1 and in a different regional orientation. Subhorizontally plunging, fault-rimmed domes and basins formed on a regional scale as a result of D2–D1 interference.

D3 Deformation

Northeast-trending D3 structures coaxially overprint D2 structures on exposure and map scales, however, generation of S3 cleavage and F3 folds is restricted to the vicinity of

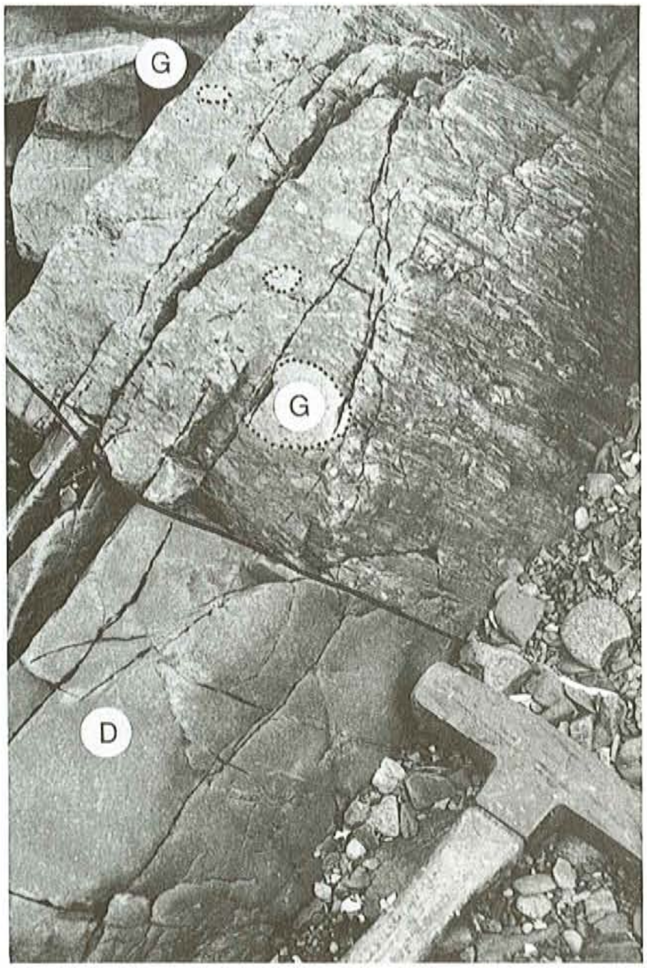

Plate 8. *L > S fabric developed in a hanging-wall sequence of Ashgillian (?) polymictic conglomerate near a southeast-dipping D2 thrust. Note that the outsized granite cobbles (G) are the least flattened of the detrital clasts, and that the lineation (a resultant shape fabric) pitches steeply down the southeast-dipping, gently inclined schistosity. Partly shown in the bottom left is one of a swarm of structurally concordant diabases (D). See Figure 3 for structural setting. Viewed obliquely looking east. UTM grid reference is 21U/XE E64945 N546345 (NTS 2E/7).*

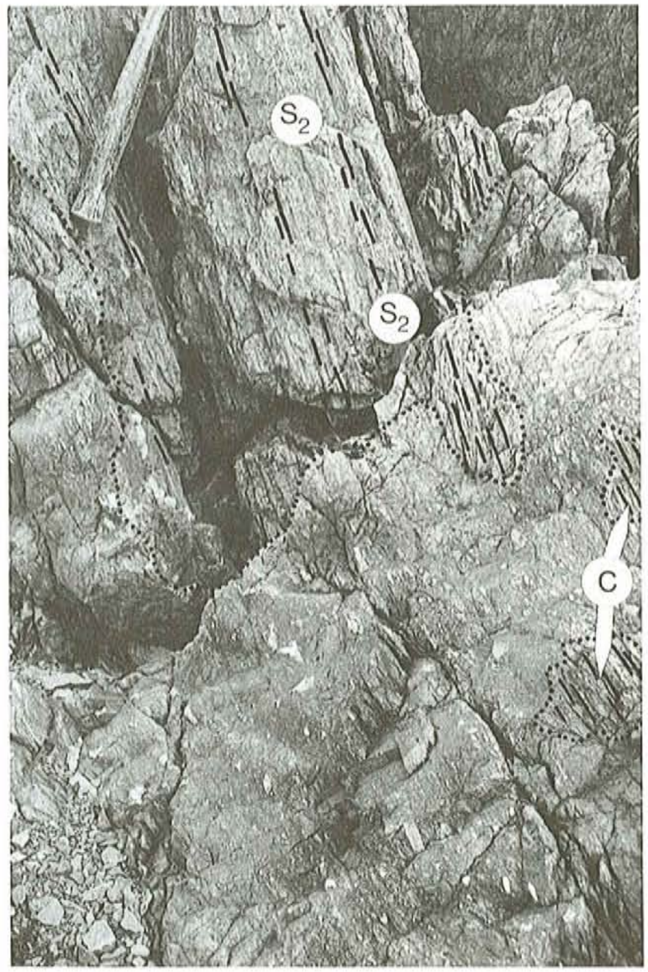

Plate 9. *Tectonic mélange, in foreground, displaying southeast-dipping S2 matrix foliation and variably D2-deformed fragments of metasediment and vein quartz. In the background, a tectonically straightened version of polymictic conglomerate, whose protolith is illustrated in Plate 8, passes laterally into mélange towards the viewer. Note the locally derived, isolated blocks of straightened conglomerate (C) within this syn-D2 mélange. See Figure 3 for structural setting. Viewed looking northeastward. UTM grid reference is 21U/XE E64945 N546345 (NTS 2E/7).*

major fault zones. In regions of small D3 but large D2 incremental strain, downward-facing S3 crenulation cleavage is sporadically developed and varies in attitude from subvertical to southeast-dipping (Figure 3). In some localities, S3 cleavage is axial planar to open, shallowly plunging, gently southeast-inclined F3 folds. In other places, vertical to steeply northwest-dipping S3 crenulations are superposed on both inverted and right-way-up strata near D2 listric faults, especially where these hanging-wall and footwall sequences begin to pass onto steeper parts of the D2 structural fan.

In regions of large D3 incremental strain, a characteristically subvertical, S3 composite foliation is axial planar to tight and isoclinal folds of bedding. In the hinge zones of such F3 folds, a strong bedding-parallel S2 fabric is commonly preserved, in places lying parallel to adjacent D2 faults. These F3-folded faults and thrust sheets are recognizable where small-scale D2 duplexing caused truncation of distinctive map units prior to the D3 deformation. Within exposures of such types of outcrop, F3 fold axes are highly curvilinear, plunging not only gently northeast and southwest but, for the most part, vertically. Vertical F3 folds of faults that had original thrust geometry are present on a variety of scales in central Notre Dame Bay. Either observed or mapped out, most though not all of these F3 folds are dextral Z-shaped structures (Figures 1 and 3).

Structures produced by localized, low-strain D3 deformation accommodate the steepening of the gently southeast-dipping D2 faults, the local overfolding of the

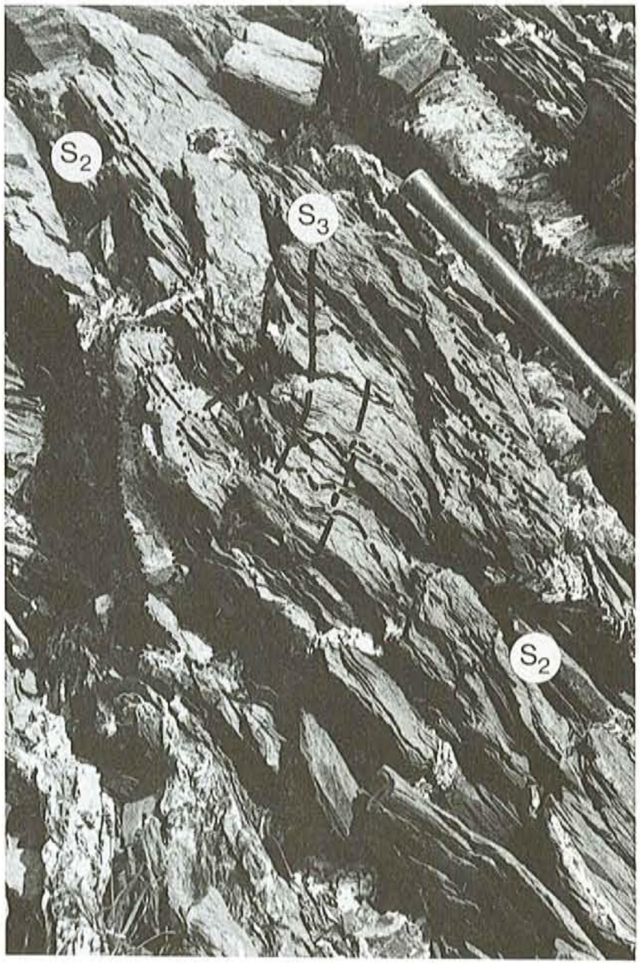

Plate 10. *Subvertical S3 crenulations and F3 open folds with steeply northwest-inclined axial surfaces plunge shallowly northeast, and coaxially overprint southeast-dipping, axial-planar S2 slaty cleavage and northwesterly overturned, asymmetric F2 folds. Viewed looking northeast, the strata illustrated occur in a largely inverted section of the Point Leamington Formation (Ashgill) in the footwall of a D2 reverse fault. Note that S3 cleavage faces downwards in the upside-down beds whereas S2 cleavage faces upwards; a consequence of the opposing senses of F3 and F2 fold vergence. See Figure 3 for structural setting. UTM grid reference is 21U/XE E62015 N548080 (NTS 2E/6).*

steeply northwest-dipping D2 faults, and the tightening of the original D2 ramp geometry of both sets of conjugate structures (Figure 3). It is unclear whether these tectonic features were caused by high-angle faulting during back-thrusting or by upright folding during wrenching. In contrast, high-strain D3 deformation affected rocks that were previously faulted on one or more occasions and inhomogeneously deformed by earlier ductile deformation, locally to the point of mélange formation. Tight, vertically plunging domes and basins defined by pre-D3 faults can be explained by either D3−D2 interference in a contractional pure shear regime or, alternatively, by sheath folding associated with non-coaxial deformation within a transpressive D3 strike-slip regime.

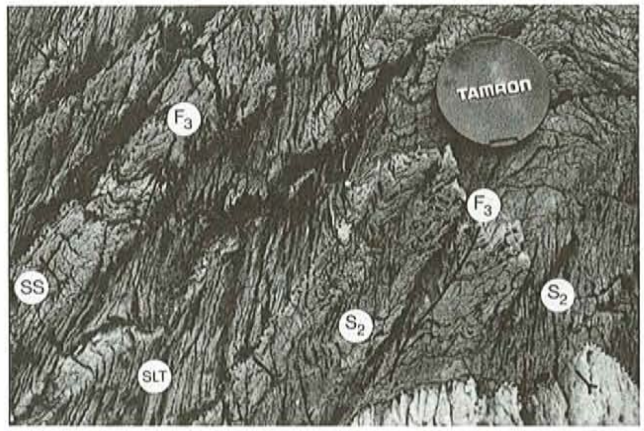

Plate 11. *Modification of consistently upward-facing S2 cleavage by downward-facing F3 minor folds in a gently dipping succession of right-way-up sandstones (SS) and siltstones (SLT) in the Point Leamington Formation, viewed looking southwest down the moderate F3 plunge. See Figure 3 for D2 structural setting of such right-way-up strata. Southeast-inclined F3 axial surfaces are observable in the relatively competent sandstone beds. However, note that the fold axes of the most asymmetric F3 folds, which have a sense of shear opposite to that deduced from the S2−S0 intersection, are contained within bedding planes. This indicates that flexural slip, with the addition of flattening strain, occurred during F3 overfolding. Lens cap is 7 cm in diameter. UTM grid reference is 21U/XE E61960 N548010 (NTS 2E/6).*

D4 Deformation

Northwest-trending D4 faults, F4 folds and S4 crenulation cleavage are typically found near D2 fault zones or where F2 folds overprint F1 folds (Figure 3). Although these D4 structures are present on various scales in rocks affected by both small and large total strain, the incremental strain associated with the D4 regional deformation is negligible. Northeast-trending D2 or reoriented D1 structures are commonly non-coaxially overprinted by D4 structures, but northwest-trending D4 and D1 tectonic features are rarely seen together in the same structural domain.

D4 strike-slip faults dip vertically and are associated with flexures displaying normal drag. In places where upright strata had a northwest strike prior to D4 deformation, offset during D4 locally produced bedding-plane shear near bedding-parallel strike-slip faults (Figure 3). Open to close F4 folds have subvertical axial surfaces; fold plunges are typically steeply to gently northwest or southeast. Axial-planar S4 cleavage is best developed in shaley or platey rock types, where it dips vertically and faces upwards, downwards and sideways. The orientation of low-strain F4 structures was largely controlled by pre-existing variations in the inclination of a highly anisotropic foliation or the homoclinal dip of beds in stratigraphic successions.

The predominant effect of D4 regional deformation was to locally reorient the D2 structures of northeast-trending

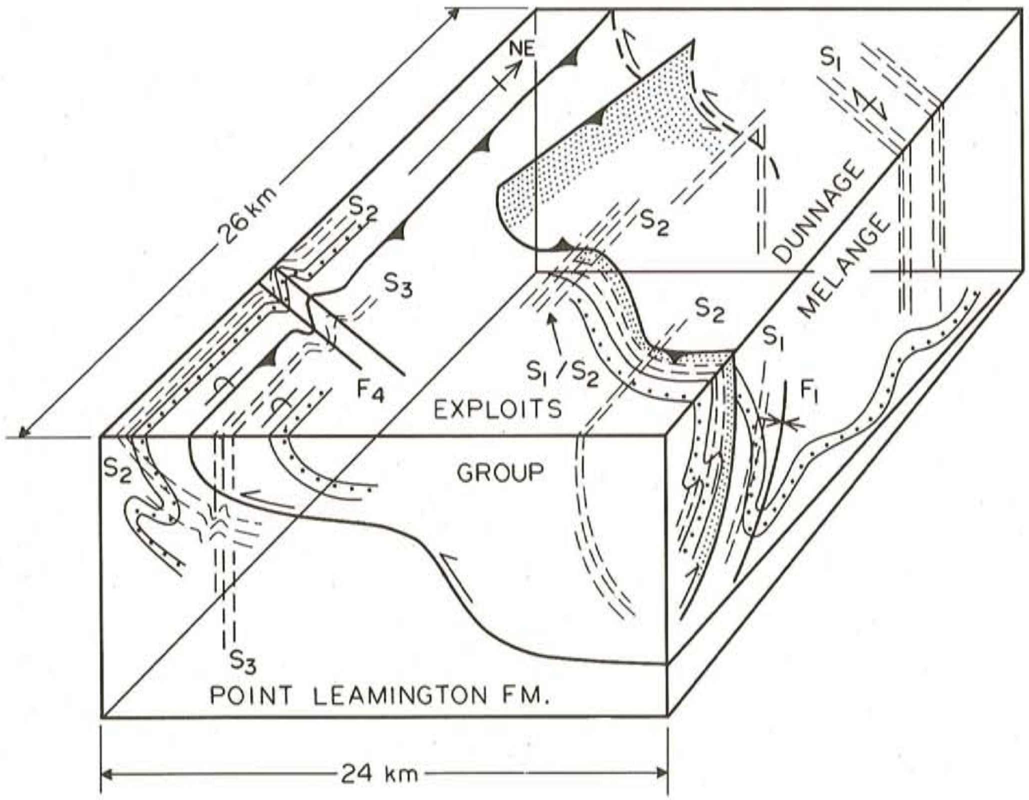

Figure 4. *Block diagram displaying a regional scale example of reorientation of a southwest-inclined D1 reverse fault by deformation related to a southeast-inclined D2 reverse fault; kindred D1 and D2 structures are also depicted. Note the localization of D3 and D4 overprinting in D2 fault zones. Tectonic excision of Lawrence Harbour Formation has occurred along the faults that bound the Point Leamington Formation, the Exploits Group and the Dunnage Mélange. Only the vertical scale is exaggerated.*

domains into parallelism with the high-strain D1 structures of adjacent northwest-trending domains (Figure 2). This generated, along certain domain boundaries, small D4 belts of braided northwest-trending faults in which the original truncation angle between D2 and D1 faults is significantly reduced.

INTERPRETATION AND IMPLICATIONS

In summary, the thrust-bounded domes and basins mapped in the northeastern part of the Dunnage Zone originated when regional D1 faults were deformed by large-scale F2 folds. Second-order domes and basins developed during locally intense D3 deformation, which modified the margins of regional fault-rimmed structures that were notably northeast-elongated. The central Notre Dame Bay flexure resulted from inhomogeneous reworking and overprinting of northwest-trending D1 structures by northeast-trending D2 structures. However, following D3 strike-slip modification of zones of braided D1 and D2 reverse faults, the flexure was tightened by F4 folds and its Z-shape amplified by D4 transcurrent faults.

The structural evolution of episodically faulted, multi-foliated and repeatedly refolded strata in this low-grade portion of the hinterland was strongly influenced by recurrent strain partitioning in orthogonally oriented domains. This feature is atypical of the coaxially trending structures in thin-skinned, foreland fold-and-thrust belts and not readily facilitated by intermittent faulting in a progressive plane-strain deformation. Preferential decoupling of Caradocian black shales and related accomodation structures in adjacent rocks may possibly be explained by the reactivation of older faults in certain Early Ordovician units, or by the mechanical influence of the depositional strike of all or parts of the back-arc succession.

Some of the main implications of this regional deformation scheme for Notre Dame Bay are (1) that the tectonic transport direction during conjugate D1 deformation was uncommonly southwestward and nowhere southeastward, (2) that the terrestrial Lawrenceton and Wigwam formations of the Botwood Group are affected by D1 deformation, as are gabbros intruding dated Llandovery rocks, (3) that D1 deformation postdated the accumulation of all dated turbidite-hosted olistostromal deposits in the Dunnage Zone, and (4) that while D2 deformation is a more common generator of block-in-matrix mélange than D1 deformation, tectonic mélange is also observed as olistoliths in olistostromal deposits. Earlier generation of tectonic mélange in older accretionary complexes is not precluded nor is its subsequent recycling into olistostromal deposits within marine basins of the Exploits Subzone.

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