Structural interpretation of the eastern Notre Dame Bay area, Newfoundland: regional post-Middle Silurian thrusting and asymmetrical folding

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The structural geometry of the eastern Notre Dame Bay area is that of an allochthonous sequence (related to F_1 thrusting and folding), folded by F_2 asymmetrical folds, and offset by F_3-related high-angle faults. F_1 folds are isoclinal and commonly intrafolial. F_2 folds are asymmetrical (generally tight) with axial surfaces that dip 30–85° southeast. The prominent northeast-striking, penetrative cleavage (S_2) is axial planar to F_2 folds. F_3 structures include chevron folds, box folds, kink bands, and local S_3 crenulation cleavage.

F_1 folds are overprinted by F_2 folds producing coaxial and mushroom interference patterns. This and the subhorizontal enveloping surface of F_2 indicate that F_1 folds were recumbent prior to F_2. A zone of F_1 folds separating Silurian turbidites from subaerial volcanics on the Port Albert Peninsula suggests F_1 was related to macroscopic thrusting, as does the association of F_1 with mesoscopic thrust faults.

F_2 folds are the most obvious structures in the area. Macroscopic examples include an anticline–syncline pair on Milleners Peninsula, an anticlinorium cored by the Dunnage mélange, and a synclinorium cored by subaerial sandstones on the Port Albert Peninsula. These folds repeat the stratigraphy across areas that have been incorrectly interpreted in terms of fault-bounded, north-younging homoclines. A shallow enveloping surface for F_2 is supported by the uniformly low metamorphic grade in the area and detailed structural profiles. In view of the shallow dip of the enveloping surface, it is possible to correlate the Dunnage mélange, the Carmanville mélange, and other mélanges in the area.

Contrary to prevailing interpretations of a structural setting involving fault-bounded tectonostratigraphic zones, we demonstrate a similar deformational history and a general continuity of macroscopic F_2 folds throughout our area. Rectilinear faults on geologic maps, used by previous workers as the boundaries between tectonostratigraphic zones, are post-F_2 features. They cross-cut F_2 folds and are at a high angle to the F_2 enveloping surface. These include the Chanceport, Lukes Arm, Dildo, and Reach Faults.

All three fold generations affect rocks ranging in age from Ordovician to Middle Silurian. Thus, irrespective of when the earliest deformation began, it continued into Silurian times.

La géométrie structurale de la région est de la Baie Notre-Dame consiste en une séquence allochtone (reliée à un charriage et à une phase de plissement F_1), caractérisée par des plis asymétriques F_2, et décalée par des failles fortement inclinées reliées à F_3. Les plis F_1 sont isoclinaux, communément intrafoliaux. Les plis F_2 sont asymétriques (généralement fermés) avec des plans axiaux inclinés de 30–85° vers le sud-est. La direction prédominante est nord-est, le clivage (S_2) affectant profondément les roches est parallèle au plan axial des plis F_2. Les structure F_3 comprennent des plis en chevron, des plis coffrés, des kink bands et un clivage local S_3 avec crénulation.

Les plis F_1 sont oblitérés par les plis F_2 produisant des patrons d'interférence coaxiaux et en champignons. Ceci combiné à la surface de l'enveloppe subhorizontale des plis F_2, indiquent que les plis F_1 étaient couchés avant le plissement F_2. Une zone de plis F_1 séparant les turbidites siluriennes d'avec les roches volcaniques subaériennes de la péninsule Port Albert suggère que F_1 était relié au charriage macroscopique, comme le démontre l'association de F_1 avec les failles imbriquées mésoscopiques.

Les plis F_2 représentent les structures les mieux exprimées dans la région. Des exemples macroscopiques illustrent la paire anticlinal–synclinal sur la péninsule de Milleners, un anticlinorium dont le coeur est formé de mélange Dunnage et un synclinorium dont le coeur est formé de grès subaériens sur la péninsule Port Albert. Ces plis entraînent une répétition stratigraphique au travers la région, laquelle fut jadis faussement interprétée comme résultant de plis monoclinaux de direction nord bordés par des failles. Le faible degré de métamorphisme affectant les roches de la région et l'étude détaillée des coupes structurales suggèrent la présence d'une surface d'enveloppe des plis F_2 localisée à faible profondeur. Considérant la faible plongée de la surface de l'enveloppe, il semble possible d'établir les corrélations entre les mélanges Dunnage, Carmanville et les autres mélanges apparaissant dans cette région.

Contrairement aux opinions courantes exprimant un contexte structural formé de zones tectonostratigraphiques limitées par des failles, nous reconstituons la séquence des évènements de déformations semblables et nous signalons une continuité générale des plis macroscopiques F_2 au travers la région. Les failles rectilignes qui apparaissent sur les cartes géologiques rapportées dans les études antérieures comme représentant les limites entre les zones tectonostratigraphiques, sont des phénomènes postérieurs à F_2. Elles traversent les plis F_2 et coupent la surface d'enveloppe de F_2 avec un angle élevé. Il s'agit des failles de Chancefort, Lukes Arm, Dildo et Reach.

Les trois générations de plis ont affecté les roches d'âge variant de l'Ordovicien au Silurien moyen. Donc, indépendant du temps du début de la déformation, elle s'est poursuivie durant le Silurien.

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Introduction

The area of this study (Fig. 1) is in the northeastern part of Newfoundland's Dunnage Zone (Williams 1978, 1979). This zone contains volcanic rocks and volcanogenic sediments believed to represent the vestiges of the Paleozoic Iapetus Ocean (Williams 1964*a*). Rocks within the study area include pillow volcanics, mélange,[1] marine turbidites, polymictic conglomerates, subaerial volcanics, and subaerial sandstones (Fig. 1), which range in age from the Ordovician Dunnage mélange (Kay 1976; Hibbard *et al.* 1977) and Davidsville Group (Currie *et al.* 1980*a*) to the Silurian Botwood and Indian Islands Groups (Twenhofel and Shrock 1937; Williams 1964*b*). Although copious stratigraphic work has been done in the area in the last 40 years and many stratigraphic names have been proposed, we have omitted stratigraphic nomenclature in Fig. 1 in favour of a lithologic map. Such a map is sufficient to explain our structural interpretations and emphasizes our belief that detailed structural studies in northeastern Newfoundland have lagged far behind stratigraphic work.

Since the work of Kay and his students in the Notre Dame Bay area (Helwig 1967; Horne 1968; Eastler 1971; Kay 1976) and Williams (1962, 1963, 1964*b*), the structure of the eastern Notre Dame Bay area has been viewed in terms of fault-bounded structurally and stratigraphically distinct terranes. For example, Williams *et al.* (1972, p. 185, 1974) divided the Dunnage Zone into three tectonostratigraphic zones, separated by faults (Fig. 1, index map), which were defined on the basis of distinct Ordovician and earlier depositional or tectonic histories. Similarly, Kay (1967, p. 588, 1976, p. 4) interpreted the area in terms of separate "sequences" defined as discontinuous fault-bounded blocks with distinct structural and (or) stratigraphic characteristics. This view of fault-bounded "sequences" in the eastern Notre Dame Bay area appears to have emerged for two reasons: (1) because of difficulties in tracing and correlating lithostratigraphic units; (2) because of working hypotheses visualizing the area as the site of Ordovician subduction and accompanying formation of tectonic mélange in an accretionary prism (Bird and Dewey 1970, p. 1045; Kay 1976, p. 38) or as a suture zone marking the final closure of the Iapetus Ocean (McKerrow and Cocks 1977) where numerous thrust or transcurrent fault slices might be expected. This interpretation of fault-bounded structurally and stratigraphically distinct terranes has dominated the map interpretations, stratigraphic models, and plate tectonic models of nearly all workers in the area.

Our interpretation of the geology of the area differs from previous interpretations in two major respects:

(1) We recognize, on the basis of overprinting relationships between fold generations and cleavage, the same folding history over wide areas in the eastern Notre Dame Bay area. We have not been able to substantiate the existence of different structural "sequences" and we do not agree with map interpretations emphasizing fault-segmented tectonostratigraphic zones in the area we have mapped. The interpretation presented in this paper is that the observed complex map patterns arise mainly from fold interference patterns generated by regional F_1 thrusting and recumbent folding followed by F_2 tight, generally upright, asymmetrical[2] folding, and F_3 kinking, chevron folding, and broad warping. Faults are indeed numerous in the area but straight-line faults drawn on most published maps must post-date F_2 folding and are thus late features superimposed upon already complexly folded rocks and not the primary tectonic features that dominate the structural style of the area.

(2) All of the fold generations can be found in rocks ranging in age from Early Ordovician to Silurian (Wenlockian) so that there is no structural justification for subdividing the area into Ordovician tectonostratigraphic zones (Williams *et al.* 1972, 1974) or for proposing a "Taconic"[3] unconformity that would separate previously deformed Ordovician rocks from post-orogenic Silurian rocks (cf. Currie *et al.* 1980*a*, p. 115). We argue that the observed penetrative structural features can all be explained by post-Middle Silurian deformations.

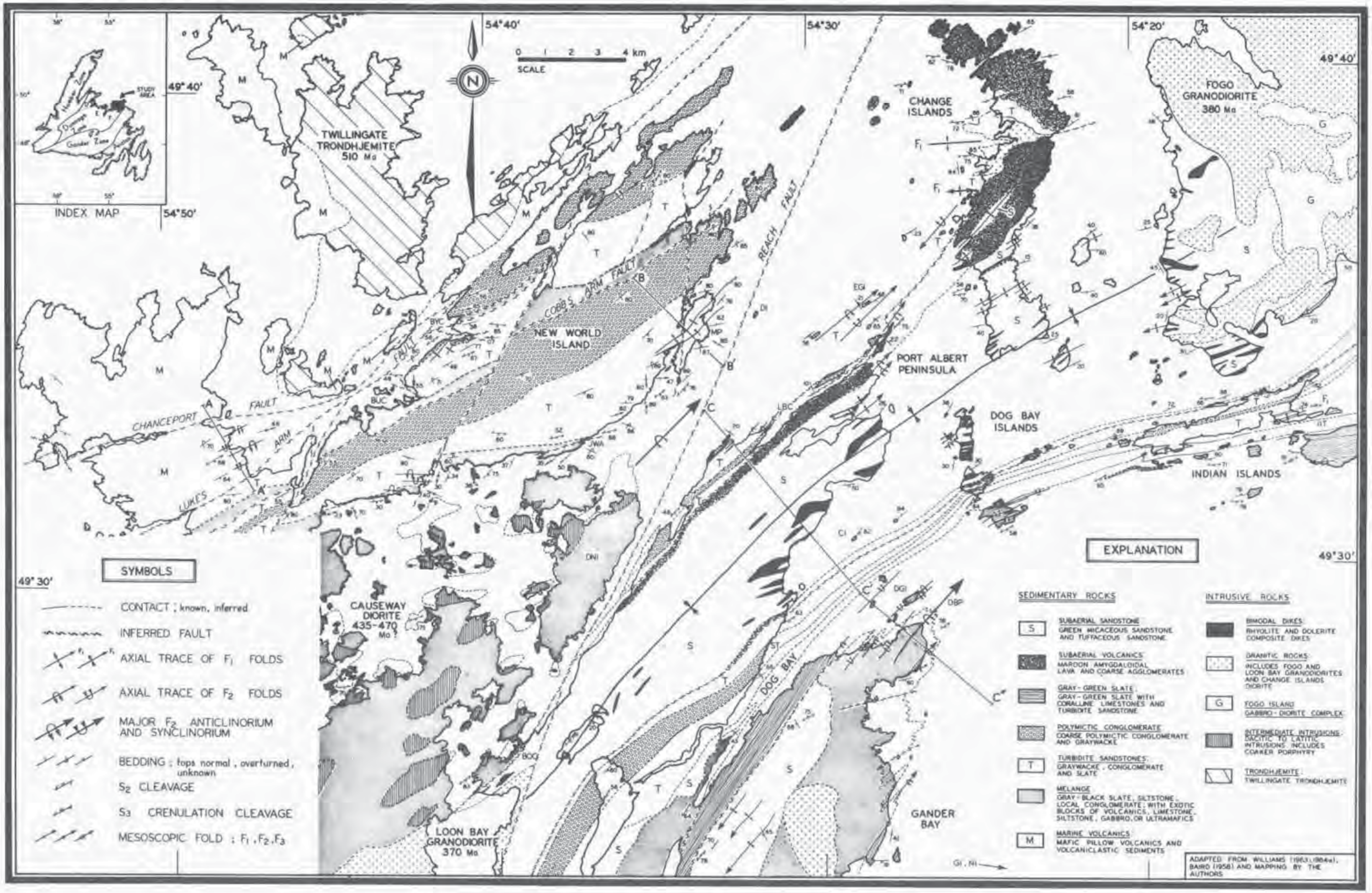
This paper presents a description of the mesoscopic

[1]We use the term mélange in a descriptive sense: a unit generally lacking well defined bedding, composed of a heterogeneous assemblage of blocks set in a fine-grained matrix of argillite or siltstone.

[2]Used here in the sense of an asymmetrical fold in which the axial surface is not perpendicular to the local enveloping surface (Hobbs *et al.* 1976, p. 167).

[3]We refrain from using the conventional terminology, Taconic (Ordovician) versus Acadian (Devonian) orogeny, in this paper because it is inconsistent with our view that orogenesis occurs progressively and diachronously along continental margins and not as temporally discrete events.

FIG. 1. Structural and lithological map of the eastern Notre Dame Bay area. Cross sections A–A′, B–B′, and C–C″ are shown in Fig. 5. Localities mentioned in text are: BUC—Burnt Cove; BOC—Boyd's Cove; BYC—Byrne Cove; CI—Charley Island; DBP—Dog Bay Point; DGI—Dog Island; DI—Dram Island; DNI—Dunnage Island; EGI—East Garden Island; GI—Green Island; IIT—Indian Islands Tickle; JWA—Joe White's Arm; LBC—Little Beaver Cove; MP—Milleners Peninsula; NI—Noggin Island; ST—Stoneville.



INDEX MAP
STUDY AREA
TWILLINGATE TRONDHJEMITE 510 Ma
SCALE
0 1 2 3 4 km
CHANGE ISLANDS
FOGO GRANODIORITE 380 Ma
NEW WORLD ISLAND
COBB'S ARM FAULT
REACH FAULT
CHANCEPORT FAULT
LUKES ARM
PORT ALBERT PENINSULA
DOG BAY ISLANDS
INDIAN ISLANDS
CAUSEWAY DIORITE 435–470 Ma
LOON BAY GRANODIORITE 370 Ma
DOG BAY
GANDER BAY
54°40′
54°30′
54°20′
49°40′
49°30′
54°50′
SYMBOLS
CONTACT ; known, inferred
INFERRED FAULT
AXIAL TRACE OF F1 FOLDS
AXIAL TRACE OF F2 FOLDS
MAJOR F2 ANTICLINORIUM AND SYNCLINORIUM
BEDDING ; tops normal , overturned , unknown
S2 CLEAVAGE
S3 CRENULATION CLEAVAGE
MESOSCOPIC FOLD ; F1 , F2 , F3
EXPLANATION
SEDIMENTARY ROCKS
S SUBAERIAL SANDSTONE: GREEN MICACEOUS SANDSTONE AND TUFFACEOUS SANDSTONE
SUBAERIAL VOLCANICS: MAROON AMYGDALOIDAL LAVA AND COARSE AGGLOMERATES
GRAY-GREEN SLATE: GRAY-GREEN SLATE WITH CORALLINE LIMESTONES AND TURBIDITE SANDSTONE
POLYMICTIC CONGLOMERATE: COARSE POLYMICTIC CONGLOMERATE AND GRAYWACKE
T TURBIDITE SANDSTONES: GRAYWACKE , CONGLOMERATE AND SLATE
MELANGE: GRAY-BLACK SLATE, SILTSTONE, LOCAL CONGLOMERATE; WITH EXOTIC BLOCKS OF VOLCANICS, LIMESTONE, SILTSTONE, GABBRO, OR ULTRAMAFICS
M MARINE VOLCANICS: MAFIC PILLOW VOLCANICS AND VOLCANICLASTIC SEDIMENTS
INTRUSIVE ROCKS
BIMODAL DIKES: RHYOLITE AND DOLERITE COMPOSITE DIKES
GRANITIC ROCKS: INCLUDES FOGO AND LOON BAY GRANODIORITES AND CHANGE ISLANDS DIORITE
G FOGO ISLAND GABBRO-DIORITE COMPLEX
INTERMEDIATE INTRUSIONS: DACITIC TO LATITIC INTRUSIONS INCLUDES COAKER PORPHYRY
TRONDHJEMITE: TWILLINGATE TRONDHJEMITE
ADAPTED FROM WILLIAMS (1963),(1964a), BAIRD (1958) AND MAPPING BY THE AUTHORS

structural features in southern New World Island, the Port Albert Peninsula, and islands in Hamilton Sound; a new map and cross section showing macroscopic structural features across the area; and a discussion of the implications of our structural interpretation for understanding the depositional and tectonic history of the eastern Notre Dame Bay area.

Description of structural features

F_1 folds

F_1 structural features are identified and defined here as those structures that can be shown to be overprinted by the regionally developed northeast-trending penetrative S_2 cleavage. More than one generation of pre-S_2 structures may exist but we cannot readily distinguish them at present and we have no evidence to contradict the interpretation that all pre-F_2 structures are of the same generation.

F_1 folds are generally isoclinal, commonly intrafolial, and are refolded by F_2 folds (Fig. 2). Intrafolial folds have been identified in several places on New World Island. The mesoscopic F_1 folds are tight to isoclinal with amplitudes up to 80 m. Generally they have steeply dipping axial surfaces and steeply plunging fold axes. They can be identified as F_1 folds because the regional S_2 cleavage cross-cuts them. Although in two-dimensional exposures S_2 commonly appears to be an F_1 axial plane cleavage, in three dimensions it can be seen to cross-cut the F_1 folds in general. Folds cross-cut by cleavage on New World Island were referred to by Anderson (1981) as "transected" folds (i.e., folds that are cut in a nonaxial planar manner by a cleavage of the same generation); however, we believe that they are of an earlier generation than the cleavage and this point can be demonstrated by the fact that the cleavage is axial planar to later folds that locally refold F_1. Mesoscopic intrafolial F_1 folds are also present farther east, for example, on the east side of Little Beaver Cove near Port Albert (Fig. 2*c* and *d*), on East Garden Island, and on Charley Island.

Fold interference patterns produced by overprinting of F_1 structures by F_2 have been observed near Joe White's Arm (Fig. 2*b*); in the coastal section from Burnt Cove to Byrne Cove on northwestern New World Island; at the east margin of the Dunnage mélange, near Boyd's Cove; at the eastern end of the Indian Islands tickle; on Green and Noggin Islands near Carmanville; and on the eastern and western shores of Gander Bay. Types of interference patterns observed are types II and III of Ramsay (1967, p. 531). Both types indicate that the axial surfaces of F_1 folds were at a high angle (close to 90°) to F_2 axial surfaces prior to F_2 folding (Fig. 2*b*). Because S_2 is generally steeply dipping, and because the enveloping surface of F_2 is subhorizontal, we infer that F_1 axial surfaces were shallowly dipping and thus F_1 folds were recumbent prior to F_2.

Mesoscopic thrust faults with displacements on the centimetre to metre scale are a third type of F_1 structure found throughout the area (Fig. 3). These features are cross-cut by S_2, for example, east of Joe White's Arm (Fig. 3*a*), and can be seen to be refolded by F_2 folds on Green Island (Fig. 3*b*). Both indicate probable contemporaneity with F_1 recumbent folding.

Macroscopic F_1 folds are also present throughout the study area. The most easily documented are folds where S_2 cleavage cross-cuts both limbs of the structure in non-axial plane attitudes and where downward-facing F_2 folds (Shackleton 1958) are found. Several examples have been defined from detailed structural sections in the area. One example is an east-trending F_1 anticline in the Change Islands that is cross-cut by S_2 (Fig. 1). Bedding–cleavage relationships on the north limb show cleavage is less steep than overturned south-dipping bedding (Fig. 1). On the south limb S_2 is also less steep than right-way-up south-dipping strata. Taken together, these relationships indicate that S_2 cuts obliquely across the fold and therefore S_2 post-dates the folding. Eastler (1969, 1971, p. 99) also recognized this structure as an F_1 anticline but considered it to be a "local aberration."

A second example is found north of Byrne Cove in northwestern New World Island. Here a kilometre-scale F_1 fold occurs in Silurian conglomerates (Goldson Conglomerate). The almost vertical plunge and the axial plane trace of this fold show the same orientations as mesoscopic F_1 folds in the immediate area and contrast with shallowly plunging F_2 folds. This large structure is therefore interpreted as F_1. In the limited outcrop examined by us so far, only one limb is exposed and it is impossible to demonstrate that the cleavage cross-cuts the fold. However, related F_1 parasitic folds in the hinge of the large structure are clearly cross-cut by S_2, which is locally defined by a preferred dimensional orientation of the conglomerate clasts.

Other macroscopic F_1 folds occur in the eastern Indian Islands, where apparent bedding–cleavage anomalies indicate overprinting by S_2, and in Gander Bay, where downward-facing F_2 folds have been observed.

The presence of both mesoscopic and macroscopic F_1 folds in several localities between northern New World Island and Gander Bay (Fig. 1) and in rocks ranging in age from Ordovician (Dunnage mélange and Davidsville Group) to Silurian (Goldson Conglomerate and Indian Islands Group) suggests that F_1 was a major folding event that continued at least into post-Middle Silurian time.

The interpretation that mesoscopic F_1 folds were originally recumbent, and the presence of minor thrust faults suggest a relationship of F_1 to thrusting. The

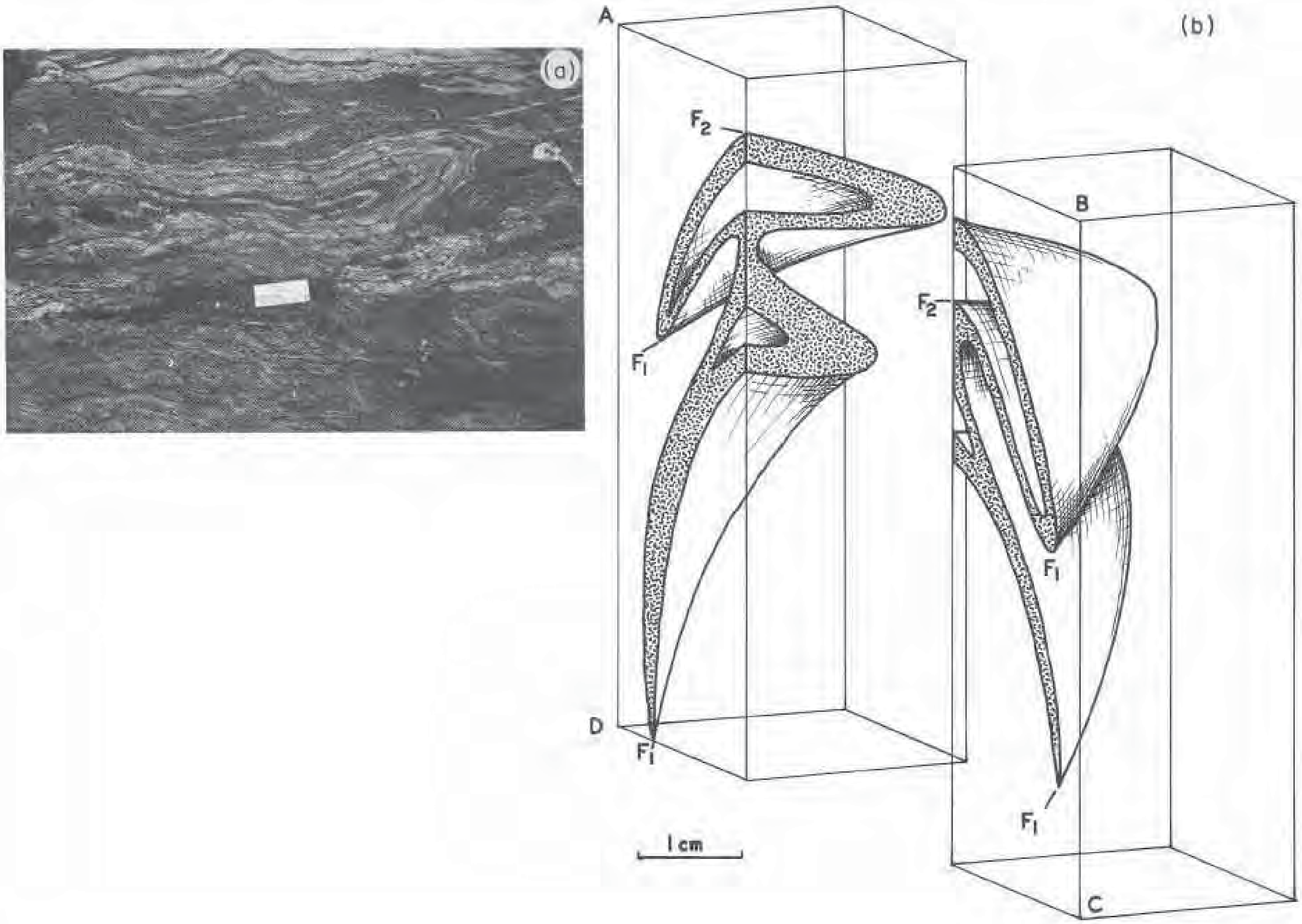


FIG. 2. F_1 mesoscopic folds. (*a*) Thrust-related F_1 fold on western Noggin Island. (*b*) Sketch block diagram showing three-dimensional interpretation of a type II interference pattern on southern New World Island, which in outcrop appears as on the vertical surface ABCD. Shaded bed is dark slate within lighter slate unit.

variable orientation of F_1 fold axes is also consistent with thrusting and may reflect different stages of "rotation" into the movement direction (Williams and Zwart 1977). Further, the presence of F_1 folds along the contact between turbidites and subaerial volcanics, from the Port Albert Peninsula to Change Islands (Fig. 1), is consistent with a thrust fault origin for this contact. This abrupt change from marine turbidites to subaerial volcanics might also be explained in terms of unconformity and the zone of F_1 folds might be attributed to soft-sediment folding during extrusion of volcanics. This explanation might suffice except for the fact that similar F_1 structures are found throughout the area in rocks of varying age and depositional history. Hence, the bulk of the evidence favours the interpretation that F_1 folds were recumbent folds formed during thrusting and the lower contact of the subaerial volcanics is a possible example of one such macroscopic thrust fault. Implications of this interpretation for regional stratigraphy will be discussed later.

One characteristic of F_1 structures is the absence (in outcrop) of a well developed S_1 axial plane cleavage. This was also noted by Eastler (1969) in the Change Islands F_1 fold and by Helwig (1970, p. 178) for pre-S_2 folds that he considered to be slump structures. Early post-metamorphic folds without axial plane cleavage have been reported from the Caledonides where they are associated with thrusting (Williams and Zwart 1977). Therefore absence of an axial plane foliation is not necessarily evidence for the soft-sediment origin of the folds. Other morphological "criteria" for soft-sediment origin of early folds (variability of fold style, curved hinge lines, and localized occurrence between undisturbed strata, to name a few that have been used; Helwig 1970) are also equivocal in light of the fact that ductile flow of hard rocks can produce the same

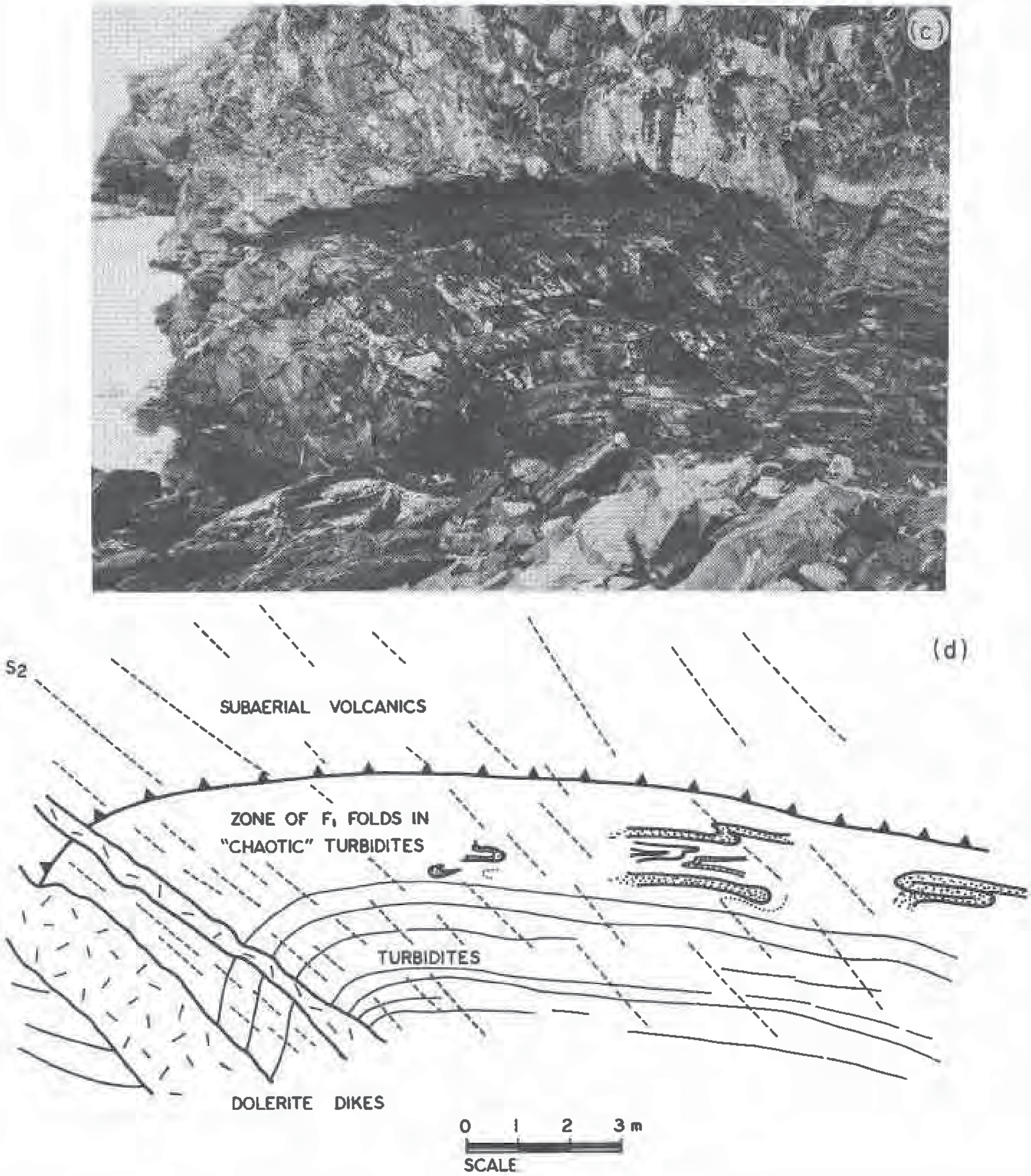


FIG. 2. (*Concluded*). (*c*) Inferred thrust fault contact between subaerial volcanics and underlying turbidites on the east side of Little Beaver Cove about 1 km north of Port Albert; looking northeast, parallel to the plunge of F_2. (*d*) Composite sketch of the area of (*c*), showing relationships between the inferred thrust contact; zone of F_1 folds, S_2 cleavage, and post-S_2 dikes. F_1 folds are exaggerated (2–4 ×) in scale.

structures (for a more detailed discussion see Hobbs *et al.* 1976, pp. 156–159). The widespread temporal and spatial occurrence of F_1 structures may be the best clue to their origin and it is more consistent with a penetrative orogenic origin than with localized slumping.

F_2 folds

F_2 folds and associated S_2 cleavage are the most obvious structural features in the eastern Notre Dame Bay area. F_2 folds are strongly asymmetrical (Fig. 4) and have northeast-trending S_2 cleavage that dips 35–85° southeast (Fig. 5). Folds vary from open to isoclinal. Fold axes, although predominantly subhorizontal, define a girdle that coincides with the average orientation of S_2 (Fig. 5). F_2 folds occur in en échelon patterns where overall shortening is taken up by different folds at different positions (Hobbs *et al.* 1976, p. 170) so that F_2 folds can be seen to die out parallel to their hinge lines (Fig. 4*c*). This en échelon pattern causes difficulty in defining macroscopic F_2 folds because individual folds may not be traceable over large distances parallel to S_2.

Mesoscopic F_2 folds are ubiquitous in the Notre Dame Bay area. Figure 4*b* shows a portion of a zone of

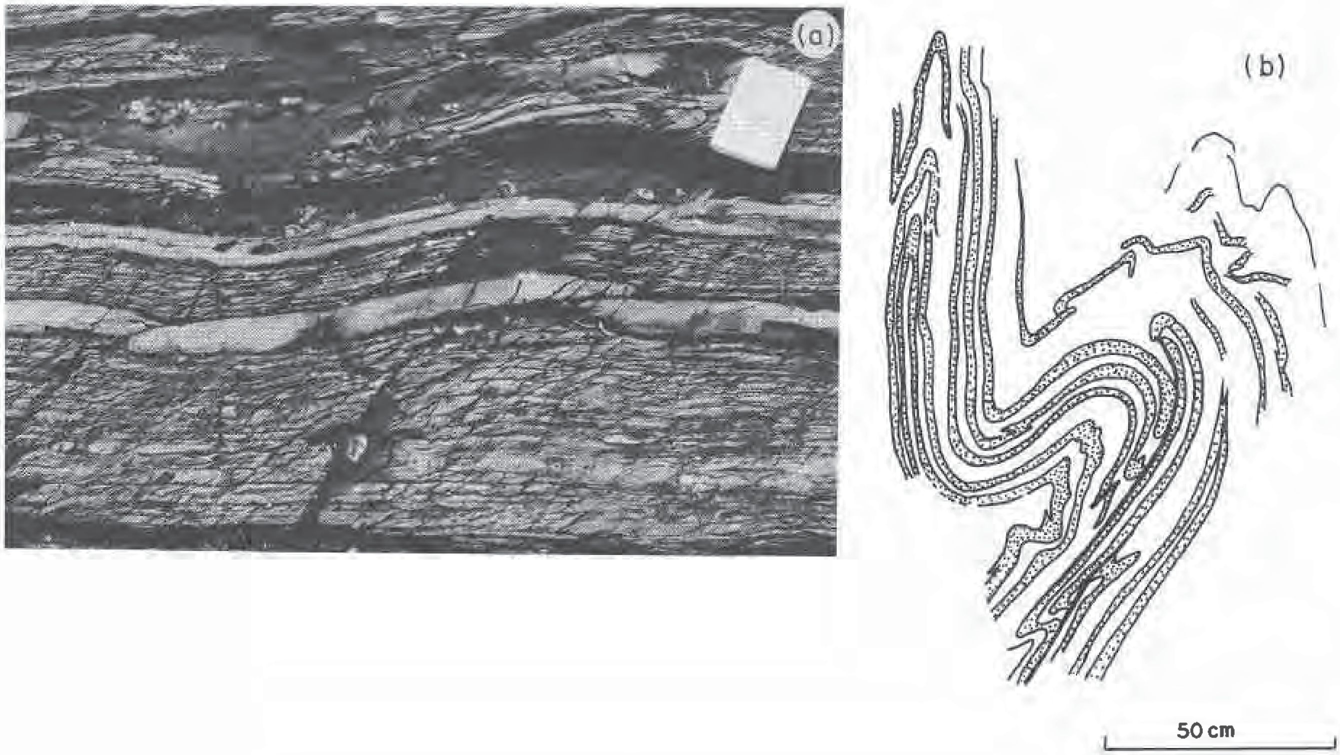


FIG. 3. F_1 mesoscopic thrust faults. (*a*) Small-scale thrust fault cross-cut by S_2 regional cleavage on southern shore of New World Island, 3 km northeast of Joe White's Arm; fracturing is related to F_3. (*b*) Sketch of folded small-scale thrust cross-cut by S_2, south side of Noggin Island.

upward-facing asymmetrical folds on Milleners Peninsula, southern New World Island, that indicate a larger synclinal axis to the southeast. Such folds contradict previous interpretations of a simple north-younging homoclinal succession (Kay 1976; McKerrow and Cocks 1978, p. 1124, 1981). Similarly, Fig. 4*d* shows upward-facing mesoscopic asymmetrical F_2 folds on the western Indian Islands indicating a larger syncline to the left (south), again contradicting earlier interpretations of a simple north-younging homoclinal succession in the Indian Islands Group (Williams 1964*b*; Eastler 1969). Truncated F_2 folds, where faulting has taken place subparallel to the axial plane (and S_2) either during or later than F_2 folding, are also common on the Indian Islands and Port Albert Peninsula. Asymmetrical F_2 folds occur on every scale, from centimetres to kilometres. Thus, only changes of asymmetry between folds of similar scale can be used to define macroscopic folds because there are parasitic folds on parasitic folds.

The S_2 cleavage is penetrative in pelitic layers and has the appearance of slaty cleavage in outcrop. It is also recognizable in many intrusive rocks in the region, in micaceous sandstones, and in conglomerates. In massive sandstones S_2 is a weakly developed fracture cleavage and in conglomerates it is defined by preferred dimensional orientation of clasts.

The regional extent of F_2 asymmetrical folds and S_2 penetrative cleavage is readily documented both by our own work and by numerous structural studies elsewhere in the Notre Dame Bay area that have documented the existence of one dominant, regionally developed cleavage (Horne 1968, p. 159; Eastler 1971, p. 101; DeGrace *et al.* 1976, p. 42; Nelson 1981, p. 435). However, delineation of macroscopic F_2 folds, a prerequisite to understanding the stratigraphy of the region, is not obvious. The en échelon pattern of F_2 folds hinders extrapolation from one area to another; the isoclinal nature of F_2 folds in slates makes location of hinge zones difficult; changes of asymmetry occur at every scale and must be used with caution; and faults subparallel to S_2 are common. Nevertheless we have defined several macroscopic F_2 folds by detailed structural profiles (noting bedding–cleavage relationships and younging directions) and regional mapping of lithostratigraphic units and fold asymmetries.

These proposed macroscopic F_2 folds are shown in Figs. 1 and 5. One example is on Milleners Peninsula (Fig. 5). As mentioned above, this coastal section was previously interpreted as part of a north-younging homoclinal succession. However, detailed structural sections, from southeast to northwest, show a transition from relatively undeformed overturned south-dipping beds into more strongly thinned beds in which S_2 cleavage progressively becomes the dominant surface

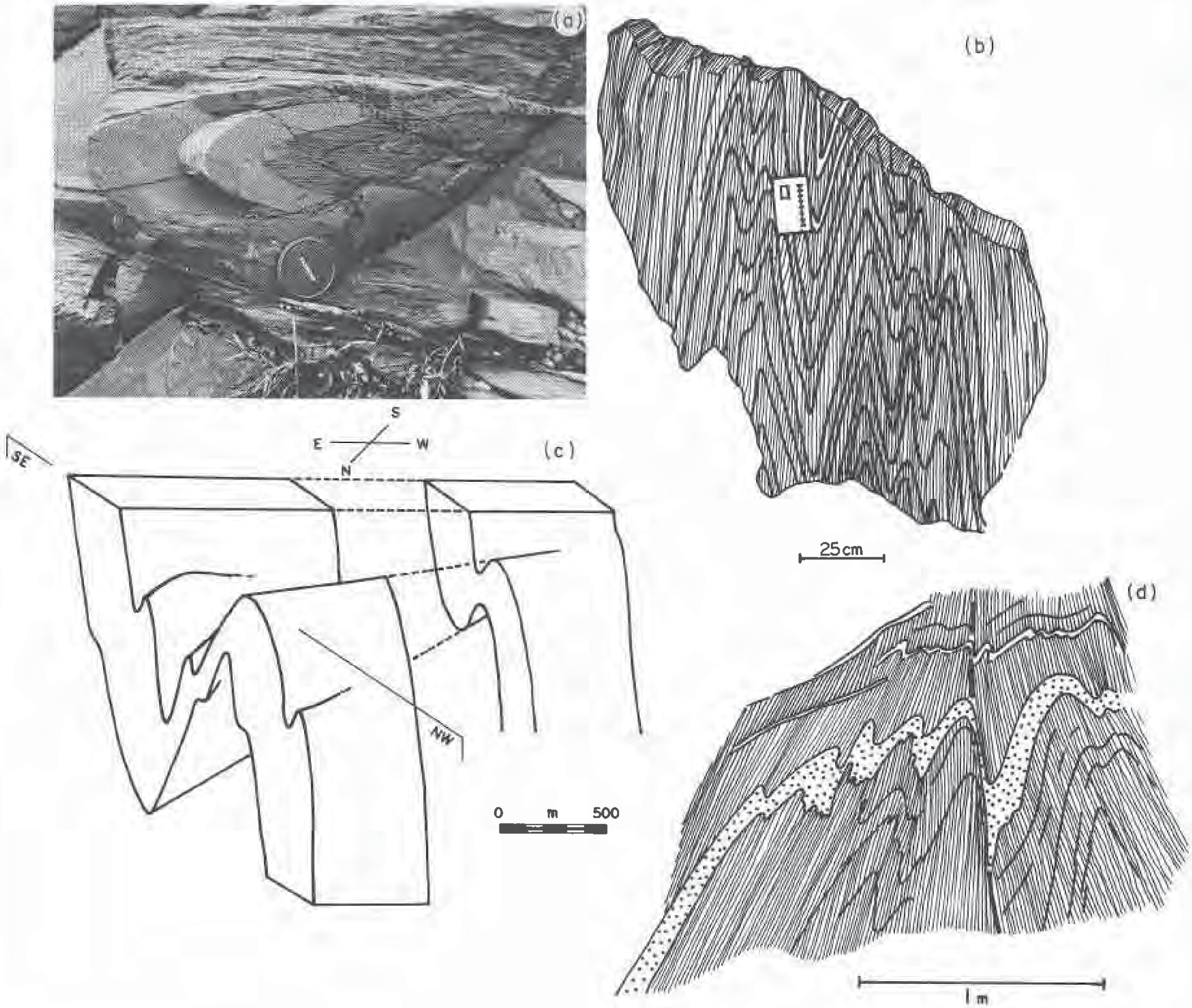


FIG. 4. F_2 folds. (*a*) F_2 fold with S_2 axial plane cleavage, southern New World Island. (*b*) Upward-facing asymmetrical folds on the right-way-up limb of the Milleners Peninsula fold, looking northeast. (*c*) Block diagram of macroscopic F_2 structure on the Milleners Peninsula, looking southwest. Asymmetry indicates a larger anticline to the southeast. Sketch shows doubly plunging axes and en échelon character of F_2. (*d*) Sketch of upward-facing F_2 asymmetrical folds on the west end of the Western Indian Island; looking west, down plunge.

and then into intensely cleaved rocks in which bedding is largely transposed into S_2. This attenuated zone marks the hinge of an F_2 syncline, as shown by a change of asymmetry of the minor folds (Fig. 4*b*), cleavage steeper than (or parallel to) bedding, and a few graded beds indicating top of sequence to the south (Fig. 5). Deformation has obliterated most sedimentary features in the hinge and south-younging limb of the syncline. Farther northwest, a similar change of asymmetry gives the approximate position of the anticlinal axial trace and then beds resume their previous overturned, steeply south-dipping attitude. The entire structure at Milleners Peninsula (shown schematically in Fig. 4*c* and in profile in Fig. 5) is a kilometre-scale asymmetrical anticline–syncline pair indicating a still larger anticline to the southeast.

Macroscopic folds on the Port Albert Peninsula show either the reverse asymmetry of the Milleners Peninsula fold pair or subhorizontal enveloping surfaces (Fig. 5). Therefore, the Dunnage mélange occupies the core of a major F_2 anticlinorium (Fig. 1). Although the details in the hinge zone of this anticlinorium are obscured in the mélange itself by the apparent chaotic aspect and lack of bedding, turbidites on several islands across the hinge zone show repeated changes of asymmetry and an overall subhorizontal enveloping surface consistent with a major hinge zone (Fig. 5).

Continuous outcrop along coastal exposures south-

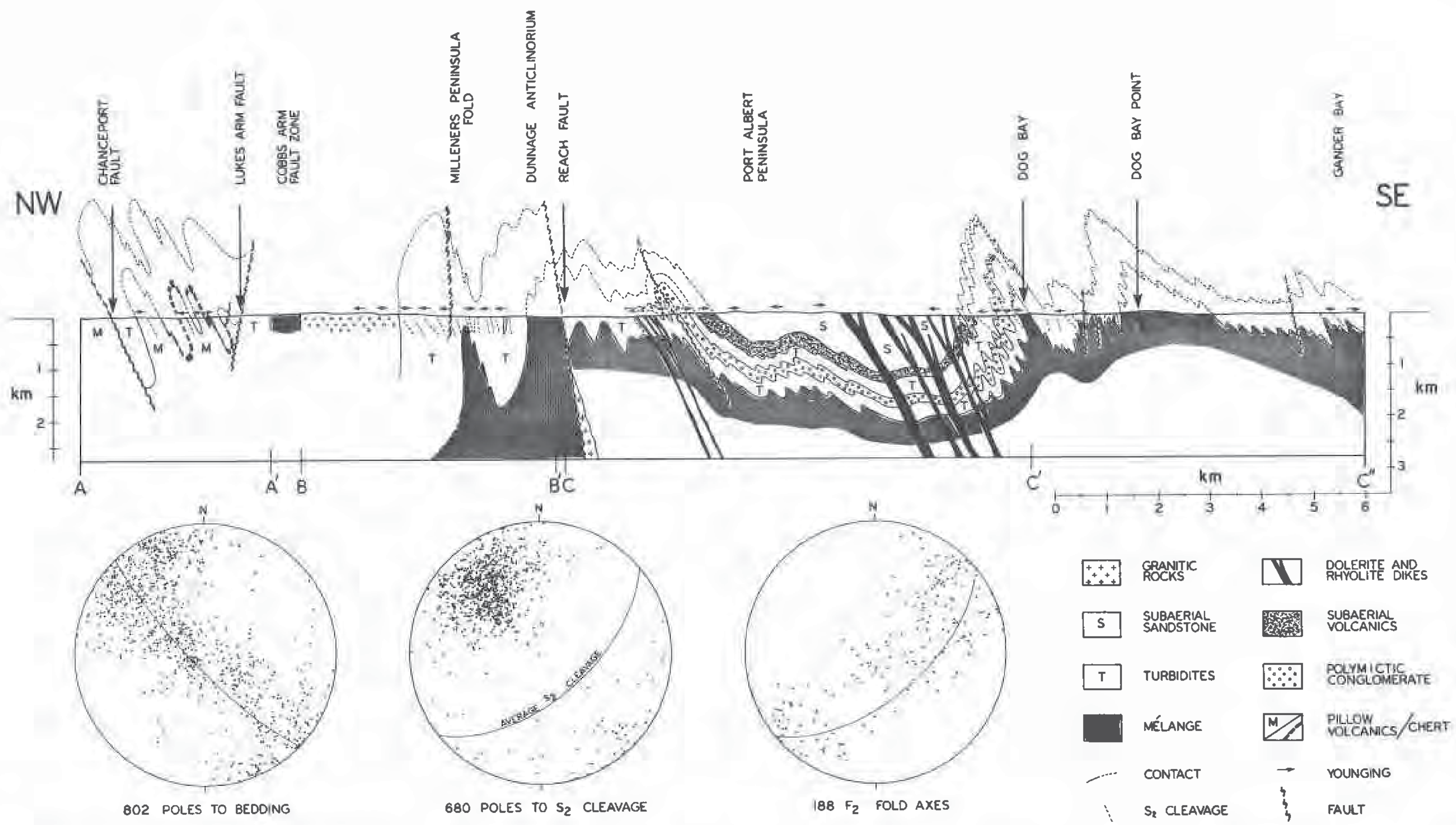


FIG. 5. Structural cross section and structural data. See Fig. 1 for location of cross section. The strong cylindricity of F_2 macroscopic folds is evident from the great-circle girdle of poles to bedding despite dispersion by F_3. Note that steeply southeast-dipping beds predominate. Poles to S_2 cleavage are also dispersed by F_3 warping but still define a strong maximum. F_2 fold axes show a great-circle distribution that coincides with the average S_2 orientation, demonstrating that F_2 plunges vary within the axial plane. Projections are lower hemisphere equal-area projections.

east of the Port Albert Peninsula show a synclinorium of comparable scale to that of the Dunnage anticlinorium. This structure was first mapped in the sandstones near Farewell Harbour by Baird (1958) and was extended to include volcanics and polymictic conglomerates by McCann and Kennedy (1974). This fold is identified not only by change of asymmetry across it (Fig. 5) but also by the repetition of stratigraphic units and abundant younging criteria. Chert-rich polymictic conglomerates on both limbs are stratigraphically underlain by turbidite sandstones and slates containing limestone beds and overlain by amygdaloidal volcanics and ripple-marked sandstones. The inferred thrust fault contact between the volcanics and underlying turbidites is also folded by the F_2 synclinorium (Figs. 1, 5).

Our interpretation of a major synclinorium across the Port Albert Peninsula agrees with that of McCann and Kennedy (1974) but differs from that of Williams (1964*b*), Eastler (1969), and Keen *et al*. (1981) who show a major fault separating the west limb and core of the fold (the Botwood Group) from the more highly deformed overturned east limb (Indian Islands Group). It is true that units look different on opposite limbs: turbidites on the east limb are "thinner bedded," conglomerate clasts are more strongly flattened, and volcanics are much thinner. However, we see no fundamental difference in lithologies (e.g., composition of clasts in the conglomerates are identical and volcanics similar in composition) and can account for observed differences in terms of different intensities of deformation and cleavage development.

Other macroscopic F_2 folds are present farther southeast, on Dog Bay Point, Indian Islands, and in Gander Bay. However, F_2 deformation is extremely intense in these areas and it is difficult to define the major fold axes. Stratigraphic repetition of fossiliferous limestones (crinoids and *Favosites* corals) suggests a northeast-plunging anticlinorium on Dog Bay Point, and bedding measurements indicate southwest-plunging folds in competent sandstones in the Dog Bay Peninsula (Fig. 1). These folds are part of a very tight system of doubly plunging, en échelon F_2 folds (Fig. 1).

F_2 folds apparently formed during northwest–southeast subhorizontal shortening. Macroscopic asymmetrical F_2 folds, with wavelengths of up to 15 km, have a subhorizontal enveloping surface, supporting the interpretation that layering was dominantly horizontal following F_1 deformation. It is significant to note that any major F_1-related thrust fault, for example, the one we propose at the base of the subaerial volcanics, must be folded by F_2 and must therefore have a sinuous trace. The traces of pre-F_2 faults can only be straight on a scale smaller than that of the folding (e.g., on the limbs of F_2 folds). Thus, most of the straight-line faults on published maps are probably post-F_2 structures.

The discrepancy between our fold-based interpretation and the homoclinal interpretations of previous workers is easily explained by the geometry of F_2 folds. The Milleners Arm structure described above is typical of F_2 folds in that the upright limb is much more deformed than the north-younging, overturned limb. Consequently, sedimentary structures are only readily recognized in the overturned limbs. Thus a cursory examination reveals only north-younging structures.

F_3 structures

F_3 structures are identified in this paper as those structures that kink or fold the S_2 regional cleavage. As with F_1, more than one generation of F_3 fold may exist. These folds appear to be relatively unimportant to the overall distribution of rock units on New World Island and the Port Albert Peninsula.

F_3 structures include open to tight folds, chevron folds, kink bands, and locally developed S_3 crenulation cleavage in pelitic layers and fracture cleavage in sandstones. On New World Island, F_3 folds generally have steeply dipping axial surfaces (although subhorizontal surfaces also occur), and on Indian Islands, F_3 axial surfaces have a wide variety of orientations. Mesoscopic F_3 folds (Fig. 6) are well developed in slate units throughout the area and appear to be spatially related to late faults.

Macroscopic F_3 folds are defined by broad warping of earlier structural elements on southern New World Island and the Port Albert Peninsula as shown by the variation in trend of S_2 (Fig. 5). As a result of F_3, local S_2 cleavage can deviate substantially from its northeast regional strike.

Timing of folding

F_1 folds were identified in all of the sedimentary units shown in Fig. 1. Fossil evidence indicates that the youngest units are Silurian (Llandoverian–Wenlockian) in age (Twenhofel and Shrock 1937; Williams 1972; McKerrow and Cocks 1978). Therefore, F_1 deformation was at least in part post-Middle Silurian in age. Either F_1 began in Ordovician times and continued into the Silurian, or F_1 was entirely post-Middle Silurian. We cannot distinguish between these two possibilities unless we assume that all thrusting took place at the same time, in which case it is post-Middle Silurian. However, in younger orogenic regions where stratigraphic control is better, thrusting is known to have occurred over a long period of time.

It follows that F_2 was also partly or entirely post-Middle Silurian in age. S_2 cleavage cross-cuts all of the sedimentary units and various igneous rocks as well (the Coaker porphyry, Change Islands "diorite," and a wide variety of basic to intermediate dikes found throughout the area). The persistence of S_2 across the boundaries between Ordovician and Silurian rocks

FIG. 6. F_3 kinking on the eastern Dog Island. Conjugate kink bands form the axial surfaces of a box fold.

suggests that F_2 was dominantly post-Middle Silurian. However, it is possible that F_2 was a diachronous deformation that began in the Ordovician locally.

F_3 affects most rocks in the area, including basic dikes on the west side of the Port Albert Peninsula. Although the age of these dikes is not known, it is probable that they are Devonian because they occur within a zone extending from the Loon Bay granodiorite to the Fogo granodiorite and are probably high-level expressions of the same plutonism. The granodiorites yield Devonian radiometric ages (Fig. 1, Williams 1964*c*). F_3 is therefore probably post-Middle Devonian in age.

Relationship of faults to folding

This section reviews some of the important published interpretations of the major faults in the eastern Notre Dame Bay area, and discusses these interpretations in the light of our structural data. Such a discussion is necessary because of the great number of faults in the area, the importance usually ascribed to the faults as boundaries between structurally or stratigraphically discrete tectonostratigraphic sequences, and the controversy in the literature regarding the nature and timing of movements on these faults (reviewed by Dean and Strong 1977). The faults are discussed from northwest to southeast (Fig. 1).

Chanceport Fault

Strong and Payne (1973, p. 1377) interpreted the Chanceport Fault (Fig. 1) as a major geologic discontinuity separating two distinct terranes: older and more highly deformed southwest-facing volcanic rocks to the north and less deformed north-facing volcanics and cherts to the south. Dean and Strong (1977, p. 105) correlated the Chanceport Fault with the Lobster Cove Fault to the west and proposed a major fault extending roughly east–west across the Notre Dame Bay area. They reported this fault to be parallel to bedding in vertical north-facing Ordovician and Silurian rocks of the southern fault block and interpreted it as a thrust that transported the northern terrane southeastward over the southern terrane during the Silurian (Silurian rocks are involved in the faulting). The thrust and bedding were then said to have been rotated to vertical attitudes during later, Acadian folding.

We have examined only a small section of the Lobster Cove – Chanceport Fault, on western New World Island (A–A′ of Fig. 1). Our observations here (Fig. 5) indicate that the fault is at a high angle to the enveloping surface of tight F_2 folds in the Chanceport Group rather than parallel to stratigraphy in a north-younging homoclinal succession. Hence, we interpret the Chanceport Fault at this locality to be a post-F_2 high-angle fault, not a folded thrust fault.

We do not dispute stratigraphic evidence for major discontinuities at various places across the Lobster Cove – Chanceport Fault and indeed we agree with Dean and Strong (1977, p. 105) that there was major thrusting (our F_1) during Silurian or post-Silurian times and that early thrusts were later folded (our F_2). However, we do not agree that the Lobster Cove – Chanceport Fault, as drawn on published maps (Dean and Strong 1977, p. 99; Keen *et al.* 1981), can be a folded thrust because, at least locally, it is a post-F_2 high-angle fault (Fig. 5).

Lukes Arm Fault

The Lukes Arm Fault, which merges with the Chanceport Fault on northern New World Island (Fig. 1), has also been proposed as a major discontinuity in the Notre Dame Bay area (Williams 1963; Horne and Helwig 1969, p. 389; Williams and Payne 1975, Fig. 2) although Dean and Strong (1977, p. 100) suggested that sediments on both sides were similar in lithology and orientation (vertical, north-facing beds) and that the fault was a bedding-plane fault without significant displacement.

We have examined only a small segment of the fault, in the area on western New World Island described by Strong and Payne (1973, p. 1368) and shown in Fig. 3 of Dean and Strong (1977). Our profile (Fig. 5) shows that the Lukes Arm Fault, like the Chanceport, is at a high angle to the enveloping surface of F_2 folds and is unaffected by the folding. It is therefore not a bedding plane fault or thrust and is interpreted as post-F_2.

Cobbs Arm Fault

The Cobbs Arm Fault bisects New World Island and, as mapped by Williams (1963), Kay (1976), and Keen *et al.* (1981), causes repetition of a thick graywacke–conglomerate assemblage (Fig. 1). This fault has been interpreted as a thrust fault by Kay and Williams (1963), Harris (1966), and Dean and Strong (1977, p. 106). In contrast, McKerrow and Cocks (1978, Fig. 2) interpreted the Cobbs Arm Zone as the stratigraphic basal part of a north-younging Silurian olistostromal unit.

We have not yet made detailed structural sections across this zone but we make two comments based upon reconnaissance studies. First, the lithologies along the Cobbs Arm Zone (mélange containing Middle Ordovician limestone, Caradocian graptolite-bearing shale, and pillow volcanics) are, for the most part, similar to lithologies seen in the Dunnage mélange, suggesting possible repetition of mélange by folding and faulting. Second, the rocks near Cobbs Arm have been complexly deformed and show the same deformation features (intense cleavage development, asymmetrical folds, and transposition of bedding) described above in the attenuated south-younging limb of the Milleners Peninsula fold. Silurian fossils have been reported in the mélange near Cobbs Arm and the Cobbs Arm Zone has been interpreted by McKerrow and Cocks (1978, pp. 1126–1127) as an olistostrome. We do not exclude the possibility of a Silurian olistostrome in this area. However, the fossils do not necessarily date the whole zone and a Silurian olistostrome is not incompatible with our structural interpretation. F_1 folding and related thrusting combined with F_2 folding and late faulting are capable of explaining the observed rock distribution.

Dildo Fault

The Dildo Fault was proposed by Kay (1976, Fig. 4) as the boundary between two tectonostratigraphic sequences: the Dunnage mélange to the south and the Dildo sequence to the north. Kay (1976, p. 42) believed it to be a transcurrent fault with a displacement of a few kilometres. Other workers (Horne 1969, p. 2453; Hibbard and Williams 1979, p. 1009) have suggested that the contact between the Dunnage mélange and "overlying" rocks is conformable, not faulted.

Although strong topographic lineaments do exist along the proposed Dildo Fault there is no persistent feature that we can relate to the "Dildo Fault" and no obvious stratigraphic displacements. More importantly, the "lineaments" do not separate two structurally distinct sequences but instead cut across various stratigraphic levels within Ordovician rocks. In places where there is evidence for a fault it is, like most others in the area, a late high-angle fault, post-dating F_2 folding. The fault is related to F_3 kinking, and apparently of little importance. The presence of intense F_1 and F_2 folding in the slates along the south coast of New World Island indicates that stratigraphic contacts are more complex than generally drawn.

Reach Fault

The Reach Fault, mapped by Williams (1964*b*), Kay (1975, 1967), and others (e.g., Patrick 1956; Keen *et al.* 1981), separates the Dunnage mélange from Silurian strata on the Port Albert Peninsula (Fig. 1). It is defined by topographic lineaments and zones of brecciation and mylonitization (Kay 1976, p. 31). The location of the trace of this fault is well constrained to the tickle east of Dunnage Island. To the north, our mapping suggests that the trace should pass between New World Island and Dram Island, as fractured chert-pebble conglomerates on Dram Island more closely resemble conglomerates on the Port Albert Peninsula than on New World Island. To the south, we redraw the major fault at the site of Kay's Holmes Point Fault rather than east of the Loon Bay granodiorite. Our reasoning for doing this is that we trace the same sandstones (progressively more fractured and hornfelsed to the south) across Kay's (1976) trace of the Reach Fault near Boyd's Cove. Further, rhyolites and basalts of Kay's Boyd's Cove complex appear similar to composite dikes farther north-east, in the Port Albert Peninsula.

The Reach Fault has been proposed as one of the major tectonostratigraphic boundaries in the Notre Dame Bay area. Williams *et al.* (1972, p. 184) used it as the boundary between tectonostratigraphic zones "E" and "F"; Kay (1975, p. 32) suggested it was a major transcurrent fault, perhaps a continuation of the Brevard Zone of the southern Appalachians; and Kennedy (1975, Fig. 10) and McKerrow and Cocks (1977) suggested it was the suture across which the Iapetus Ocean finally closed in Devonian times.

In contrast, like Dean and Strong (1977, p. 106) we interpret the Reach Fault to be a late high-angle discontinuity with only moderate displacement. The straight trace of the fault truncates the major F_2 folds (Fig. 7), indicating a post-F_2 age. Furthermore, we have been unable to demonstrate any stratigraphic discontinuity and the large-scale Dunnage anticlinorium appears to persist across the fault toward the Change Islands. This suggests that displacements are small. It could be that displacements are large and the match of structure is fortuitous. However, this is inconsistent

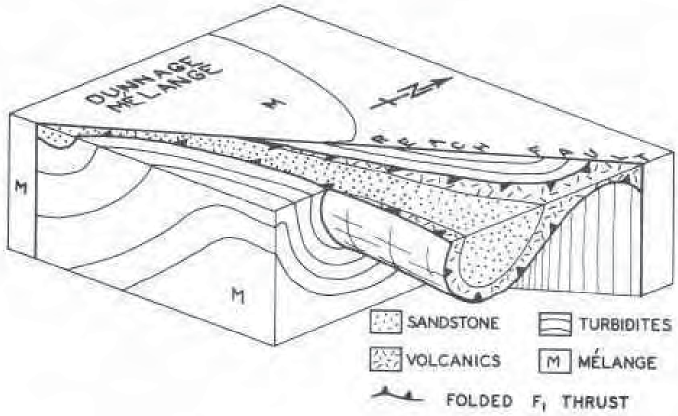


FIG. 7. Three dimensional sketch of relationships along the Reach Fault. F_1-related thrust fault and F_2 syncline are both truncated by the high angle Reach Fault.

with present mapping, which shows that the Reach Fault dies out rapidly to the south within Ordovician and Silurian sediments (Keen *et al.* 1981). All of the other interpretations require that the Reach Fault be a major structure with displacement measurable in tens of kilometres.

Indian Islands "thrust"

Both Williams (1964*b*) and Eastler (1969, p. 119) proposed a fault separating the Silurian Botwood Group to the north (Williams 1964*b*) from the Silurian Indian Islands Group to the south (Twenhofel and Shrock 1937; Baird 1958). It extended from the north side of Dog Bay, through Middle Dog Bay Island, and between the Indian Islands and Fogo Island (Fig. 1). This fault was named the Indian Islands thrust by Eastler (1971) who believed that the Indian Islands Group had been thrust over the Botwood Group during F_2 folding (his F_2 shows the same relationship to cleavage as our F_2 and is therefore assumed to be identical). This fault is not shown in Fig. 1 because we see no evidence of its existence and we interpret the strongly deformed rocks of the Indian Islands Group as part of the attenuated limb of the major F_2 synclinorium in the Port Albert Peninsula. Furthermore, we correlate polymictic conglomerates south of the fault (near Stoneville) with those found on the western Port Albert Peninsula and see no justification for separating rocks north and south of this fault on the basis of stratigraphy (Williams 1964*b*, 1972) or structural style (Eastler 1969).

However, Fig. 1 shows a fault in a slightly different position in this same area, at the base of the subaerial volcanics instead of at their top. Extrapolating from the contact on the west side of the Port Albert Peninsula, we interpret this fault to be an earlier (F_1-related) thrust fault, now folded by F_2, which brought subaerial volcanics over the turbidites, conglomerates, and slates. The difference between Eastler's (1969) and Williams' (1964*b*) interpretations and ours is an important one. Their boundary separates distinct geologic terranes whereas our fault separates stratigraphic units and, like those units, is folded by F_2.

Rogers Cove Fault

Williams (1964*b*, 1972) proposed a fault in Rogers Cove on the west side of Gander Bay (3 km south of the south margin of Fig. 1), separating the Silurian Indian Islands Group to the north from Ordovician rocks to the south (see also Keen *et al.* 1981). In contrasting interpretations, Currie *et al.* (1980*a,b*) proposed an angular unconformity between Ordovician and Silurian rocks in this same general area and Wu (1979) mapped a conformable contact between Ordovician and Silurian rocks north of Rogers Cove.

The fault proposed by Williams (1964*b*, 1972) and shown by Keen *et al.* (1981) is unsatisfactory because we have mapped the same slates, containing calcareous sandstone pods, on both sides of Rogers Cove (as did Wu 1979) suggesting no great offset across this proposed fault.

There are also difficulties with the angular unconformity proposed by Currie *et al.* (1980*a,b*). Their evidence for the angular unconformity was that black pelites of the upper Davidsville Group (their unit 10) were more deformed (i.e., contained an extra cleavage) than siltstones of the Indian Islands Group (unit 11). It is true that in outcrop black slates north of Rogers Cove do contain a strongly developed, subhorizontal S_3 crenulation cleavage that cannot always be recognized in the overlying siltstones. However, it is present in some localities. This is the significant point because cleavage is generally better developed in mica-rich units than in quartz-rich units (e.g., Sorby 1853) so that identifying numbers of deformations on the basis of numbers of cleavages in this situation is invalid. Because we can trace S_3 continuously across the proposed unconformity (5.5 km north of Rogers Cove and on Dog Island) and because we find the same folding history in both Ordovician and Silurian rocks, our interpretation is that S_3 is simply more strongly developed in the finer grained, micaceous slates than in the siltstones and silty slates of Gander Bay. We see no structural evidence that the Davidsville Group was deformed, then eroded, prior to Indian Islands Group deposition.

Summary and implications for geological map interpretations

Our evidence indicates that most of the rectilinear faults shown on published maps are late features superimposed upon already complexly deformed rocks. This deformation involved three generations of folding and affected rocks in widely separate areas and rocks of diverse ages. Our view is that an understanding of this folding history is of paramount importance in correlating stratigraphic units, proposing depositional models, and ultimately in relating observed sedimentary and tectonic features to plate tectonic models. In contrast to earlier workers, we wish to emphasize that different fault-bounded blocks have the same tectonic history.

An understanding of F_2 provides the key to the regional deformation history. F_2 folds are asymmetrical folds with subhorizontal enveloping surfaces. Their geometry dictates that layering was subhorizontal prior to F_2 (i.e., at the end of F_1 folding). This observation is supported both by the uniform low metamorphic grade seen throughout the area and by our observations of type II and III fold interference patterns produced by superposition of F_1 and F_2 folds. Because layering was subhorizontal following F_1 and because we find F_1 folds throughout the eastern Notre Dame Bay area, we believe that F_1 was a major thrusting episode.

This conclusion takes the form of a working hypothesis and requires a great deal of further work to relate stratigraphy and structure in the Dunnage Zone. The implications are far reaching. If one accepts a tectonic history involving regional folding and thrusting (F_1) followed by asymmetrical folding (F_2), and later kinking and high-angle faulting (F_3), then two important implications follow. First, all stratigraphic contacts and F_1-related thrust faults will be complexly folded. Second, at least major parts of the orogen are likely to be allochthonous.

The shallowly dipping enveloping surface of F_2 results in the repetition of major stratigraphic units across macroscopic F_2 folds. One example, on the scale of the orogen itself, is the repetition of Caradocian graptolite-bearing shales throughout the Dunnage Zone (Dean 1978). The appearance of these units over a lateral distance of about 100 km, at a uniformly low metamorphic grade, is additional evidence for a shallowly dipping enveloping surface for F_2 folds in the Dunnage Zone. A second example is the possible repetition of mélanges in the eastern Notre Dame Bay area. Pajari *et al.* (1979, p. 1450) correlated the Carmanville mélange with the Dunnage mélange on the basis of similar ages and lithologies. In a broad way, this proposed correlation fits our structural interpretation. In contrast, McKerrow and Cocks (1977, p. 494) argued that Ordovician fossils from the Dunnage mélange belong to a North American province whereas Ordovician fossils from the Davidsville Group (which contains the Carmanville mélange) had stronger affinities with faunas from the southeast side of the Iapetus Ocean. On this basis they argued that the Reach Fault is the suture marking the closure of Iapetus. However, the interpretation of a European province for fossils in the Davidsville Group was based on a pygidium of a single trilobite. Considering the uncertainty in identification of this single fossil (McKerrow and Cocks 1977, p. 494), the absence of supporting fossil evidence for a wide ocean between New World Island and the Davidsville Group (Stouge 1980*a*), and difficulties in interpretation of faunal provinces in general (Stouge 1980*b*), faunal evidence for a suture in the eastern Notre Dame Bay area is unconvincing.

With nappe tectonics followed by two superimposed deformations, we expect to find major geologic discontinuities that would represent the step from one structural level (i.e., one nappe) to another. Defining these F_1 nappes is difficult because of the intensity of F_2 folds and especially because of F_3-related high-angle faults in the area. We tentatively suggest that the area of the Twillingate terrane (Williams and Payne 1975) in northern New World Island may represent a window into a structurally lower nappe or even into autochthonous basement (cf. Williams and Malpas 1972).

Another example is the abrupt transition from marine turbidites and volcanics to Silurian subaerial volcanics and sandstones. Williams (1967, 1979) has used this evidence to support the interpretation that a large part of the orogenic activity had ceased prior to the widespread deposition of these subaerial rocks across the orogen. This interpretation relied on the assumption that the lower contacts of the Silurian subaerial assemblages are angular unconformities. However, our work in the Port Albert area suggests that the contact is an F_1-related thrust fault. We therefore consider it probable that the entire assemblage of Silurian subaerial volcanics and sandstones that extends from Fogo Island southwestward to Rodeross Lake (the Botwood Belt of Williams 1967, p. 99) is allochthonous. One of the difficulties in distinguishing between these two interpretations is that late high-angle faults form the present boundaries of much of the Botwood Belt and obscure the original contact relationships. This is also the problem throughout the Dunnage Zone: late high-angle faults form the boundaries between many map units and obscure the nature of the original contacts. This is the situation that one expects in an area where the enveloping surface is close to horizontal and late high-angle faults are common.

A description of the area of the Reach Fault serves to illustrate the problem. As shown schematically in Fig. 7 (and in map view in Fig. 1), the Reach Fault is a high-angle fault that truncates the major F_2 synclinorium in the Port Albert Peninsula. This F_2 syncline folds stratigraphic contacts and, we believe, also folds the F_1-related thrust fault contact between subaerial volcanics and underlying turbidites. Northeast of Dunnage Island, on the eastern side of the Reach Fault, the basal contact of the subaerial volcanics is well exposed and can be shown both to be related to F_1 folds and to be folded by F_2. Southwest of Dunnage Island, the basal contact of the subaerial volcanics is not exposed and these rocks are juxtaposed with Ordovician mélange. If possible continuations of the Reach Fault are sought, e.g., through the Loon Bay granodiorite and along the west side of the Botwood Belt, one can map a regional-scale fault zone separating distinct geologic terranes (tectonostratigraphic zones) over most of its length (see Williams *et al.* 1972; McKerrow and Cocks 1977, p. 491; Keen *et al.* 1981). However, our point is that movement on these faults is much later than the F_1 deformation that originally brought the two terranes into contact, so that late high-angle faults, although they may represent considerable displacement, are not the key features in unravelling the orogenic history of the area.

Very similar problems arise along the Lobster Cove, Chanceport, and Lukes Arm Faults, where no stratigraphic units can be traced from one side to the other but structural geometries indicate that the observed discontinuities are high-angle faults. Thus, although in a general way one terrane has indeed been thrust over another (Dean and Strong 1977), the observed (and mapped) rectilinear faults are not the thrust faults.

The mélange problem

One long-standing problem in orogenic zones has been the interpretation of mélange as units that owe their chaotic aspects either to processes related to sedimentation, to deformation, or both. The prevailing interpretation of mélanges in the Notre Dame Bay area has favoured the former, considering them to be mainly olistostromal units where "mixing" has taken place in unlithified sediments at the sediment surface due to gravity sliding and slumping contemporaneous with sedimentation (Hibbard and Williams 1979; Pajari *et al.* 1979). In accordance with Hsu (1974), this olistostromal interpretation has considered the units to be stratigraphic units, separated from overlying and underlying units by depositional contacts.

However, it is difficult or impossible to distinguish olistostromes from tectonic mélanges (tectonic units bounded by shear surfaces), especially in terranes that have suffered pervasive shearing (Hsu 1974, p. 331). In view of the proposed deformational history, the interpretation of mélanges as "tectonic" or "sedimentary" needs to be made with caution. We would like to emphasize that all of the observed products of deformation in the eastern Notre Dame Bay area (thrust faults, initially recumbent folds without axial plane cleavage, asymmetrical folds, "chaotic bedding," disharmonic folds, and mélanges) can also be found in orogenic zones such as the Alps and Caledonides where they have developed in rocks that were previously metamorphosed (e.g., Williams and Zwart 1977).

Therefore it is possible that all the observed deformational features in this area of northeast Newfoundland have developed after lithification. With the exception of convolute bedding in turbidites, we know of no proven soft-sediment deformation. The observation of concentrations of F_1 folds in several places at the contacts of mélanges (e.g., along the southern shore of New World Island, in the Indian Islands tickle, and in Gander Bay) provides some support for this concept.

If the mélanges are products of hard-rock deformation, i.e., zones of intense strain associated with F_1 thrusting, their significance for tectonic modeling is changed. A given mélange in general would be expected to cut across the stratigraphy so that its age at least in part would be younger than the youngest rocks cut. All mélanges in Fig. 1 could be related to F_1 deformation and therefore entirely, or partly, post-Middle Silurian in age. If the mélanges are tectonic in origin, neither the presence of Ordovician or Silurian fossils within mélanges nor the presence of mélange within otherwise coherent Ordovician and Silurian stratigraphy (cf. Hsu 1968, p. 1067) would be compelling evidence for their paleogeographic setting, i.e., for Ordovician subduction (Bird and Dewey 1970, p. 1045; Kay 1976, p. 41), Ordovician olistostrome development in a back-arc basin (Hibbard and Williams 1979), or Silurian olistostrome development in a trench (McKerrow and Cocks 1978, p. 1130).

Even if the mélanges are stratigraphic horizons instead of thrust zones, there is still no necessity to invoke olistostromes of different ages to explain the mélanges within the area of Fig. 1 (McKerrow and Cocks 1978). Correlation of the Carmanville and Dunnage mélanges has already been suggested (Pajari *et al.* 1979), and correlation of both with the Cobbs Arm and Dog Bay mélanges would also be consistent with our structural interpretation. With a shallowly dipping enveloping surface for F_2, there is a strong possibility of the Dunnage mélange outcropping in any large F_2 anticline. Hence, we believe that at least part of the Cobbs Arm Fault Zone may be Dunnage mélange exposed in the core of an F_2 anticlinorium and locally placed in contact with Silurian rocks by a combination of folding and faulting.

The significance of mélange for depositional and tectonic models of the Dunnage Zone is still unclear. Until definitive data accumulate, future work should follow the method of multiple working hypotheses, considering it possible that mélanges represent: (1) thrust faulting in lithified sediments, (2) thrust faulting in unlithified sediments, (3) olistostromes, or some combination of the three.

Discussion

Two major implications of our work in the eastern Notre Dame Bay area are: (1) deformation involved macroscopic thrust faulting; and (2) much and perhaps all of the penetrative deformation was post-Middle Silurian in age. The former (when combined with evidence for thrusting in Silurian–Devonian rocks along the Baie Verte lineament (Williams 1980*a*, p. 431), in the western Notre Dame Bay area (Dean and Strong 1977), in the Buchans area (Thurlow 1981), and in south-central Newfoundland (Colman-Sadd 1980) implies that post-Middle Silurian thrusting took place throughout the Dunnage Zone. Hence, major portions of the Dunnage Zone may be allochthonous.

This appears to be in conflict with the interpretation that the Newfoundland Appalachians are an autochthonous (or rooted) orogen (Williams 1964*a*, 1980*a*,*b*). Evidence cited in favour of a "rooted" orogen includes: (1) the interpretation that Silurian subaerial rocks across the orogen were deposited unconformably on Ordovician sediments that had been previously deformed during orogenic events that marked the closure of Iapetus; and (2) the absence of Silurian ophiolites and continental margin sediments within the orogen (Williams 1979, 1980*a*).

Our structural interpretation in the eastern Notre Dame Bay area casts doubt on the first argument. We believe the subaerial Silurian assemblage is in thrust fault contact (at least locally) with Silurian turbidite and conglomerates and is not unconformable on previously deformed rocks. This interpretation seems reasonable for the length of the Botwood Belt at least and, if extrapolated elsewhere, the distribution of Silurian rocks across the orogen may be related to thrust faulting, not to post-orogenic sedimentation. The second argument in favour of a rooted orogen is also questionable. There are numerous examples of probable Silurian pillow volcanics and Silurian turbidite sequences in the Dunnage Zone that could well represent thrust slices of Silurian oceanic basalts and continental margin sediments, respectively. If one accepts regional-scale thrusting as part of the deformational history within the Dunnage Zone, almost any rock distribution is possible.

The second implication of our data, that major thrusting continued into post-Middle Silurian times, requires some rethinking of the timing of orogenesis in Newfoundland. Because Middle Ordovician ophiolite emplacement is well documented on the west coast (Williams 1980*a*), we suggest that plate convergence was relatively long-lived in the northern Appalachians and may have continued for 50–100 Ma, from Middle Ordovician into Devonian and Carboniferous times (cf. Colman-Sadd 1980, p. 1014). Reconstruction of the paleogeography at various stages during convergence (i.e., position of island arcs and trenches, direction(s) of subduction, and configuration of sedimentary basins), in our view, will only be possible after the geometries of F_1 nappes are defined. This, in turn, requires an understanding of the geometry of later deformations, F_2 and F_3.

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