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Sediment slump structures: a review of diagnostic criteria and application to an example from Newfoundland

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Abstract—In the study of the history of deformed sedimentary rocks it is important that the cause of the deformation and the timing of deformation relative to metamorphic and tectonic events be assessed. There is a continuous gradation between the deformation of freshly deposited sediments by gravitational forces and the deformation of well-lithified sediments by tectonic forces, so determining the degree to which gravity, tectonism and lithification influenced deformation can be very difficult. The characteristics that may be considered in determining the origin of deformational structures in sedimentary rocks can be divided into five categories: Ductile deformation structures (1) can provide definitive criteria for recognizing post-lithification deformation, but not pre-lithification deformation. This also holds for (2), brittle deformation structures and décollements. Overprinting of sediment reworking or remobilization structures (3) are the best criteria for recognizing pre-lithification structures. Fabrics (4) can be very useful but are as yet poorly understood, and there are misconceptions in the literature about what sort of fabrics are or are not found in unlithified sediments. Spatial relationships (5) may also tell us a great deal, but are most useful when taken in conjunction with other types of evidence.

Complex fold patterns in sandstones on Farmer Head, north-central Newfoundland, provide a case study for criteria that may be used to determine the degree of lithification during deformation. Although these folds have been interpreted as slump folds by earlier workers, fabrics and spatial relationships point to a tectonic post-lithification origin for the structures, a conclusion which has significant implications for the interpretation of the regional geology.

INTRODUCTION

THE DISTINCTION between 'soft-sediment' and 'hard-rock' structures in ancient rocks is an important one to make in any investigation of deformed sedimentary strata, but it is not the only important one: 'soft' sediments may be deformed by tectonic processes, and 'hard' rocks may be deformed solely under the influence of gravity in a surficial environment (see Maltman 1984 for discussion and terminology). It is necessary to assess both the degree of lithification at the time of deformation, and the cause of that deformation, be it local current shear, local density gradient, gravity acting on a slope, glaciotectonic processes, or the convergence of lithospheric plates. Recognizing these factors in ancient rocks is difficult, and often impossible, because few unequivocal criteria exist (Maltman 1984, and references therein).

Descriptions of 'soft-sediment' deformation structures and lists of their characteristics have been published, but these are frequently derived from studies of disrupted strata in ancient rocks (e.g. Jones 1937, 1940, Williams & Prentice 1957, Williams *et al.* 1969, Helwig 1970, Woodcock 1976a & b, Bell 1981, Buggisch & Heinitz 1984, Visser *et al.* 1984, Eyles & Clark 1985). Because deformation structures in ancient rocks are the ones that tend to be in question, it may be more profitable to examine modern sediments (e.g. the Deep Sea Drilling Programme as described in DSDP reports) in order to assess structures actually produced when unlithified sediments are deformed. The following study is a critical review of criteria which have historically been used to assess the degree of lithification and cause of deformation in ancient rocks, with reference wherever possible to phenomena observed in modern unlithified sediments.

To study all possible combinations of degrees of lithification and causes of deformation is far beyond the scope of one paper, so this study is focused specifically on subaqueous slump structures, particularly near-surface slump folds formed in unlithified sediments, although some of the factors discussed will have broader applications. 'Slump' structures are here defined as deformation structures produced by down-slope movement of sediments that maintain their continuity on the scale of layering. They are distinguished from 'glide' deposits, in which the displaced blocks suffer little or no internal deformation, and 'mass flows', in which internal cohesion is lost, and which may contain clasts, blocks or bedding fragments in a variably sheared matrix (after Nardin *et al.* 1979).

It has been recognized (e.g. Hobbs *et al.* 1976, pp. 156–159, Maltman 1984) that most sedimentary deformation structures are ambiguous with regard to the exact cause of their formation, which means that, when faced with questionable structures, "the geologist has to assess the cumulative weight of several not infallible criteria" (Fitches & Maltman 1978, p. 245). Such an approach is applied here to the analysis of 'chaotic' structures on Farmer Head in north-central Newfoundland, Canada.

DIAGNOSTIC VALUES OF FEATURES FOUND IN DEFORMED SEDIMENTS

Characteristics that may be considered when determining whether preserved structures are the result of deformation before rather than after lithification, or of down-slope movement rather than tectonism, are here divided into five categories. Each of these is outlined below, and the validity of each as a diagnostic criterion is discussed.

Ductile deformation structures

Most discussions of features characteristic of slump folds are dominated by descriptions of ductile deformation structures. The list below is a combination of characteristics described by Williams *et al.* (1969), Helwig (1970), and Blatt *et al.* (1980):

(a) distorted and overturned strata;
(b) thickening, thinning and boudinage of strata;
(c) striated folds or fragments;
(d) rolled up fragments of strata;
(e) detached fold blobs;
(f) curvilinear fold hinges;
(g) piled up, recumbent, or nappe-like folds, which may or may not be overturned in opposing directions;
(h) folded boudins;
(i) chaotic structure not cut by open fractures or vein filling.

Of these characteristics, recumbent folds overturned in opposing directions (g) may be characteristic of prelithification folds if it can be demonstrated that the over- and underlying beds are undeformed (Williams *et al.* 1969), which is difficult to do in many cases. In metamorphic rocks, sheath folds and interference patterns may have this morphology.

The remaining features are found in slumped sediments, but they can also be found in tectonized sediments and sedimentary rocks. At best, they can only augment other evidence to support an interpreted slump origin for folds in ancient rocks (e.g. Farrell 1984).

Some ductile features are found only in tectonically deformed sediments or sedimentary rocks. These are:

(a) metamorphic or diagenetic minerals that are kinked, folded, or otherwise deformed plastically by the structure in question;

(b) veins of secondary minerals or igneous intrusions that have been plastically deformed around or within the structure. To be diagnostic, these must still retain the imprint of the strain imposed by the deformation (e.g. unrecrystallized calcite veins in which twin lamellae bend around the structure, or, in folded quartz veins, a crystallographic preferred orientation fabric that is geometrically and genetically related to the fold; Williams 1983). Care must be taken to recognize veins or intrusions that formed along planes of weakness following a pre-existing structure (e.g. veins injected around the noses of pre-existing folds; Mawer 1987);

(c) fossils, or igneous and metamorphic lithic clasts deformed by the structure. Sedimentary lithic clasts and concretions may be included here if it can be demonstrated that lithification occurred before deformation. If concretions are bounded by the top and bottom of a single layer, they may have grown parallel to a previously deformed layer, as is discussed in the section on Farmer Head later in this paper.

Brittle deformation structures and décollements

Brittle structures, or structures in which cohesion is lost across a plane or zone in the host rock, are also common in sediments deformed before lithification. The forms these may take include:

(a) truncated upper and/or lower surfaces of folded intervals (e.g. Rettger 1935, Potter & Pettijohn 1963, pp. 156–158, Williams *et al.* 1969, Horne 1970) including décollement surfaces and the 'welded contacts' of Helwig (1970). These surfaces lack secondary mineral fibres. In tectonized unlithified sediments, décollements may be zones of well-developed preferred dimensional orientation of grains along shear surfaces, but such fabrics have not, to the writers' knowledge, been reported in similar structures in unlithified sediments deformed only by slumping;

(b) microfaults that do not truncate or deform single grains, or contain secondary vein minerals, but may be filled with redistributed grains from the host sediment. These may be the 'kink structures' of van Loon *et al.* (1985). If they form a locally penetrative fabric, they may appear to be a crenulation or solution cleavage (Farrell 1984);

(c) clastic dykes that do not truncate clasts or grains in the host sediment, or contain angular brecciated fragments of fossils, or igneous or metamorphic rocks. They must be distinguished from diatremes or neptunian dykes.

Décollement, microfaulting and clastic dykes may all be found in tectonized sediments and rocks deformed after lithification. They can be recognized as tectonic if they cut grains, clasts, concretions, veins, dykes or fossils, or if they are filled with secondary minerals; however, the absence of these features does not preclude tectonic origins.

Overprinting of sediment reworking or remobilization structures

The best criterion for recognizing soft-sediment deformation structures is the presence of early cross-cutting structures. These include:

(a) erosional or current reworking structures on the depositional base of overturned strata (e.g. Helwig 1970, Morris in Fitches & Maltman 1978, Farrell 1984). Examples might be the presence of undeformed channels, scours, tool marks, ripples, rainprints or epichnial ichnofossils imposed on the overturned limb of a recumbent fold;

(b) load casts on the depositional top of overturned disrupted strata. These may be difficult to distinguish from pinch-and-swell or strata folded after load casting;

(c) undeformed elutriation structures, particularly those that can be traced to mud volcanoes and spring-pits on what was the sediment–water interface at the time of formation (e.g. Gill & Kuenen 1958). The latter point is important, because dewatering and injection structures may be associated with tectonic deformation at deeper levels in the sediment pile;

(d) overprinting by undeformed concretions. Crimes (1966) described convolute laminae overgrown by calcareous concretions. Since the carbonate content of a concretion can give an estimate of the porosity of the sediment at the time of formation (Raiswell 1971, Curtis *et al.* 1972, Hudson 1978), it can also give an estimate of the degree of compaction and depth of burial at the time of deformation. If it is recognized that the concretion is not epigenetic (i.e. formed after the consolidation of the enclosing sediment—see Raiswell 1971) then distorted laminae preserved in the concretion must have been deformed while the sediments were still unlithified;

(e) the presence of undeformed biogenic burrows cross-cutting the deformation structure (e.g. Kleist 1974, Hobbs *et al.* 1976, p. 157). There are organisms which bore into lithified sediments, and care must be made to distinguish burrows from borings. Borings may be recognized in that they cut across single grains and rarely intersect themselves (Ekdale *et al.* 1984).

In utilizing these criteria, caution must be used to recognize primary structures imposed on paleosols or unconformable contacts. Further, the role played by tectonism in producing structures containing any of the above features must be assessed through consideration of the local and regional geological framework.

Fabrics

The presence or absence, and nature, of secondary fabrics in deformed sediments can be a key factor in determining the timing and environment of deformation. In sedimentary rocks, most fabrics involve a preferred dimensional orientation (PDO) of grains and minerals, so it is useful to understand how and when PDO fabrics are formed. In freshly deposited coarse-grained sediments, grains may have an imbricate PDO which, if not destroyed by bioturbation, may be enhanced by compaction. Such a fabric is dependent on the magnitude and orientation of local currents, so grain orientation varies along the length of the deposit and will not be uniform over any distance (e.g. Hiscott & Middleton 1980).

Unlike sands and gravels, the fluid dynamical properties of clay-sized particles prevent them from being deposited with a PDO, even if they are not flocculated (see Blatt *et al.* 1980, p. 121). The formation of a PDO fabric in natural systems, especially those that have been bioturbated, therefore requires some degree of compaction (see Moon & Hurst 1984). Fabrics in unlithified muds are difficult to study, but in those examined in DSDP cores from the Brazil Basin, PDO fabrics were not found above 45 m sub-bottom depths and 250 kPa overburden pressures (Faas & Crocket 1983). Sand and silt particles (Curtis *et al.* 1980, Grainger 1985) and foraminifera tests (Faas & Crocket 1983, Cowan *et al.* 1984) further inhibit the development of PDO fabrics by interacting with platy minerals and hindering grain rotation during compaction. This suggests that it may not be possible for near-surface slump folds to have genetically related axial-planar PDO foliations.

PDO fabrics in deformed sediments have been studied experimentally (e.g. Maltman 1977) and in natural systems (e.g. Moore & Geigle 1974, Lundberg & Moore 1981, Maltman 1981, Cowan 1982, Johnson 1983, Cowan *et al.* 1984, Ritger 1985; see also contributions in Fitches & Maltman 1978). In *tectonized* fine-grained sediments, anastomosing domainal layer-silicate fabrics, sub-parallel to sub-perpendicular to bedding, have been recognized in DSDP cores (Arthur *et al.* 1980, Cowan 1982, Lundberg & Moore 1981, Cowan *et al.* 1984). These fabrics have been recognized at minimum sub-bottom depths of 127 m (Lundberg & Moore 1981), and about 200 (Cowan *et al.* 1984) and 300 m (Arthur *et al.* 1980), and have always been found associated with tectonism at active continental margins. The sediments are described as being 'partially consolidated' (Cowan *et al.* 1984). Johnson (1983) describes similar fabrics produced in glacial tills by shear induced by the overriding Laurentide ice sheet. There is no evidence that lenticular domainal fabrics can be formed without considerable overburden (confining) pressure and/or shear in the sediment pile.

'Vein structures' described by Lundberg & Moore (1981), Carson *et al.* (1982), Cowan (1982), and Ritger (1985), are found at sub-bottom depths greater than 100 m in DSDP cores from convergent margins, and have preferred dimensional orientations of platy minerals at high angles to bedding. Ritger (1985), suggests that 'vein structures' are formed by a combination of pore-water overpressuring and tensile fracturing. This model, and Cowan's (1982) simpler extension fracturing model, do not require tectonism as a driving force. Pore-water overpressuring by rapid burial, for example, and/or simple down-slope creep under gravity may be all that are required to generate these structures. A foliation similar to 'vein structures' was described by Gray (1981) in tectonized calcareous mudstones of the American Piedmont.

Maltman (1977) studied fabrics in muds deformed experimentally by triaxial compression, and 'direct' and 'distributed' shear. The structures produced were zones of shear along discrete surfaces, kinks, and crenulations, especially at the boundaries between layers of different composition; however, while the strain rates used in the experiments were similar to those expected for slumping and sediment creep (10^{-3}–10^{-7} s^{-1}), the normal and confining stresses used were higher than would be expected in a normal slump environment. They represent a depth below the sediment–water interface of greater than 84 m in the shear tests, to a depth of 1800 m in the triaxial compression tests (depths calculated using sediment porosity and density data from Hamilton 1976). The porosity of clays used (maximum of 40%) are also much lower than is generally found above approximately 400 m sub-bottom depths for most marine sediments; thus, the conditions under which Maltman's shear experiments were performed are not conditions that would be found in natural sediments, and the conditions of the triaxial tests would only apply for depths greater than those at which slumping occurs. He reported the presence of most of these structures in sedimentary rocks (Maltman in Fitches & Maltman 1978), but, aside from the shear zones which resemble the anastomosing domainal fabric discussed above, they have not been described for modern deformed sediments.

Deformation fabrics, then, have not been reported in modern sediments above 100 m sub-bottom depths. At depths greater than this 'vein structures', at high angles to bedding, and anastomosing domainal PDO fabrics, oblique to bedding, can be found. In glacial tills, PDO fabrics formed by shearing due to overriding ice sheets have been reported, and these also represent deep structures. It is not expected that genetically related grain foliations of any of these types will be found in surface slumps that are less than 100 m thick. Most slumps are less than 100 m thick (Haner in Fitches & Maltman 1978), and Mills (1983) stresses the shallow levels at which soft-sediment deformation occurs. Down-slope deposits thicker than this fall into that grey(er) area where gravity and tectonically generated structures overlap—the 'high order sedimentary' or 'tectono-sedimentary' fields of Max (in Fitches & Maltman 1978). Down-slope mass movements of this scale are olistostromes (e.g. Moore *et al.* 1976, Naylor in Fitches & Maltman 1978), and no great degree of internal coherence is to be expected, except where the sediments are already lithified (e.g. Ineson 1985).

Early students of penecontemporaneous folding claimed that the presence of an axial-planar foliation is diagnostic of tectonic folding (Rettger 1935, Nevin 1949, Potter & Pettijohn 1963). More recently, Williams *et al.* (1969) described non-tectonic folds in Devonian sedimentary rocks from the Bunga Beds of Australia, and these folds have an axial-planar PDO foliation. Later, Moore & Geigle (1974) reported axial-planar PDOs in slump folds from the Gulf of Mexico. Thus, it has been demonstrated that the presence of an axial-planar foliation is not diagnostic of tectonic folds; however, it has not been demonstrated that surface slump folds have genetically related foliations, as is discussed below.

The fabrics described by Moore & Geigle (1974) are found in recumbent folds in untectonized sediments from the Gulf of Mexico. The folds were recovered from sub-bottom depths of 300 m and down to the hole bottom at 770 m (Ewing *et al.* 1969). This means that the fabrics were observed in sediments that had already undergone compaction and burial, which, in fine-grained material, can produce a marked fissility parallel to bedding, and therefore parallel to the axial planes of recumbent folds. Even if the Gulf of Mexico slump folds did form at or near the surface, it is probable that the subhorizontal axial-planar PDO foliation is a later overprint resulting from compaction. This was postulated by Maltman (1981) for probable slump folds in the Powys Trough of Wales. The PDO foliations in folds from the Gulf of Mexico are indistinguishable in detail from those formed by tectonism in the Aleutian Trench (Moore & Geigle 1974), but the Aleutian folds were not recumbent—the presence of an axial-planar PDO inclined to bedding might be one way of distinguishing tectonic folds from surface slump folds.

Williams *et al.* (1969) also recognized axial-planar PDO fabrics in otherwise undeformed Devonian strata in Australia. In this case, the folds have varied orientations, and axial planes are locally almost perpendicular to bedding. What distinguishes these folds from the example of Moore & Geigle (1974) is that they were probably not formed at the sediment–water interface (Williams *et al.* 1969), and therefore may not have been generated by near-surface down-slope movement. It therefore remains to be demonstrated that axial-planar foliations may be formed during near-surface slumping.

Microfaults may be interpreted as crenulation or pressure-solution cleavage (Farrell 1984). The axial-planar cleavage of Bell (1981) in mid-Paleozoic sandstones that were seemingly deformed before lithification appears to be a locally penetrative foliation of microfaults. This is substantiated by Bell's description of a lineation formed by the intersection of microfaults and bedding.

In summary, therefore, while surface slumps may not have genetically related foliations, with the possible exception of a penetrative fabric of microfaults, they may be overprinted by compactional fabrics that are close enough to parallel to axial surfaces to be deceptive. Consequently, the presence of a PDO fabric is not sufficient evidence to infer a tectonic origin for that fabric, neither is the presence of a foliation inclined to bedding: 'vein structures' in unlithified sediments form at high angles to bedding, and may form in the absence of tectonic stresses, and imbricate inequant sand grains and pebbles tend to remain oblique to bedding, even after compaction. Neither of these fabrics, however, is an axial-planar foliation. 'Vein structures' are not found near the sediment–water interface, and are readily recognized by their spaced nature and the fact that they are confined to fine-grained layers. Imbricate fabrics are variable in orientation vertically and laterally in the sediment pile, and are confined to coarse-grained layers. Mudstones interlayered with imbricate sandstones will have a fabric produced by compaction and parallel to bedding, and so there will be no fabric oblique to bedding that is traceable from one layer to the next.

The significance of bedding-parallel foliations in the interpretation of the deformational history of sedimentary rocks has been discussed by a number of workers (e.g. Williams 1972, Hobbs *et al.* 1976, p. 153, Maltman 1981, Biermann 1984, Grainger 1985). Such a foliation may be a primary compactional fabric enhanced by the formation of new minerals (e.g. Williams 1972, Hobbs *et al.* 1976, p. 153, Maltman 1981), or may be a new foliation formed during tectonic deformation (e.g. Biermann 1984, Grainger 1985). The presence of a PDO of metamorphic minerals parallel to bedding is not enough to prove that a foliation is primary rather than secondary, or that related folds are tectonic rather than slump folds.

If a foliation is defined by, or overprints, minerals that are broken or kinked (e.g. kinked micas, Williams *et al.* 1977), it is considered sufficient evidence that the foliation is tectonic in origin.

Spatial relationships

One of the most often cited characteristics of sedimentary slumps is the isolated stratigraphic occurrence of disrupted intervals. A single traceable disrupted horizon in a sequence of flat-lying unmetamorphosed sedimentary rocks can be reasonably interpreted as a tectonized interval if there is sufficient exposure to demonstrate that it crosses the stratigraphy. A slump horizon may cut through strata beneath the disrupted sediment, but, since it is a surficial feature, it cannot cut up into overlying strata; in other words, because the sediment overlying a slump horizon must have been deposited after slope failure, the same unit can never be found both above and below a slump horizon.

Sediment failure on a slope need not be a one-time occurrence, as illustrated by the depth of approximately 400 m of interlayered folded and planar sediments penetrated by DSDP drills in the Gulf of Mexico (Ewing *et al.* 1969). The absence of a restricted disrupted horizon does not preclude a slump origin for deformation. Conversely, isolated décollement surfaces are comon features of tectonized rocks. Since both slumped sequences and tectonically folded sequences may range from a single layer to many hundreds of metres in thickness, the scale of a given set of disrupted strata is of limited value in distinguishing between the two modes of deformation.

Slump structures are recognized as showing spatial variation between extensional and contractional structures, and also showing overprinting of both in a single exposure (Jones 1937, Williams & Prentice 1957, Woodcock 1976b, Farrell 1984, Visser *et al.* 1984). In ancient rocks, however, such relationships are difficult to recognize as having been contemporaneously developed. Strain overprinting during a single tectonic deformational event has been reported, and is a natural product of rotational deformation (Hobbs *et al.* 1976, p. 47, Lister & Williams 1983). Thus strain overprinting is not a useful criterion for distinguishing between penecontemporaneous and tectonic structures.

On a slope, sediment slumping may accelerate into other kinds of mass sediment gravity flow (Lowe 1979, Nardin *et al.* 1979, Blatt *et al.* 1980, Broster & Hickock 1985, and Postma 1986), so a spatial relationship between distorted strata and disaggregated and homogenized sediments and olistostromal horizons is cited as characteristic of penecontemporaneous deformation. In ancient rocks this may not be a useful criterion to apply in light of the long-lasting controversies over the tectonic vs penecontemporaneous origin of mélanges (Hsu 1974). The proximity of indications of basin instability (debris flow conglomerates, turbidites, etc.) to disrupted strata is useful supporting evidence for an interpretation of slump folding, but independent evidence must exist to make a reliable diagnosis.

One of the best ways of recognizing tectonic deformation structures is the correlation of the geometry and morphology of a given structure with regional trends that affect entire stratigraphic sequences, igneous rocks, massive sulfide bodies and metamorphic complexes. The differences in rheologic behavior between contrasting lithologies or those with contrasting orientations may make the recognition of a given structural element across a region difficult (Williams 1985). If, however, a set of folds with similar morphology, for example, are penetrative throughout strata of widely differing ages or throughout a sequence that contains lava flows, it can reasonably be assumed that those folds are tectonic in origin. On the other hand, slump structures need not be chaotic (Hanson 1971), so the presence of a regular geometry alone is not sufficient evidence of tectonic deformation.

CONTROVERSIAL STRUCTURES ON FARMER HEAD

Farmer Head is the classic exposure of 'chaotic' folds on New World Island, north-central Newfoundland. Heyl (1936) believed that all folds in the region ('Bay of Exploits') were genetically related to faulting. Horne (1970) described the folds in the Sanson Formation at Farmer Head as 'slump folds', and Helwig (1970) described 'slump folds' in the same unit in the New Bay Area, west of New World Island. Since then, other workers have adhered to the 'slump' fold interpretation, and have used it as evidence to bolster geotectonic models for the Notre Dame Bay area that involve extensive penecontemporaneous deformation (Kay 1976, Dean 1978, McKerrow & Cocks 1981, Arnott 1983, Lorenz 1984, Arnott *et al.* 1985). This apparent profusion of 'soft-sediment' deformation structures makes a detailed study of one well known and well exposed occurrence both timely and pertinent.

Location and description

Farmer Head lies at the extreme southwest tip of New World Island, and the structures in question occur within the kilometre or so of barren sea cliffs between Farmer Head and Spirit Cove (Fig. 1). The rocks are dirty turbiditic sandstones and interlayered shales of the Upper Ordovician Sansom Formation. Though the sandstones were metamorphosed only under lower-greenschist facies conditions (Horne 1969), they were intensely folded and cross-cut by late felsic dykes and high-angle faults.

Folds range from 1 to 10 m in wavelength and from a few centimetres to 15 m in amplitude, varying from tight

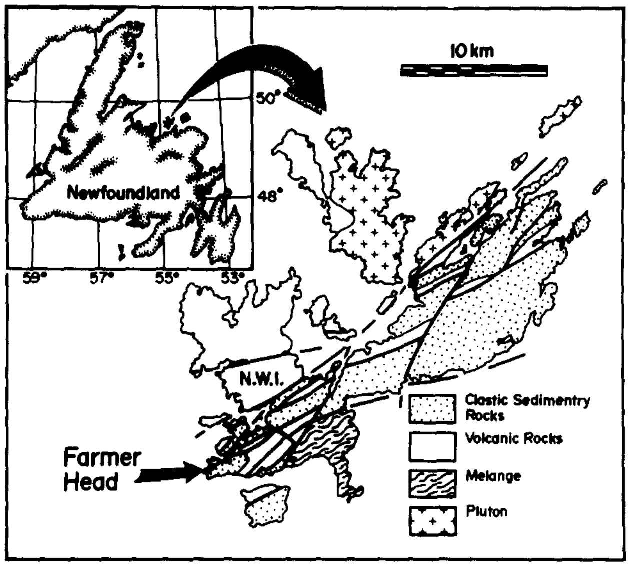

Fig. 1. General geology of New World Island (N.W.I.). Heavy lines mark faults. Inset shows position of New World Island in Newfoundland.

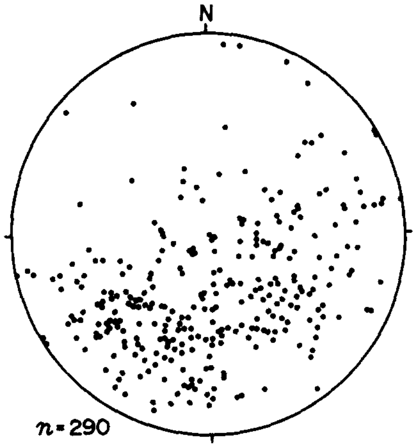

Fig. 2. Lower hemisphere equal-area projection of 290 fold axes on Farmer Head. There is no obvious pattern to axis distribution, beyond a higher density of data points in the southern hemisphere of the projection. This reflects the fact that strata generally dip moderately to the south.

and angular to broad and open warps. The tight angular folds are approximately parallel-type folds in sandstone layers, but shaly interbeds more closely resemble similar folds; while broad open warps are variably parallel or concentric. A detailed description of the tight folds may be found in Horne (1970).

Evidence for slump folding

The following evidence has been cited in favour of a slump origin for the folds on Farmer Head (Horne 1970):

(a) the disharmonic and chaotic nature of the folds—no regular geometry of fold orientation and distribution was recognized (Fig. 2);

(b) the presence of welded contacts and absence of slickensides—the rocks on Farmer Head are well indurated and do not fracture easily along bedding planes, hence the 'welded' nature of the contacts between disturbed and undeformed horizons. Folded layers are truncated top and/or bottom, but no clear erosional surfaces have been noted;

(c) the absence of veining, extensional fractures and other brittle deformation features—the only faults with associated breccias and open spaces are obviously late and cross-cut all structures;

(d) the abundance of ductile faulting—faults like that in Fig. 3(a) are common, and lend credence to the possibility of ductile deformation in unlithified sediments;

(e) the irregular non-boudin-like thinning of fold limbs;

(f) the absence of cleavage—no cleavage was recognized on Farmer Head beyond a bedding-parallel parting in argillaceous layers that was interpreted as primary.

It was recognized by Horne (1970) that none of the above are conclusive on their own, but, taken together, they led him to conclude that the folds on Farmer Head are in fact slump structures. In support of this interpretation it should be noted that the deformed strata are turbiditic, which indicates that the environment of deposition was one in which slumping could be expected to occur.

Evidence for tectonic deformation

There are five main arguments to support interpretation of the 'chaotic' structures of Farmer Head as a product of tectonism of lithified sedimentary rocks:

(a) geometrical analysis indicates that the folds on Farmer Head are not chaotic despite their complex appearance in outcrop. Two generations can be discerned on the basis of orientation and geometry: (i) a generation of tight angular folds (Figs. 3b and 5) that plunge along a generally E–W-trending girdle; and (ii) an overprinting generation of broad, open warps that plunge along a steep NW–SE-trending girdle. The complex outcrop patterns can be explained in terms of the non-coaxial overprinting of these two fold generations (Fig. 6). In Fig. 7, the two fold generations are distinguished and plotted separately, and Farmer Head is divided into orientation domains. There is a regularity of fold orientation within each domain, and axial surfaces of the two fold generations, where determined, intersect at angles of 40–78°;

(b) brittle deformation structures genetically related to the folds, although rare, are present. These are particularly common in the noses of the tight folds, where movement has occurred on small reverse faults, in competent layers, to accommodate volume differences between the limbs and closures of the folds (Ramsay 1967, p. 401) (Fig. 5). Like the microfaults described by Farrell (1984) and others, many fault planes are seen in thin section to be filled with fine-grained material from the host rock. Locally, however, the faults are infilled with crystalline calcite, indicating brittle behaviour and the opening of voids in the rock at the time of deformation. This is not to be expected in the near-surface deformation of unlithified sediments;

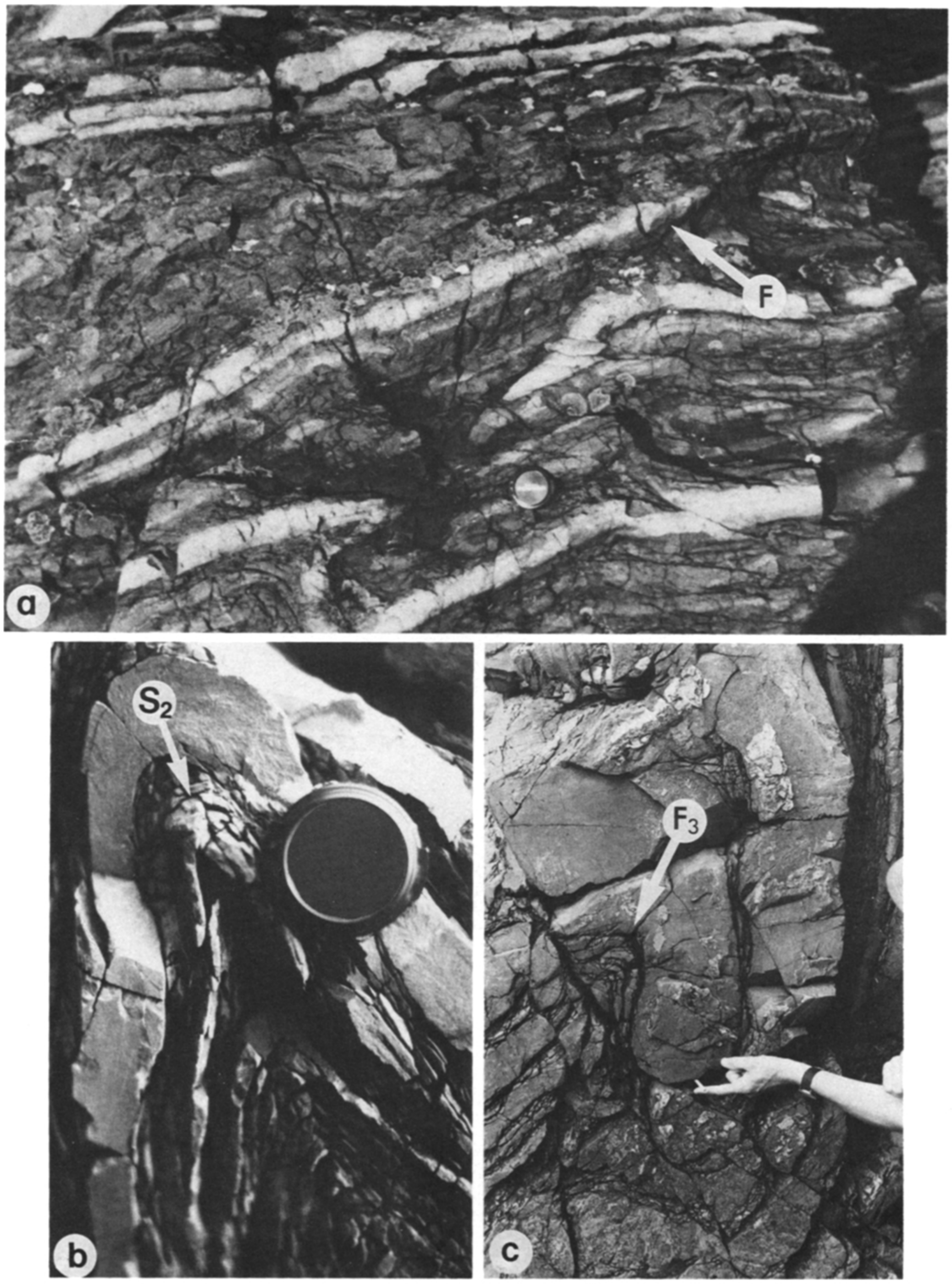

Fig. 3. (a) Ductile fault (F) and associated folds in turbiditic sandstone. Fault extends diagonally down from upper right-hand corner. Notice the 'welded' nature of the fault (i.e. the lack of any open fracture plane or vein filling). Lens cap is 55 mm across. (b) Cleavage (S_2) folded around F_3 closure. Lens cap is 55 mm across. (c) Early fold (closure near hand) refolded by F_3 in Domain I of Fig. 5.

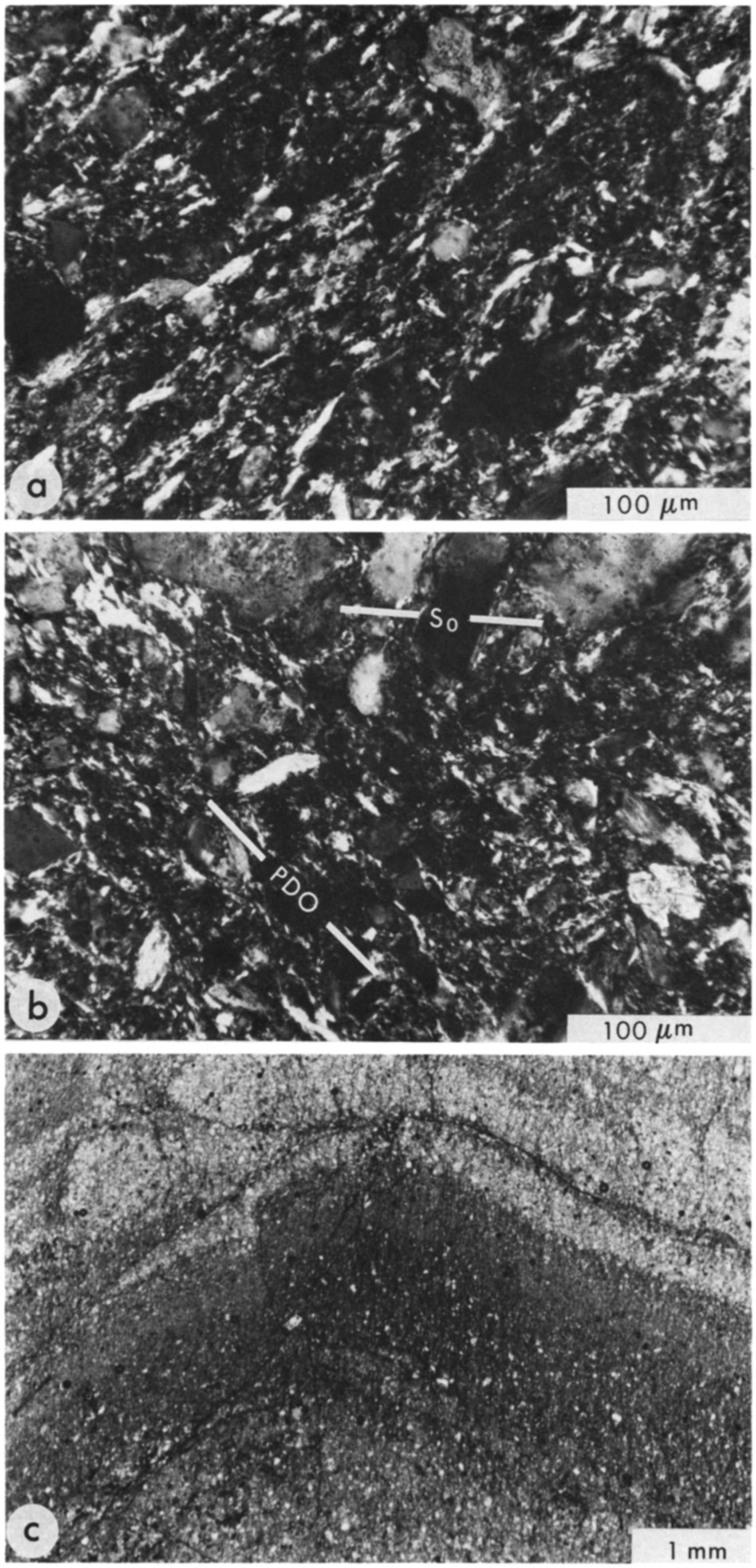

Fig. 4. Photomicrographs of foliations in tight angular folds. (a) Domainal fabric in shale layer. (b) Preferred dimensional orientation (PDO) fabric in interlayered shale and sandstone. Bedding (S_0) is parallel to top of photo. The foliation shown in (a) and (b) is folded by F_3. (c) Axial plane cleavage in nose of F_3 fold. This cleavage overprints the fabric in (a) and (b).

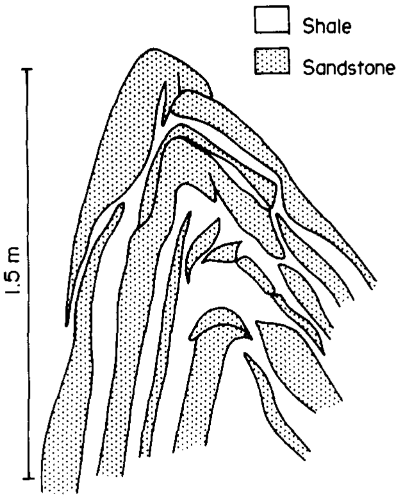

Fig. 5. Sketch of tight angular fold (F_3 of Fig. 7) showing small-scale reverse faults in the closure. These faults are locally filled with calcite.

(c) bent calcareous concretions have been found in the noses of two angular folds at the westernmost tip of Farmer Head. The massive indurated nature of the rock there and the flatness of the outcrop surface prohibit sampling, so the concretions could not be studied in detail. The concretions are oblate to prolate, and are all confined to a single bed. The fact that laminae within beds pass straight through the concretions without being deflected or attenuated indicates that the concretions were formed after the sediments had been subjected to some degree of compaction, so it is possible that the bent concretions grew after the sediments had been folded, and that their shapes were determined by the shape of the enclosing layer; however, if the concretions formed before deformation, their folding required confining pressures far in excess of those that can be reached in surface slumps. Fractures in the concretions that radiate around the fold closure also suggest a hard-rock origin for the folds, although it could be argued that they post-date folding and "owe their orientation to the pre-existing mechanical anisotropy of the folded rock" (Hobbs *et al.* 1976, p. 159). Thus, the presence of the folded concretions and their radial fractures supports the hypothesis of tectonic deformation of lithified sediments, but does not constitute concrete evidence;

(d) folds on Farmer Head deform a non-primary foliation defined by the PDO of platy minerals. In fine-grained layers the foliation is domainal, with septae of well-oriented micas separated by domains of less-affected grains (Fig. 4a). This type of fabric may be developed by deformation of unlithified sediments. A primary compactional origin is ruled out for the fabric because it is not parallel to bedding, and it passes undisturbed into sandy layers from the shale interbeds (Fig. 4b). In the more intensely folded portions of Farmer Head the angle between bedding and cleavage is low, but the bending of cleavage around fold closures can be seen, even at the outcrop (Fig. 3b).

In the noses of the tighter folds, this PDO foliation is overprinted by an axial-plane cleavage defined by seams of fine-grained material (Fig. 4c). The seams truncate the tiny calcite veins associated with the reverse faults. Because the fold axial planes are statistically parallel to

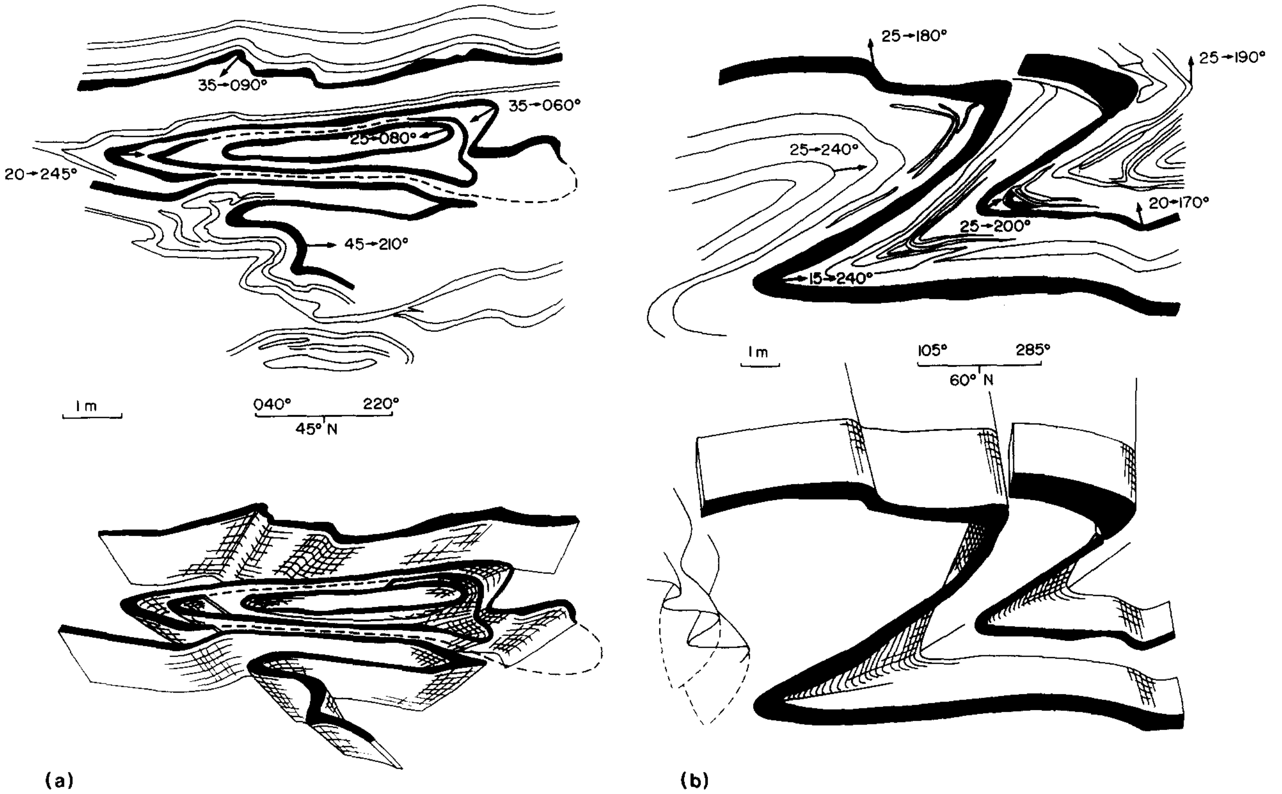

Fig. 6. Outcrop patterns and block diagrams showing doubly-plunging nature of folds. The orientations of sketch planes and fold axes are indicated on each diagram. (a) Folds in Domain II of Fig. 7. (b) Folds in Domain V of Fig. 7.

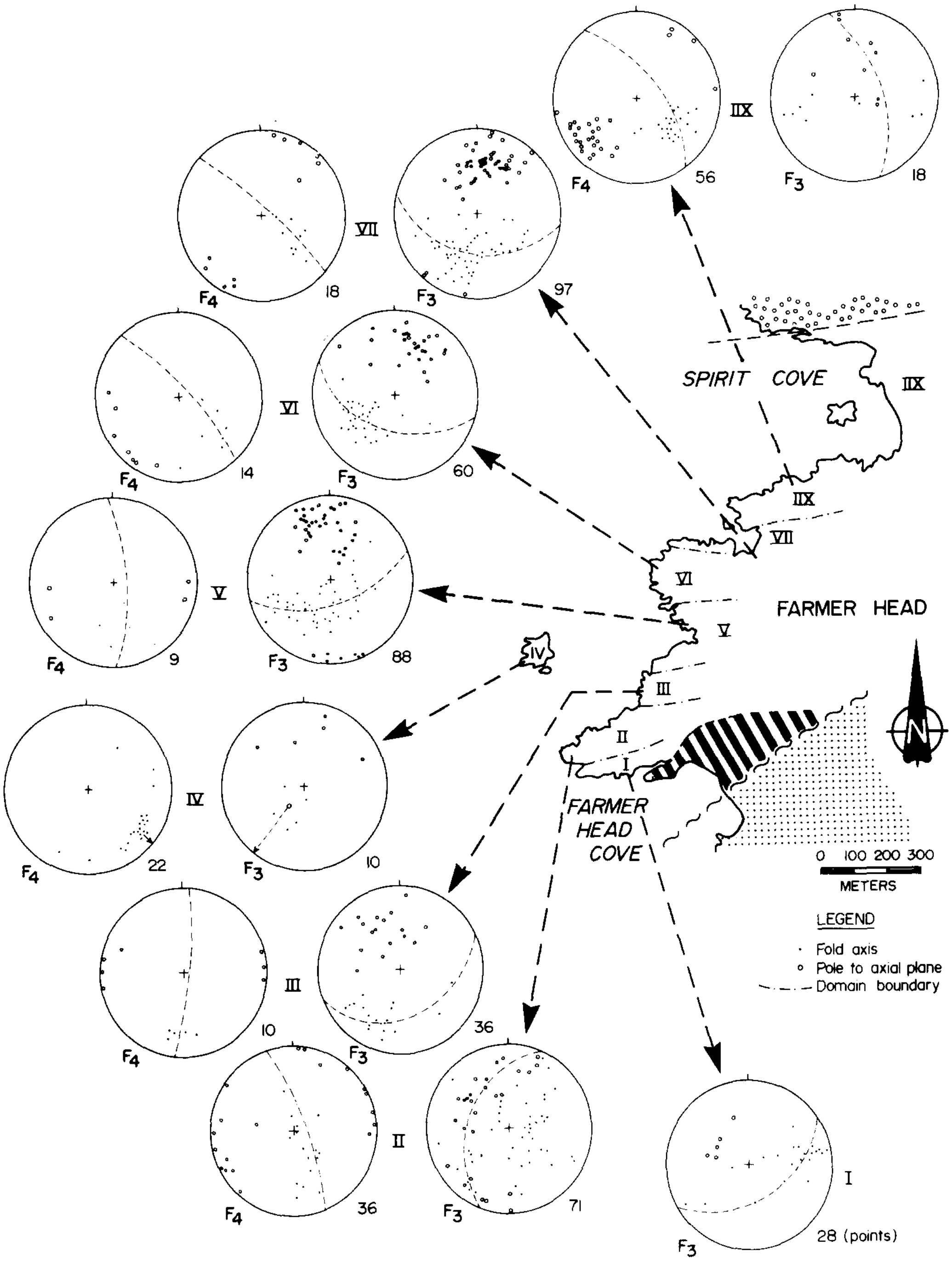

Fig. 7. Equal-area projections of fold orientations from eight domains on Farmer Head. The domains are cylindrical about the broad open warps labelled F_4. The tight angular folds are labelled F_3. Scatter in the orientation distribution is a palimpsest effect of at least one earlier fold generation. The great-circle distribution of F_3 axial planes in Domain II, for example, may have been generated by refolding around the nose of an earlier megascopic fold. The number of data points represented is given at the lower right of each projection.

regional bedding, this foliation cannot stand on its own as evidence of tectonic deformation: such a fabric could have been produced by compaction and enhanced during metamorphism. In this case, however, the axial-planar foliation overprints a non-primary foliation;

(e) the two fold generations on Farmer Head can be correlated by morphology and orientation with F_3 and F_4 folds elsewhere on New World Island. Three fold generations have been recognized on southwestern New World Island; F_1, F_3 and F_4 (Elliott 1985). No definite F_2 folds have been found, and the gap in the numbering reflects the fact that the regional cleavage (S_2) overprints F_1 folds and is folded by F_3. The F_3 and F_4 fold generations and S_2 cleavage affect all strata, including volcanic rocks, and lithologic ages vary from Tremadocian to Llandoverian (Horne 1969).

Further evidence, on Farmer Head, that the F_3- and F_4-type folds there were formed after some deformation had already occurred is provided by two exposures of tight folds refolded by F_3-type folds (Fig. 3c). The earliest foliation appears to be axial-planar to these folds and they may therefore be F_2, but the exposures are two-dimensional, and this relationship cannot be confirmed.

We can assess the evidence for and against slump folding on Farmer Head with reference to the categories of diagnostic features (1)–(5) discussed in the first part of this paper:

(1) ductile structures (folding, faulting, boudinage, pinch-and-swell) are common on Farmer Head, but it cannot be demonstrated that any metamorphic or diagenetic minerals were deformed plastically during deformation; therefore, the evidence provided by ductile structures is ambiguous;

(2) brittle structures (décollement, microfaults) are abundant, but they do not visibly offset lithic clasts or grains. They do, however, locally contain vein filling of secondary minerals, which indicates that lithification was advanced before deformation;

(3) sediment reworking or remobilization structures are absent on Farmer Head. There is no evidence of bioturbation or elutriation, and none of the concretions were observed to preserve distorted laminae. This category, then, provides us with no evidence as to the timing and cause of deformation on Farmer Head;

(4) of the two fabrics found on Farmer Head, the earlier cross-cuts layers of different lithology, and is correlated with the regional tectonic S_2 foliation. It is folded by the earlier generation of 'slump' folds. The second cleavage overprints the first and truncates calcareous veins in the rock, and must have formed after the rocks were lithified. This is strong evidence for a post-lithification origin for both generations of 'slump' folds;

(5) the turbiditic nature of the sandstones of Farmer Head indicates that basin instability was a factor during deposition; however, regional relationships show that the folds on Farmer Head were formed during the same event that affected rocks of Tremadocian to Llandoverian age, including volcanic flows. This is strong evidence for a tectonic origin for the folds.

The cumulative evidence favours the conclusion that the intense folding of sediments on Farmer Head occurred after lithification, and relatively late in the deformational history of the area. The findings of this study were applied to other 'soft-sediment' structures on southwestern New World Island, particularly the distorted strata in Horne's (1969) 'chaotic member', and, for the same reasons as given above, most of these were found to be tectonic 'hard-rock' structures. Other structures are still enigmatic, like the possible F_2 folds on Farmer Head, and rootless folds elsewhere that are overprinted by the regional cleavage. Such folds, however, are minor in scale and distribution.

CONCLUSIONS

The folds on Farmer Head are a good example of the kind of structures that need to be studied carefully in order to most accurately interpret the post-depositional history of a region. Because of their morphology, the folds were thought originally to be slump folds, but a combination of geometric analysis, regional correlation and microscopic examination of fabrics led finally to their interpretation as post-lithification tectonic folds, and to a reassessment of earlier ideas about the regional geology.

In general, the most 'obvious' origin of deformation structures in a sequence of sedimentary rocks may not be the most likely. Only close attention to details such as overprinting by sediment reworking or remobilization structures, the presence of deformed minerals, the nature of fabrics and the spatial distribution of structural elements, will provide the clues needed to constrain the timing and nature of deformation. Any, or all, of these details are significant, but very few can stand on their own. Taken together, they lead to the most accurate interpretation, even if the final conclusion must be that a definitive interpretation cannot be derived from existing data.

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