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FIELD TRIP GUIDE

Syn-sedimentary high-strain zones versus post-lithification Shear zones in the Albert Formation of southeastern New Brunswick

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INTRODUCTION AND PURPOSE

The idea for this field trip stemmed from discussions that arose from a talk presented by my co-workers and I at the 2004 GAC-MAC joint annual meeting in St. Catharines, Ontario, entitled "Strain features and deformation mechanisms in syn-sedimentary high-strain zones" (Wilson et al. 2004). Structures described in that talk have some characteristics of syn-sedimentary high strain zones resulting from mass wasting processes that have previously been described in the literature. However, discrimination of such structures from those formed in 'tectonic' shear zones after the sediment has become completely lithified is not straightforward (see below). Such discrimination is important, for a number of reasons. The presence of deposits resulting from mass wasting processes can be used to infer the presence of an unstable slope during deposition, and the orientations of structures within the deposit may be used to infer orientation of that slope (Jones 1939; Corbett 1973; Woodcock 1979; Bradley and Hanson 1998). Mass wasting deposits may bring coarser proximal sediment into environments of distal fine-grained deposition, leading to wedge-out of coarse-grained slumps into fine grained downslope material, forming lithologic hydrocarbon traps (Galloway 1998). Mass wasting deposits may also provide information on the mechanisms that triggered them, leading to improved understanding of the sedimentary environment and/or tectonic history of an area. Syn-sedimentary slump deformation is also interesting from a structural point of view, because of the unique conditions (low temperatures and very low confining pressures) under which it occurs, allowing study of deformation mechanisms and processes active at the sediment/water interface and in the shallow subsurface. In regional tectonic studies it is critical to discriminate high strain zones formed by syn-sedimentary mass wasting processes from those formed in fault or shear zones, in order to avoid errors in interpreting regional kinematics and tectonic history.

The problem of establishing criteria to discriminate between syn-sedimentary high strain zones and post-lithification shear zones has been extensively discussed (e.g.Williams et al. 1969; Helwig 1970; Davies and Cave 1976; Woodcock 1976; Howells et al. 1977; Lisle 1977; Fitches and Maltman 1978; Woodcock 1978; Maltman 1984; 1994; Pickering 1987; Elliott and Williams 1988; Blewett 1991; Paterson and Tobish 1993). A number of potential criteria for discriminating syn-sedimentary mass wasting deposits from post-lithification tectonic shear zones have been suggested. However, problems arise because many criteria are not universally accepted, and those that are accepted are uncommon and not widely distributed. The criteria used may be divided into two broad types; those related to timing of the high-strain zone relative to sedimentation, and those related to timing relative to processes of lithification.

Criteria related to timing relative to sedimentation aim to use cross-cutting features of sedimentary origin to establish whether deformation occurred during sedimentation or not. All workers agree that the presence of an erosional surface at the top of a high-strain zone is clear evidence that the zone was syn-sedimentary. The problem lies in unambiguously identifying an erosional surface. Truncation of underlying folded beds is not in itself adequate, as tectonic shear zones may also truncate beds (e.g. Elliott and Williams 1988). Some criteria that have been suggested include surfaces that are burrowed, especially if burrows cut folds, and sand dykes, especially when associated with sand volcanoes (e.g. Elliott and Williams 1988). While the presence of an erosional surface at the top of a high-strain zone is persuasive, its absence does not necessarily preclude a broadly syn-sedimentary origin, as weak sediment layers at depth may take up some deformation related to mass wasting occurring at the sediment surface (e.g. Coniglio 1986).

Criteria related to timing of deformation relative to processes of lithification are more complex, because lithification consists of several subprocesses (diagenesis, consolidation) and occurs over an extended period of time, and because much information about the lithification process will have been lost in a completely lithified rock. For these reasons, such criteria are considered less useful. These criteria include evidence of brittle structures (especially veins) and evidence of high water content during deformation. Evidence from foliations also falls into this category. For example, if folds are cut by a bedding-parallel crenulation cleavage that can be related to compaction of the initial sediments, those folds must have formed prior to significant compaction, before the sediment was lithified (Farrell and Eaton 1988).

The aim of this field trip is to examine structures of both syn-sedimentary and post-lithification origin in the alluvial-fluvial-lacustrine Albert Formation of southeastern New Brunswick. The origin of inferred syn-sedimentary structures and possible criteria for discriminating syn-sedimentary mass wasting deposits from post-lithification tectonic shear zones will be discussed.

REGIONAL CONTEXT

The rocks examined in this field trip form part of the Upper Palaeozoic Maritimes Basin (Roliff 1955; Williams 1974). The Maritimes Basin is the largest intermontane basin in the Appalachian mountain chain, covering around 148,000 km^2, of which approximately two-thirds is offshore in the Gulf of St. Lawrence (Figure 1). In southern New Brunswick, rocks of the Maritimes Basin lie unconformably upon basement of several peri-Gondwanan terranes assigned to the Avalon Zone of the Appalachian Orogen (e.g. Williams 1979; Barr and White 1996). The basement rocks are cut by a number of northeast-trending shear zones that were reactivated as brittle faults during the late Devonian and Carboniferous (e.g. Leger and Williams 1986). The Maritimes Basin is divided into a number of subbasins. The subbasins are of variable geometry, and include linear grabens, half-grabens, fault-bound wedges or rhomboid pull-apart basins (St. Peter 1992). The subbasins are separated from each other by exposed basement uplifts or by condensed late Devonian-Carboniferous sections overlying shallowly buried basement uplifts (St. Peter 1992; 1993; 2001); the subbasins and intervening uplifts in southeastern New Brunswick are shown in Figure 2. The rocks examined in this field trip are within the Moncton Subbasin. The subbasins within the Maritimes Basin show evidence of basin inversion recorded by the presence of a number of unconformities and disconformities within the sedimentary sequence. The principal periods of inversion occurred following deposition of the Horton Group in late Tournaisian time and during the late Carboniferous or early Permian Alleghanian orogeny (e.g. Ruitenberg and McCutcheon 1982; St. Peter 1992; 1993). Proto-Atlantic rifting of the Maritimes Basin began in the Triassic, or possibly late Permian (e.g Greenough 1995), and led to formation of the Mesozoic Fundy Basin.

The stratigraphy of the Maritimes Basin has been summarised by a number of authors, including Kelley (1967), Howie and Barss (1974; 1975), Williams (1974) and van de Poll (1995). In the field trip area, the strata can be divided into six groups, in ascending order the Horton, Sussex, Windsor, Mabou, Cumberland and Pictou groups (Norman 1941a;1941b; Gussow 1953; Carter and Pickerill 1985; St. Peter 2002; Keighley 2005; Wilson 2003; 2005). The stratigraphy of the field trip area is outlined in Table 1. This field trip concentrates on rocks of the alluvial-fluvial-lacustrine Albert Formation.

The Albert Formation forms part of the basal Horton Group, and is of early Tournaisian age. It is economically important because it contains exploitable quantities of natural gas in the area northeast of the town of Sussex. Two wells are currently in operation, providing gas for the processing mill at the Potash Corporation of Saskatchewan mine at Penobsquis. The Albert Formation consists of three members, in ascending order, the Dawson Settlement, Frederick Brook, and Hiram Brook members (e.g. Greiner 1962; 1974; Macauley *et al*. 1984; Carter and Pickerill 1985a; 1985b; van de Poll 1995); it should be noted that these members are likely to some degree lateral equivalents. The Dawson Settlement Member consists mainly of coarse- to fine-grained sandstone with intercalations of shale; the Frederick Brook Member consists of kerogeneous and dolomitic shale (including high-grade oil shale) and minor sandstone; the Hiram Brook Member consists of kerogeneous and calcareous siltstone, shale and sandstone. Field mapping and interpretation of seismic reflection profiles shows that in the study area, deposition of the Albert Formation was accommodated by normal-sense movements on northeast- and east-trending faults (Wilson 2003).

Deformation structures identified in the field and in seismic reflection profile interpretations generally comprise high-angle brittle faults, in many cases multiply reactivated, and kilometre-scale open folds, at least away from major fault zones. Within the Albert Formation, anomalous bedding-parallel ductile high-strain zones are observed at some localities. These are interpreted as syn-sedimentary high-strain zones related to mass wasting processes, and form the object of this field trip.

FIELD TRIP

The location of stops refers to the green kilometre markers posted along the highway. The generalised geology of the field trip area showing the location of the field trip stops is shown in Figure 3.

For the first two stops, the road runs close to the trace of the Kennebecasis River Fault. In these outcrops, bedding is steep to slightly overturned, and generally facing northwest. Proximity to the fault has led to the formation of folds of tectonic origin. At stop 4, several anomalous bedding-parallel ductile high-strain zones of inferred syn-sedimentary origin are exposed. At stop 3, deformation of both ‘tectonic’ and syn-sedimentary origin is observed. Stop 5 is a good place to illustrate some of the regional stratigraphic relationships.

Safety issues

All of the stops for this field trip are along New Brunswick highway 1, between the village of

Norton and town of Sussex. Please note this is a busy four-lane highway, so wear reflective clothing, take care when getting in and out of the vans, and be especially careful when crossing the highway. Some of the rock exposures are several metres high, and hard hats should be worn. Be aware of overhangs, and keep off unstable benches. Some of the exposures comprise steeply-dipping shales, and these are deteriorating and have steep scree-slopes of shaly debris at their base. Be careful when walking on these slopes. A limited number of hard hats and traffic vests will be available, but participants should preferably bring their own.

Stop 1: 177 km. 'Tectonic' deformation of the Albert Formation

Travelling eastbound on Highway 1, this stop is on the right hand side immediately after the exit for Norton and Cassidy Lake, just after the 177 km marker.

At this locality shales, sandstones and grits of the Albert Formation are exposed, and folded into a large-scale, westward-verging, shallowly southward-plunging anticline. In the core of the major fold, minor folds are exposed, and are superficially similar to folds attributed to syn-sedimentary deformation processes elsewhere along the highway. However, a number of observations suggest that they are parasitic folds related to the larger structure. Firstly, the folds do not occur in a stratigraphic, sharply-bound layer, with undeformed strata lying both above and below. Undeformed rocks may be traced laterally into deformed rocks. Secondly, there is a reversal in way-up across the zone of minor folds. Thirdly, constructions of the axis and axial plane of the large-scale fold based on measurements of bedding plot within the fold hinge and axial plane populations of the minor folds. Fourthly, the fold hinge and axial plane measurements of the minor folds both show point-maximum distributions, while in high-strain zones inferred to have formed through syn-sedimentary processes, axial plane measurements plot on a great-circle girdle (see under stop 4).

Deformation at this locality is thought to relate to the northeast-trending Kennebecasis River Fault, the surface trace of which lies immediately northwest of the highway (Figure 3). The fault brings Albert Formation rocks in the hangingwall over Mabou Group rocks in the footwall. Although the fault is northeast-trending, the axial plane of the overturned fold at this locality trends approximately 020°. If the fold is en-echelon with respect to the fault, the sense of asymmetry indicates dextral movement. It is likely that the movement on the fault was somewhat oblique, with a strong component of southeast-side-up movement. Since the fault juxtaposes Albert rocks against Mabou rocks, at least part of the deformation must post-date the Mabou Group, that is, must be later than Namurian A or so.

Stop 2: 180 km. 'Tectonic' deformation of the Albert Formation

Travelling eastbound, pull off onto the shoulder after the 180 km marker and before the crash barriers begin on the right hand side. Cross the eastbound lanes of the highway (CARE!), and walk eastwards down the rough track at the side of the small hill in the highway median. Skirt around the hill to the small outcrop on the north side of the median. This is stop number 2.

Here steeply-dipping, northeast-striking, northwest-younging rippled sandstones are juxtaposed against steeply-dipping, northeast-striking southeast-younging rippled sandstones across a northtrending fault of inferred sinistral displacement. Further to the west, a similar fault of inferred sinistral displacement brings more northwest-younging rocks against the southeast-younging ones. The switches in younging direction across the faults are explained as the result of juxtaposition of northwest-younging and southeast younging limbs of northeast-trending tight folds by the faults. The presence of such folds is thought to be related to the Kennebecasis River Fault. Farther to the west, the rocks are cut by a northeast-trending fault. Drag of bedding into this fault suggests that the fault is of reverse displacement.

Stop 3: 182 km. 'Tectonic' and syn-sedimentary deformation

Travelling eastbound, pull off onto the shoulder just after the 182 km marker. The long outcrop on the right hand side of the road is stop number 3.

The rocks here are steeply dipping, and the shaly nature of the rock exposed here means that the outcrop is rapidly deteriorating. Please be careful of your footing here, and please try to damage the outcrop as little as possible. Several spectacular features (e.g. Figure 4a) have already been lost.

We will park at the southwest end of this outcrop. Boudins of inferred syn-sedimentary origin may be observed. The examples shown in Figure 4a no longer exist, but other examples are visible towards the top of the outcrop (Figure 4b), and some examples may be found in the shale scree at the base of the outcrop. The boudins are generally 15-25 cm in diameter, are up to at least several metres in length and typically have a mullioned appearance. Some examples show a strong fissility perpendicular or sub-perpendicular to the long direction of the boudins, which may break up into discoids on the order of 1-5 cm thick. In cross-section boudins may be near-circular, elliptical, aerofoil-shaped, or complex, although they are generally somewhat flattened in the plane of master bedding; aspect ratios vary from approximately 1.1:1 to 5.2:1 (Figure 5). When sectioned along their long direction, the boudins show a cm-scale parallel lamination cut at a high angle by normal-sense microfaults (Figure 5a). When sectioned perpendicular to their long direction, the boudins show complex internal fold patterns in many cases (Figures 5b to 5d and 5f). In one example a sheath fold is observed with its axis parallel to the long axis of the boudin (Figure 5d and 5e). The matrix to the boudins consists of grey fine sandstone, siltstone and mudstone containing a rough fissility parallel to master bedding, breaking the rock into rough sheets 1-3 cm thick. No deformation is visible within the matrix at the meso-scale. However, thin section observations show that the matrix is intensely deformed, with centimetre scale folding with axial planes parallel to bedding, and disaggregation of layers (Figure 6). The boudins are thought to be detached remnants of folded layers that have been further folded and sheared during syn-sedimentary deformation (see under stop 4).

A little to the east of the boudin locality, recumbent folds with hinge-lines gently plunging towards the south may be observed (Figure 7). The hinges of these folds are broken, and the folds are assumed to be tectonic in origin. No other tectonic folds of similar orientation are known in this part of the basin, and their origin remains somewhat enigmatic.

A little further to the east, a surface with spectacularly preserved sand volcanoes may be seen. The sand volcano-bearing surface lies above a bedding-parallel zone of folding. The folding becomes less coherent upwards, until just below the sand volcano surface the rock consists of rafts and blocks of shale floating in a matrix of sandstone. The upper part of the deformed unit is cut by numerous sand dykes. One of the shale blocks in the upper part of the unit is cut by a sand dyke that may be traced upwards into the sand volcano-bearing horizon (Figure 8). This provides evidence that the deformation here occurred prior to the sedimentation of the overlying layers, that is, at the sediment-water interface. Sand volcanoes on the top surfaces of syn-sedimentary slumps have been described from the Namurian of Ireland by Gill and Kuenen (1957).

Approximately 40 paces to the east of the sand volcano locality, another bedding-parallel high-strain zone can be seen. Here refolded isoclinal folds may be observed (Figure 9). The upper contact of the high-strain zone may be examined in detail. Above the folded strata, a thin layer of undisturbed fine sandstone may be seen. The contact surface is lumpy in appearance, and in places the deformed underlying strata may be seen poking up through the undeformed layer. There is no evidence of any kind of tectonic contact here, and the contact is considered to be erosional. This is further evidence that deformation in this case must have occurred at the sediment-water interface.

Approximately 140 paces further to the east, another bedding-parallel high-strain zone may be observed.

Because it can be shown here that deformation occurred at the sediment-water interface, it is suggested that the deformation is related to slope failure and mass wasting during deposition, i.e., the high-strain zones represent syn-sedimentary gravity slumps.

Stop 4: 185 km. Syn-sedimentary high-strain zones

As we drive from stop 3 to stop 4, note the rocks we pass on the way. We are crossing over a major northeast-trending anticline in the Albert Formation. Travelling eastbound, stop 4 is the large outcrop on both sides of the highway just after the 185 km marker. Pull off onto the shoulder at the eastern end of the outcrop.

Here there are four excellent sections exposed on either side of the highway. Wear traffic vests at this stop, and use caution when crossing the highway. Note that the outcrop is deteriorating. Look out for overhangs, and wear hard hats. Keep off the benches on the south-facing sections, as these are unstable. On the south side of the eastbound highway lanes, an ATV track runs along the shoulder. Keep an eye out for ATVers.

We will park at the northeast end of this outcrop. Here the Albert Formation dips gently towards the northeast. As we proceed southwestwards and down-section, medium- to coarse-grained, wave-rippled sandstone of the Hiram Brook Member give way to finely interlayered units of organic and dolomitic shale, and packages of mixed shale, siltstone and sandstone of the Frederick Brook Member. We will walk out all four sections here, and discuss our observations.

A stereoplot of measured fold hinge and axial plane orientations from these outcrops is shown in Figure 10. Note that fold hinges plot in a point maximum distribution, being shallowly plunging to the northeast or southwest, and fold axial planes vary around the hinge orientation. Boudins are parallel to fold hinges.

Section 1 (south side of eastbound highway lanes)

Within the Hiram Brook Member, there is generally little evidence of deformation. However, some sandstone beds contain disrupted and contorted beds and laminae that may be related to modification of the layers by sediment grain flows.

Within the finely interleaved organic and dolomitic shales of the Frederick Brook Member, numerous bedding-parallel high-strain zones can be observed. These differ from the zones previously observed at stop 3 in both scale and style. Here the high-strain zones commonly show a fold-thrust geometry (Figure 11a), with folds on the order of 1-2cm in wavelength and amplitude. Contacts between deformed units are commonly difficult to define, as in many cases the high-strain zones are stacked, with no undeformed strata between them. In general, lower contacts appear to be detachment surfaces with no truncation of underlying beds (Figure 11b), although examples of truncation do exist (Figure 11a). Upper contacts generally show deformed strata truncated by overlying strata that may or may not be deformed. Others show truncation of undeformed overlying strata against the upper contact of the high strain zone, showing that in these cases deformation did not take place at the sediment-water interface (Figure 11c). In some places along the north side of the highway median, folded bedding-parallel siderite veins may be seen (Figure 11d). These lines of evidence suggest that at least some of the deformation in these units occurred at depth, and after some degree of diagenesis had occurred. However, deformation related to surficial mass-wasting may propagate to depth somewhat (Coniglio 1986), so such observations do not preclude a broadly syn-sedimentary origin for the deformation. While some of the contacts in the shales appear to contain thin layers of fault gouge, in most cases gouge is absent, and in any case it must be demonstrated that the gouge zones formed at the same time as the deformation within the high-strain zones for a tectonic origin for the high-strain zones to be proven.

Towards the west end of the outcrop, a typical intraformational sand-shale high-strain zone may be observed. A similar zone is pictured in Figure 12a. The zone is on the order of 1 m thick, and consists of folded and contorted bedding layers with undeformed strata lying both above and below. Again, the lower contact is a detachment surface with no apparent truncation of underlying layers, while at the upper contact deformed strata within the high-strain zone are truncated by overlying undeformed strata (Figure 12b). Again, there is no evidence that the contact here is tectonic, and it is therefore interpreted as an erosional contact.

We will cross the highway here (CARE!), and walk up-section along the south side of the median.

Section 2 (south side of median)

At the west end of this section, open folds with wavelengths of a few metres and amplitudes of a metre or two can be observed, illustrating the variation in scale of folds (Figure 13a). The folds are truncated by overlying strata, again suggesting an erosional surface. There is also a tighter fold that propagates through the truncation surface, but is truncated at a higher surface. This suggests that slumped strata are not necessarily stable, and may slump further after they have come to rest. Also at this locality, boudinaged sandstone and silt/mudstone layers may be observed (Figure 13b). The long axis of the boudins is parallel to fold axes within the high-strain zones.

As we continue to walk up-section, keep an eye out for further high-strain zones, with spectacular isoclinal folds with axial planes recumbent in the reference frame of bedding, and re-folded isoclinal folds. Also look across the highway lanes to the opposite outcrop. A series of open intraformational folds, upright in the bedding reference frame, can be observed (Figure 14). Contrast these with the refolded fold observed at stop 3 (Figure 9). This shows the variability in style and orientation of folds. We will walk to the east end of the section, and cross the median via the ATV track at the end of the outcrop.

Section 3 (north side of median)

As we walk down-section again, look closely at the finely interleaved organic and dolomitic shales. In some cases, bedding-parallel veins of siderite are folded (Figure 11d). This shows that deformation occurred after some degree of diagenesis had occurred.

At the west end of this section, folded shale, red siltstone and sandstone is exposed. In places, detached fold hinges and aerofoil-shaped hinge fragments may be seen within a matrix of deformed shale (Figure 15). These structures are thought to be precursors to the boudins seen at stop (Figures 4 and 5).

Cross the westbound lanes of the highway here (CARE!).

Section 4 (north side of westbound highway lanes)

At the west end of this section, bedding-parallel high-strain zones with fold wavelengths and amplitudes of a few tens of centimetres may be seen. Here the folds are tight to isoclinal, and gently inclined to recumbent in the reference frame of bedding. Samples of folds from this locality show an incipient axial planar transposition fabric defined by microfolds and microfaults in the fold core (Figure 16b and c). In one case, muddy material in the fold core has been injected into the fold hinge, and parasitic folds are of the opposite sense than would be expected (Figure 16a). The boundary between the muddy material in the fold core and surrounding material is very sharp, suggesting a strong rheological contrast. These observations suggest that there was still a considerable amount of fluid in the rocks when deformation occurred, that is, that significant consolidation had not yet taken place.

Further to the east, a spectacular example of truncated folds can be seen in mixed shale and fine sandstone (Figure 17). Refolded folds may be seen here, with the F2 generation being upright to steeply inclined in the reference frame of bedding.

Up-section, further examples of deformed organic/dolomitic shales can be seen.

Stop 5 (if time): 190 km. Regional geological relationships

At this stop, polymictic pebble and cobble conglomerate assigned to the Hazel Hill Member of the Round Hill Formation (Sussex Group: see Table 1) disconformably overlies organic shale of the Albert Formation (Horton Group). The disconformable contact is marked by a soil horizon, and can clearly be seen at this locality. Slickensided calcite veins provide some evidence that the contact may have been reactivated as a fault. In the McCully gas field to the northeast of this stop (Figure 3), the contact between Sussex Group and Horton Group rocks is an important angular unconformity. The unconformity/disconformity marks a period of post-Horton, pre-Sussex basin inversion.

In the distance to the northwest, the headframe of the Potash Corporation of Saskatchewan potash and rock salt mine at Penobsquis can be seen. The mine exploits a northeast-trending salt wall composed of evaporites of the Cassidy Lake and Clover Hill formations (Windsor Group: see Table 1). Rocks of the Cumberland Group are folded into a forced anticline above the salt structure, and are cut by salt-linked faults. Thus the formation of the salt structure is thought to relate to a period of contraction and basin inversion that occurred after deposition of the Cumberland Group, that is, later than Westphalian A (Wilson 2003).

After this stop, vans will leave to take participants to the airports. Thanks for coming on this field trip, and we hope you enjoyed your stay in New Brunswick.

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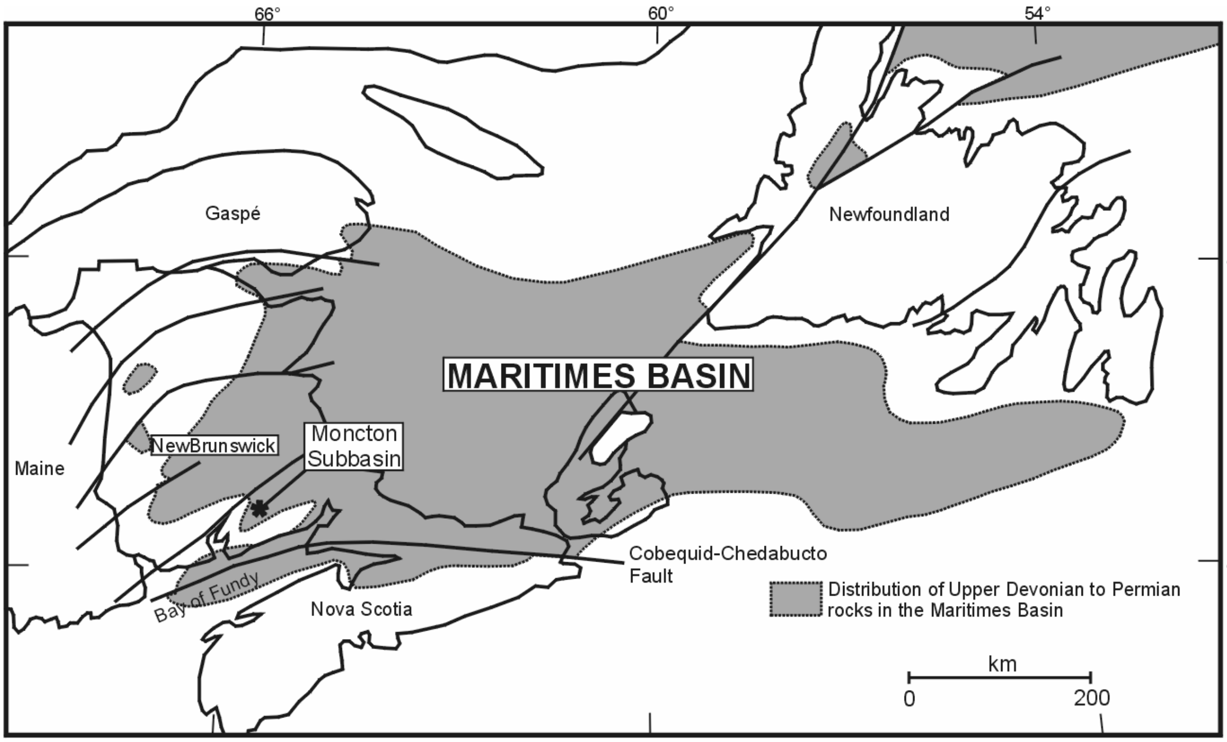

Figure 1: Map showing the areal distribution of the Maritimes Basin. Redrawn after Martel (1987).

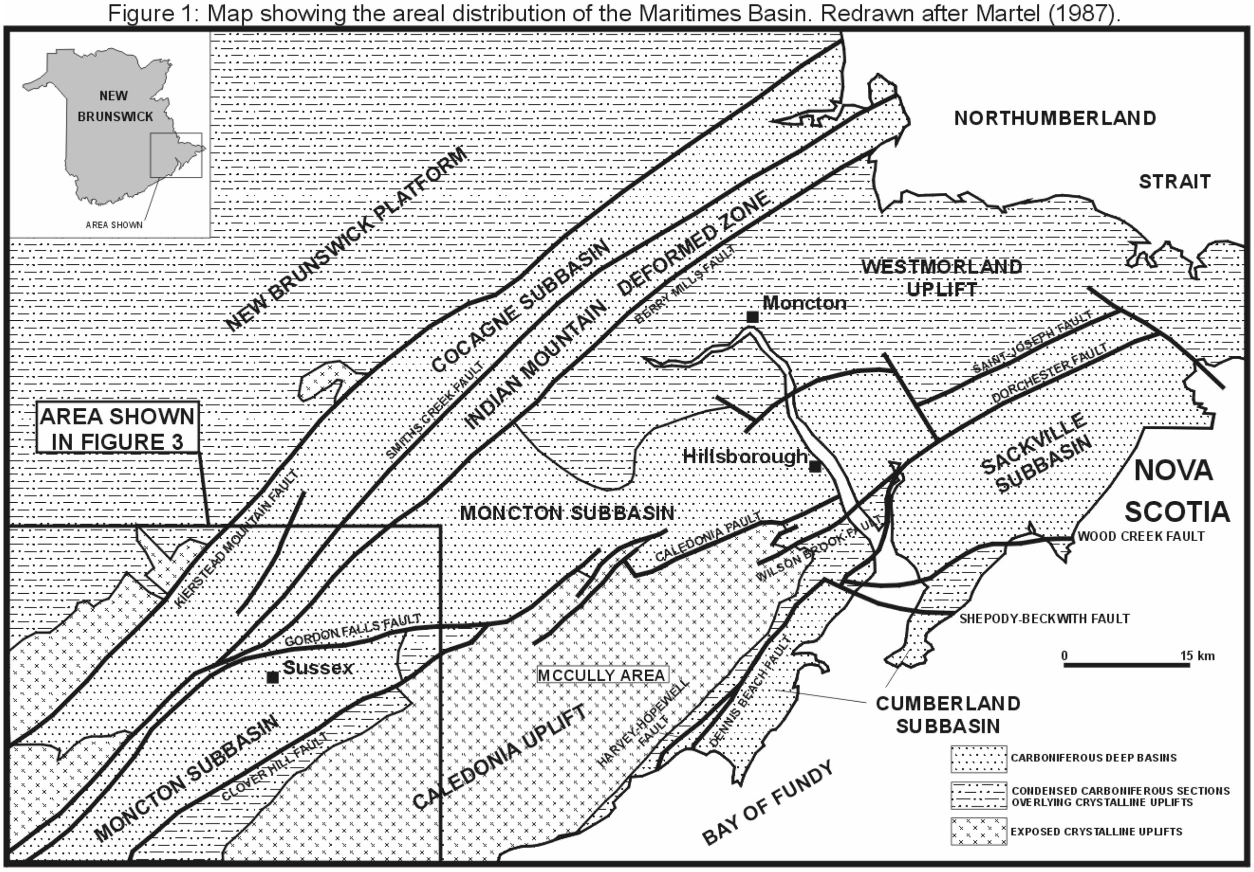

Figure 2. Map of the Maritimes Basin, showing the subbasins, the intervening uplifts and the major fault systems. Redrawn after St. Peter 2001.

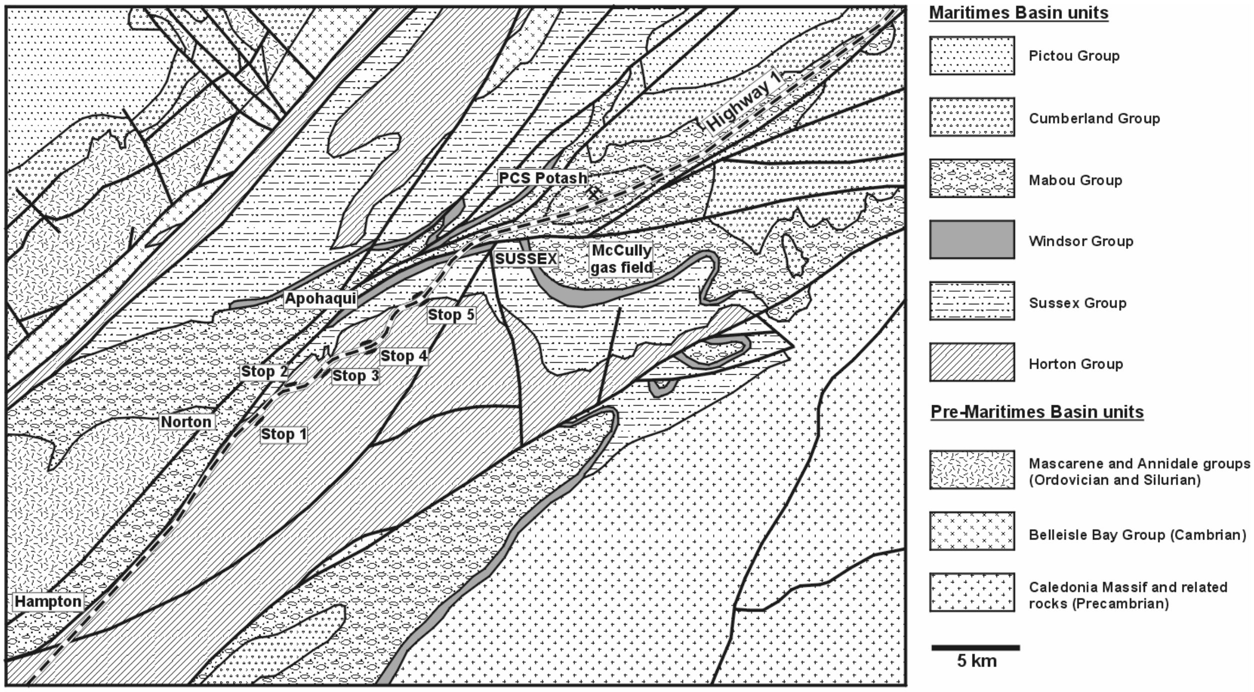

Figure 3. Simplified geological map of the western Moncton Subbasin, showing the stops for this field trip.

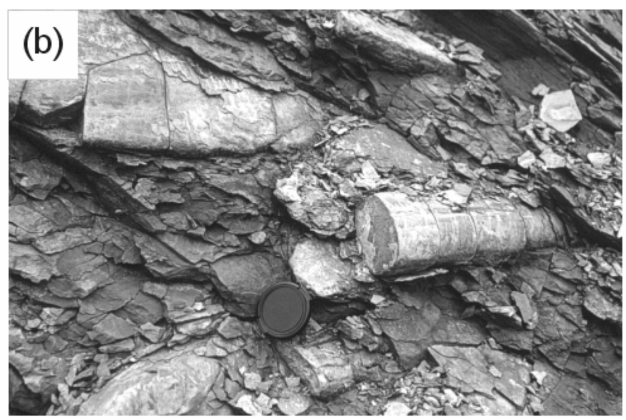

Figure 4. Boudinage in high strain zones at stop 3. (a) Isolated boudins parallel to bedding, in a matrix of deformed sandstone and shale. Due to deterioration of the outcrop, these examples no longer exist. However, similar examples may be observed in the shale pile at the base of the outcrop.
(b) Isolated boudins in a matrix of deformed shale, cut by regularly spaced fractures forming a discrete fabric. These examples are found near the top of the outcrop.

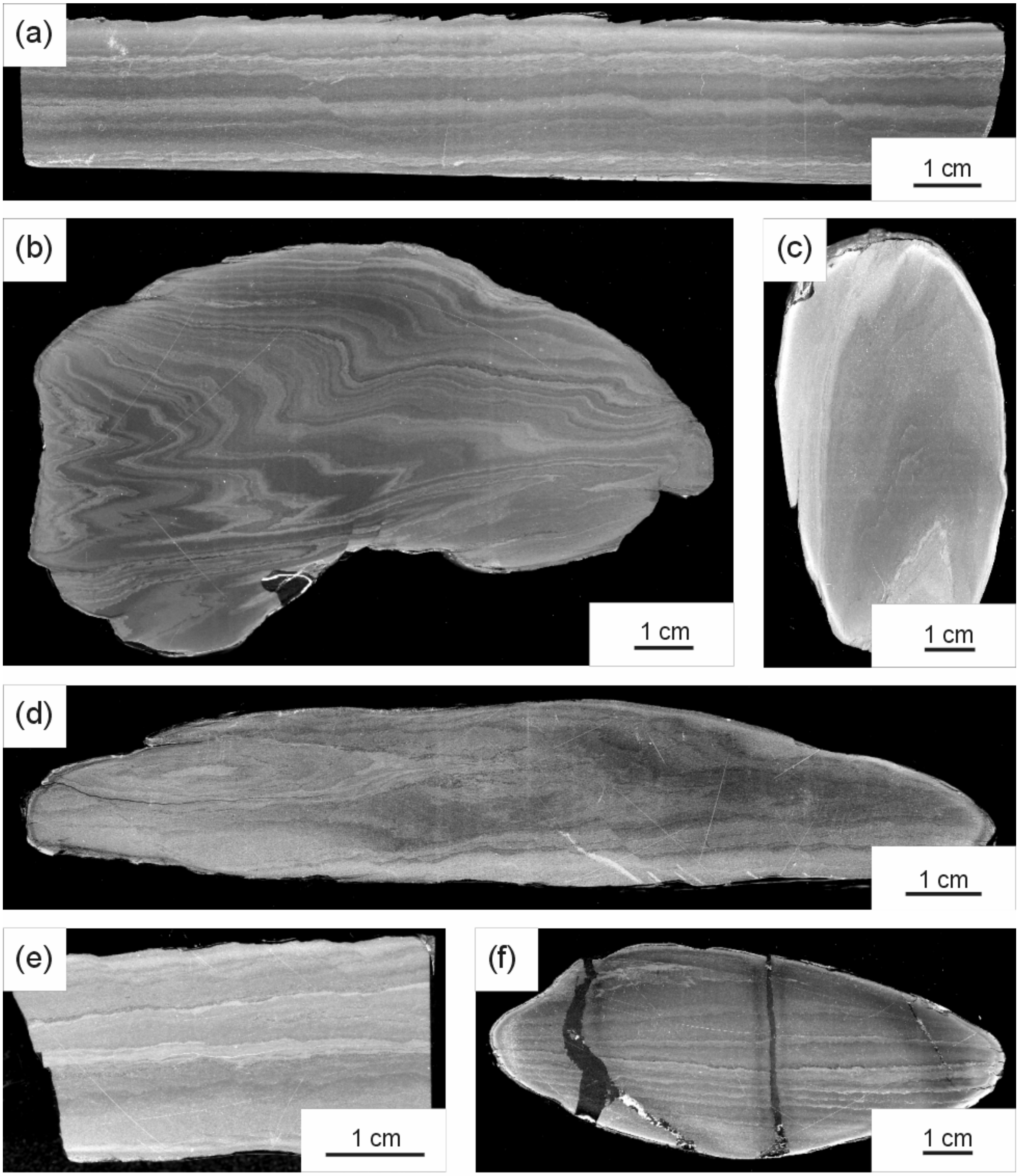

Figure 5. Polished slabs of boudins; (a) and (e) are cut parallel to the long axis of the boudin, (b), (c), (d), and (f) are cut perpendicular to the long axis. (a) Parallel lamination cut by normal-sense microfaults. (b) Complex internal folding. (c) Fold hinge enclosed within a boudin. (d) Sheath fold within a boudin (in top left corner of slab). (e) Slab cut perpendicular to the slab shown in (d), showing the sheath fold closing towards the left hand end of the slab. (f) Slab showing simple parallel lamination. Black areas within the slab are cracks in the sample filled with epoxy.

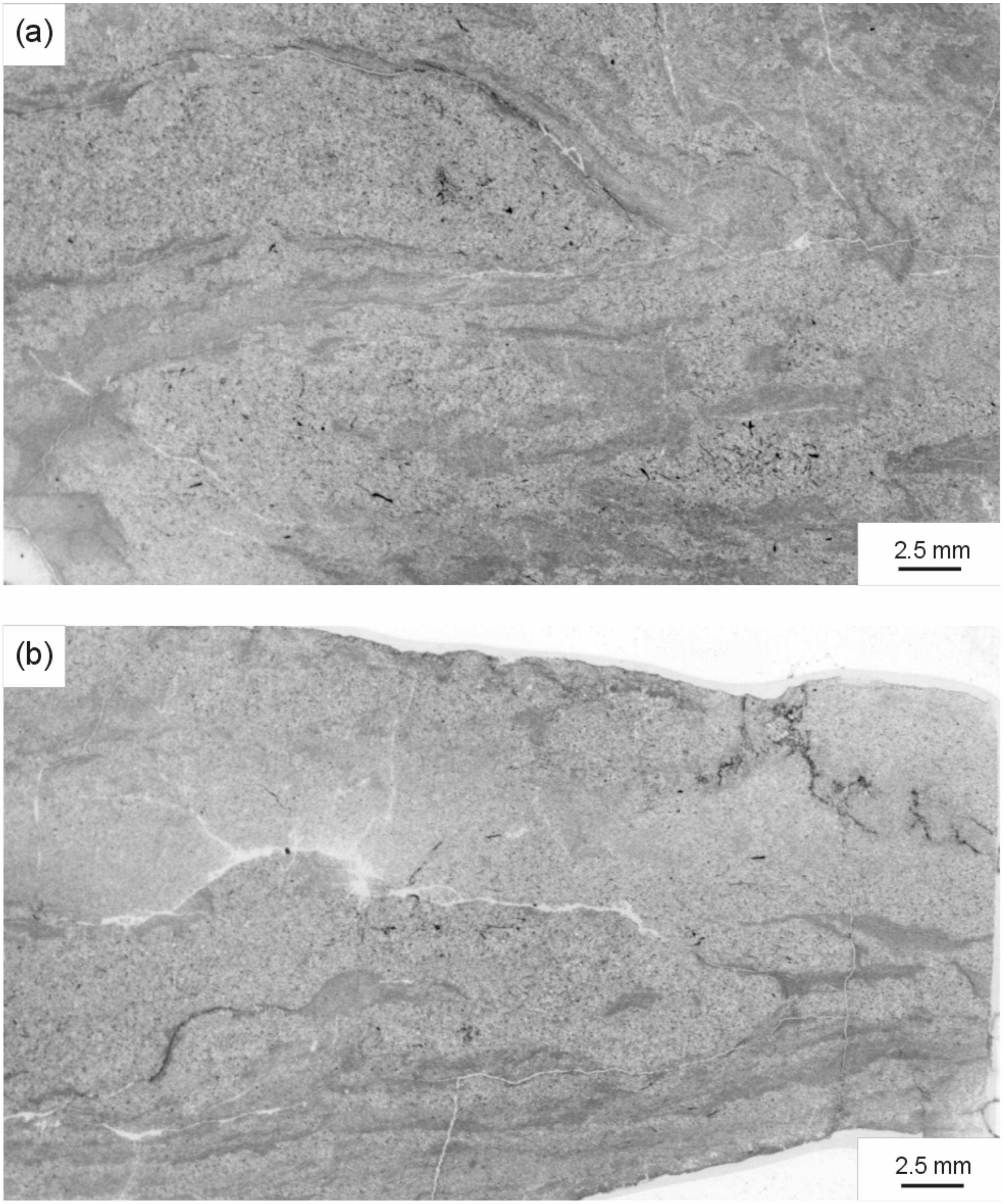

Figure 6. Deformation in the matrix to the boudins pictured in Figure 4a. (a) Folds with axial planes sub-parallel to the rough fissility developed in thematrix, which is in turn sub-parallel to master bedding. (b) Disaggregation of fine-grained layers in the matrix.

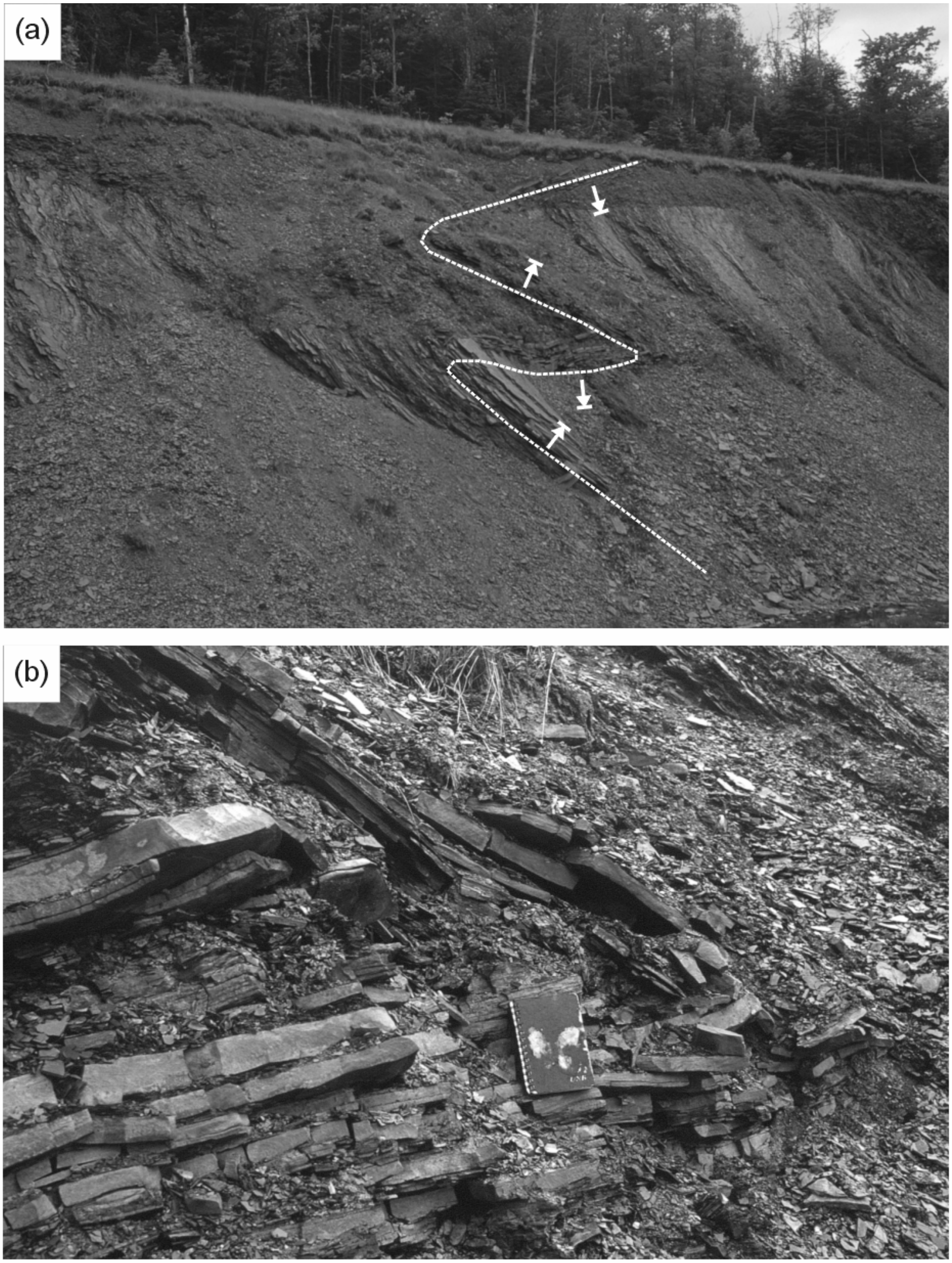

Figure 7. (a) Tight, shallowly southward-plunging, recumbent to gently inclined folds at stop 3. Inferred way-up shown. (b) Detail of broken fold hinge.

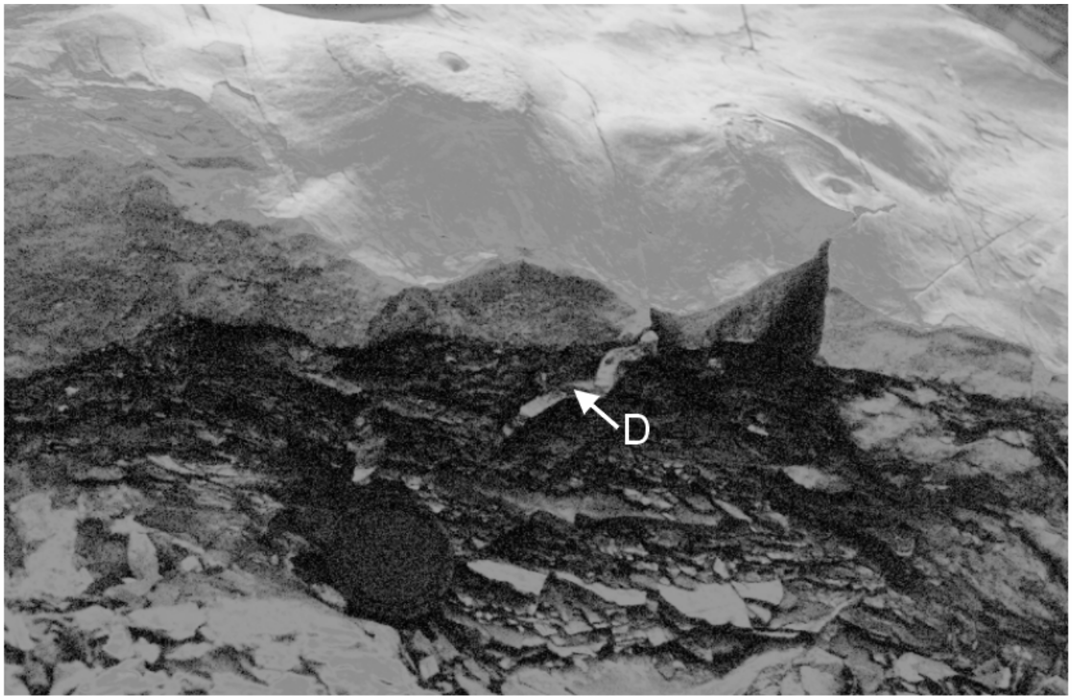

Figure 8. Sandstone dyke (labelled ‘D’) associated with sand volcanoes, and cutting an isolated shale block at the top of an intraformational high-strain zone at stop 3.

Figure 9. Refolded isoclinal fold in an intraformational high-strain zone at stop 3

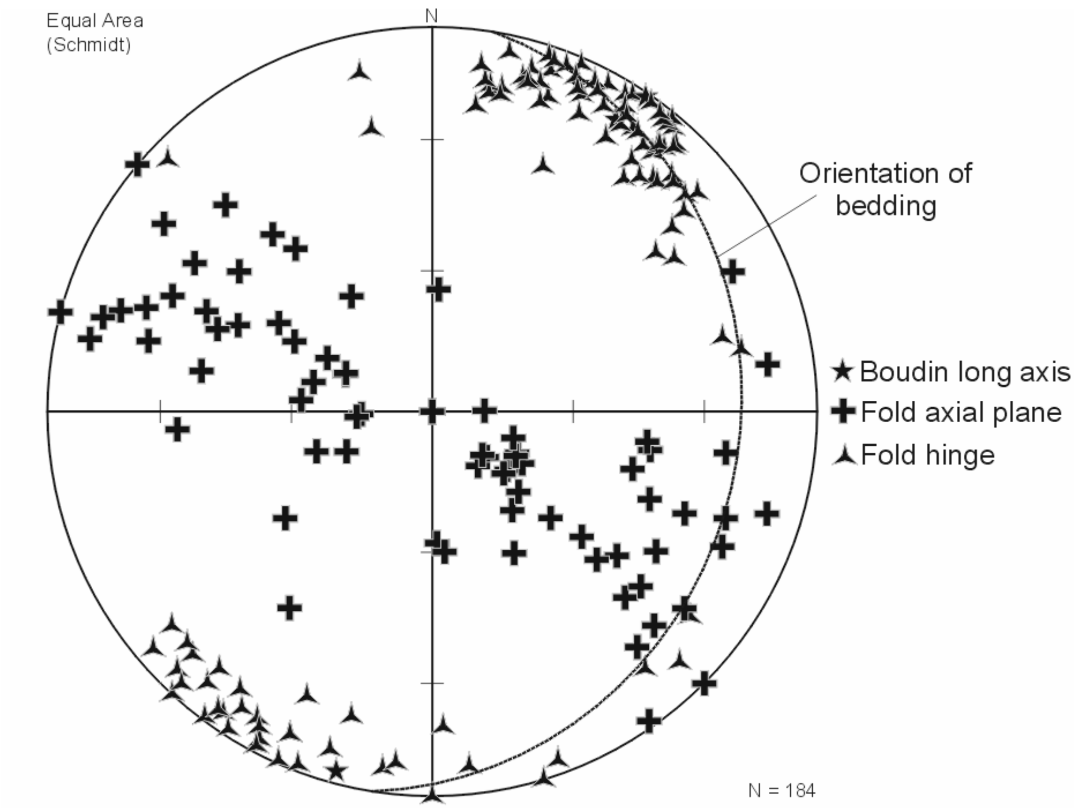

Figure 10. Raw data from measurements of folds and boudins at stop 4. The great circle shows the mean orientation of bedding.

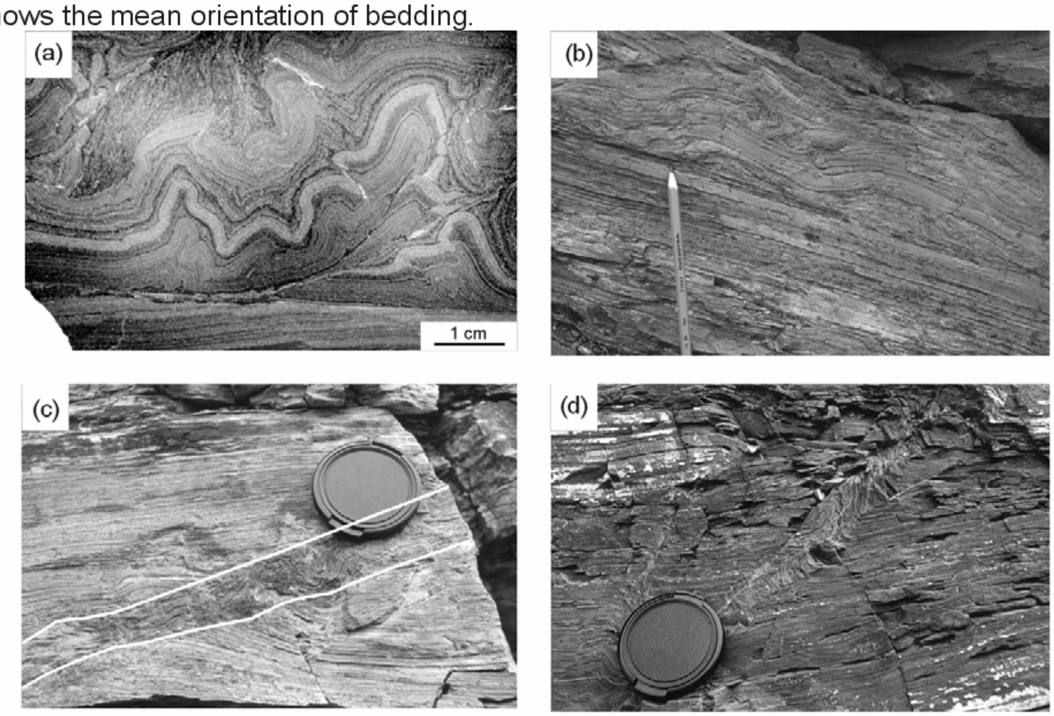

Figure 11. High strain zones developed in dolomitic/organic shales. (a) Computer scan of a large thin section, showing the typical fold-thrust geometry of the high-strain zones within the organic/dolomitic shales. Note that underlying laminae are truncated by the basal detachment of the zone. (b) Lower detachment surface of a high-strain zone, showing no truncation of underlying layers. (c) A high strain zone that truncates overlying strata, indicating it cannot have formed at the sediment/water interface. (d) Kink-like fold, showingfolding of bedding-parallel siderite veins.

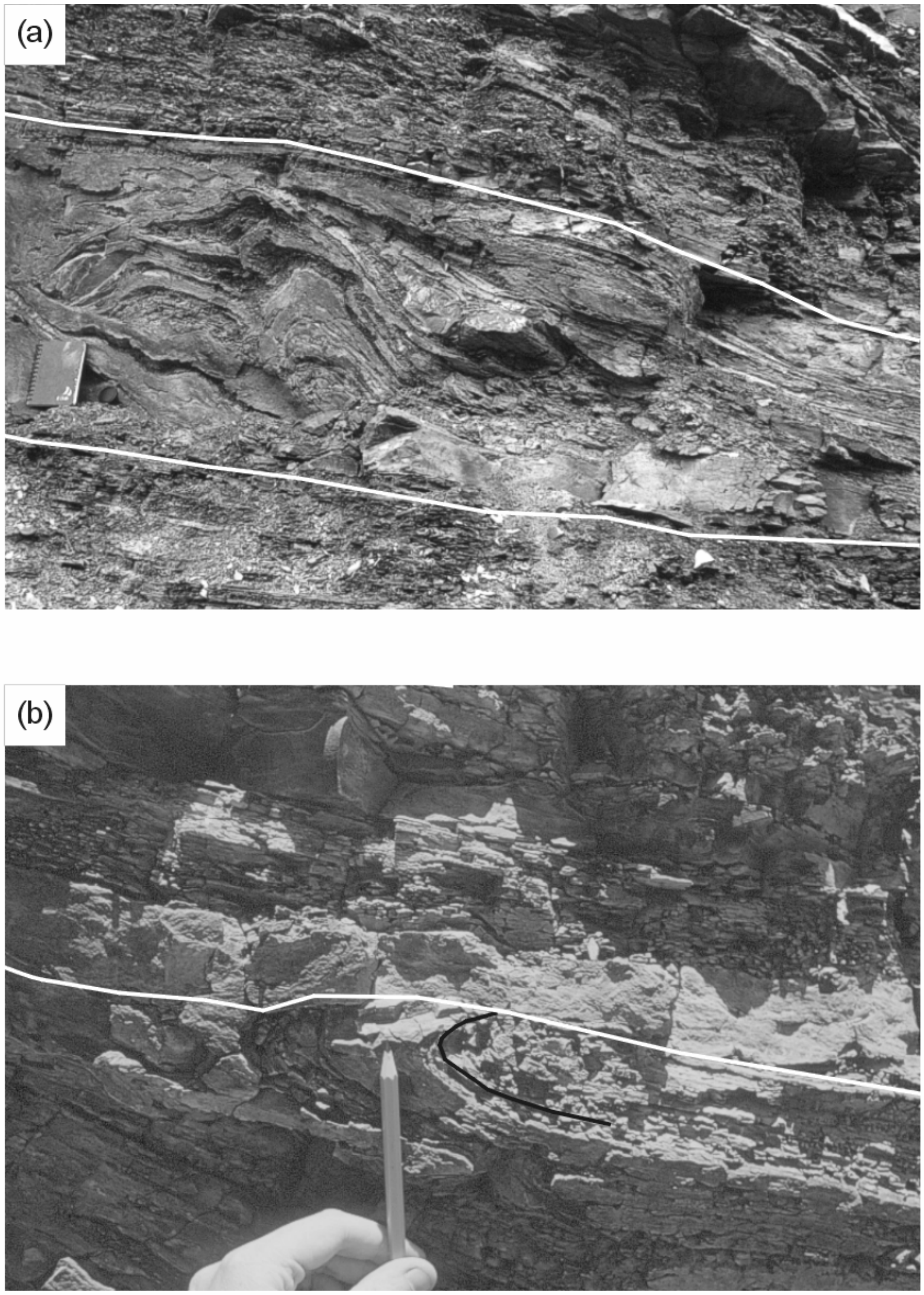

Figure 12. (a) Intraformational high-strain zone at stop 4. Note tightly folded strata within the zone, sharply overlain and undderlain by undeformed strata. (b) Upper contact of the high-strain zone shown in (a), showing truncation of folds by overlying undeformed layers.

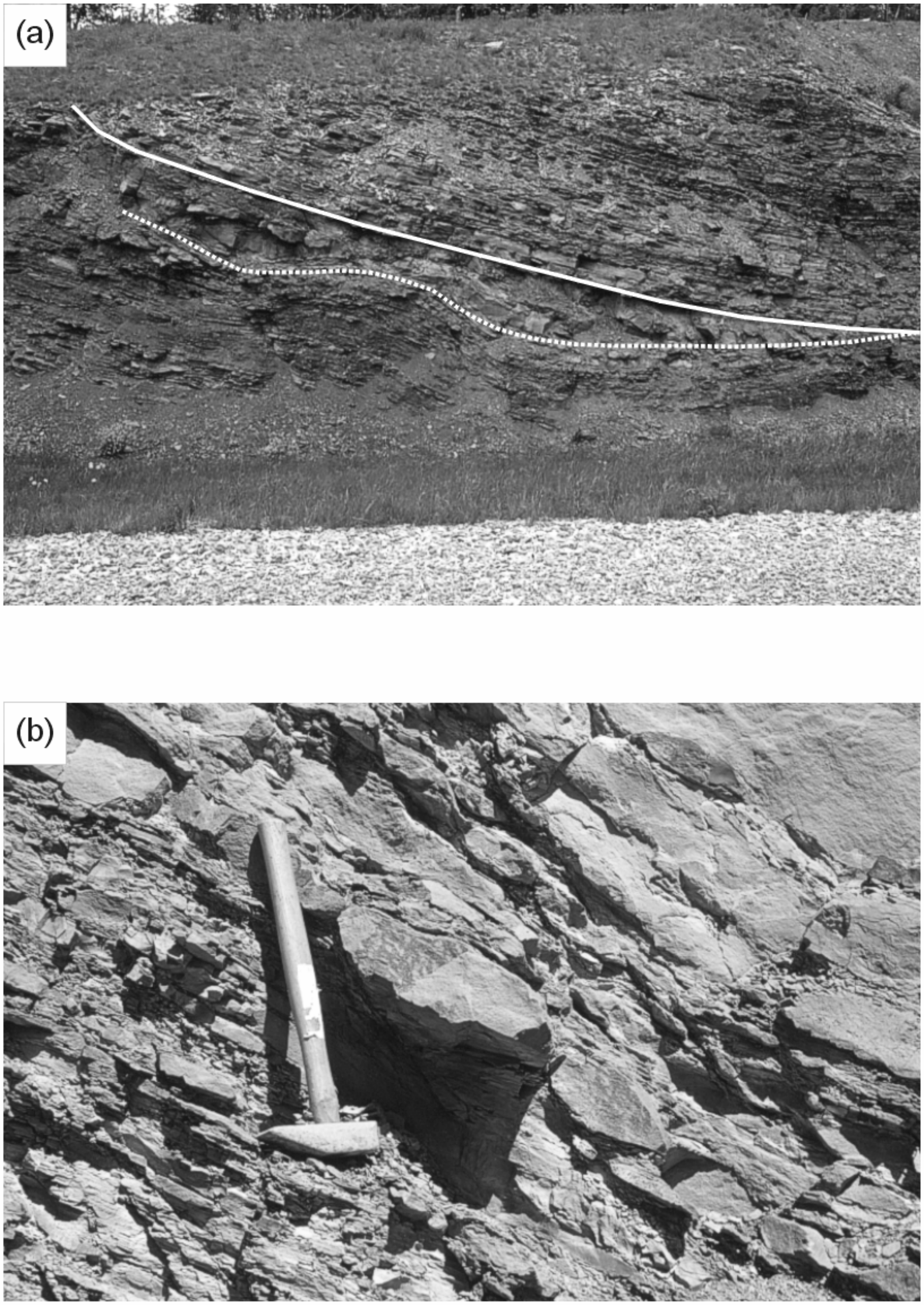

Figure 13. (a) Truncation of open folds by overlying undeformed strata at stop 4.
(b) Boudinage of sandstone layers at stop 4.

Figure 14. Intraformational open folds, upright relative to bedding. Compare these with the folds shown in Figures 13a and 9.

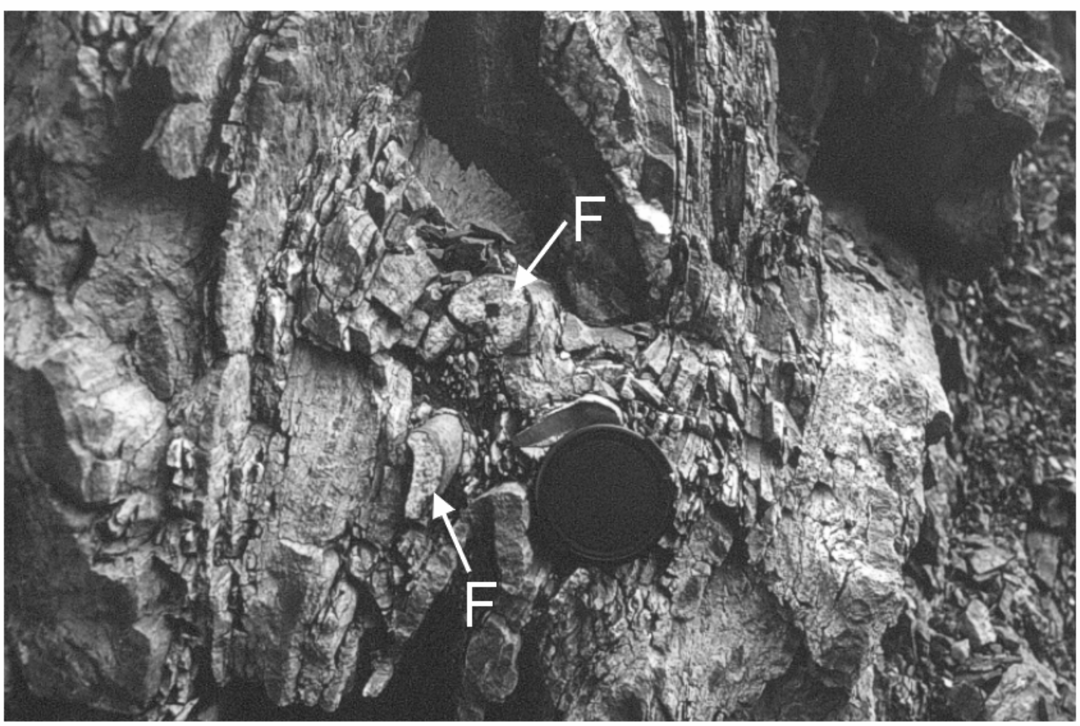

Figure 15. Detached fold hinges and aerofoil-shaped fold remnants (labelled ‘F’) in a matrix of deformed shale. These may be precursors of the boudin-like features seen in Figures 4 and 5.

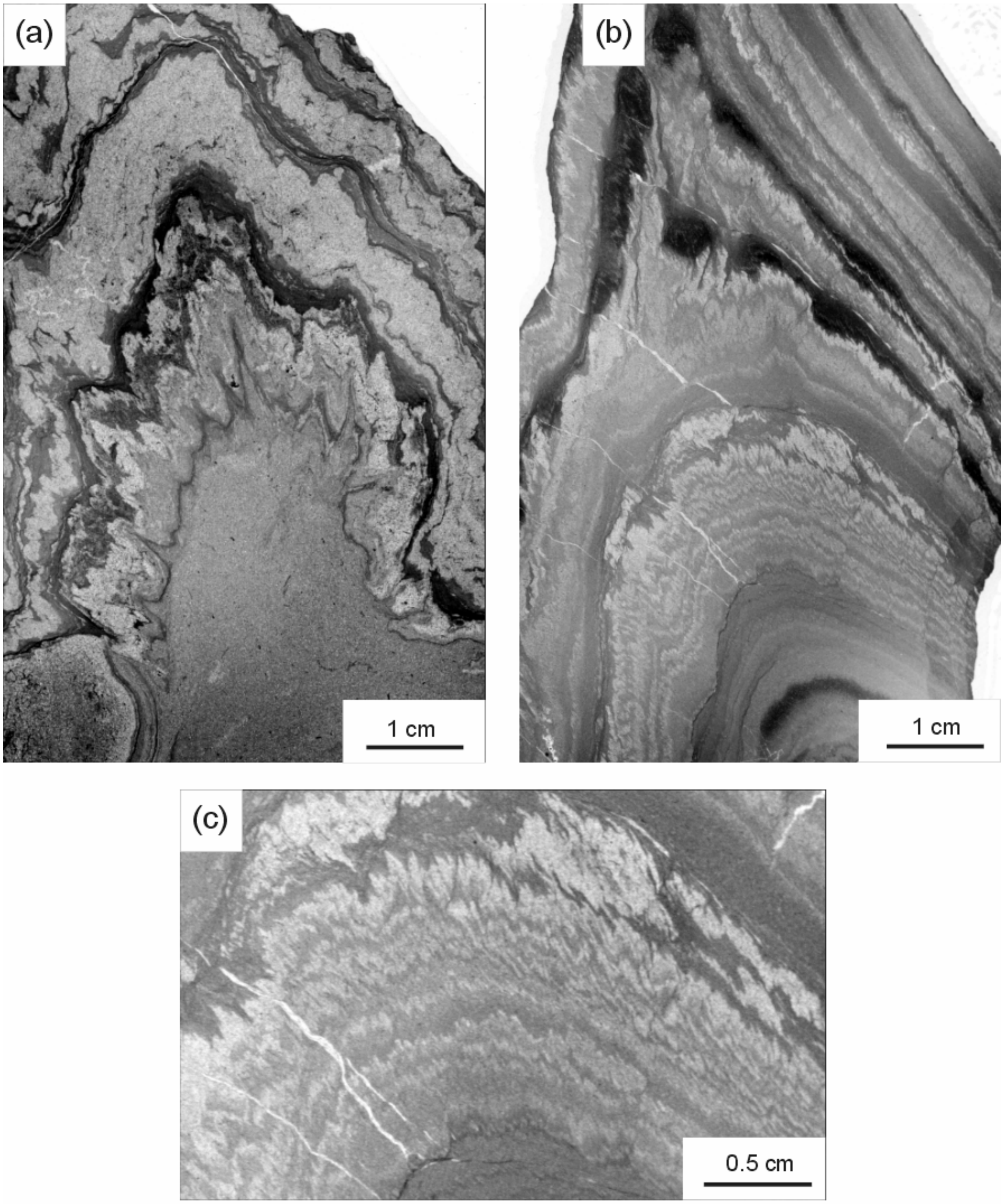

Figure 16. Micro-observations of folds from high strain zones. (a) Muddy material in the fold core has a sharp contact with other material, suggesting a large competency contrast. The muddy material has been injected in flame-like structures into the fold hinge. (b) Tight fold with a broken hinge, showing an axial planar spaced cleavage. (c) A closer view of the spaced cleavage seen in (b).

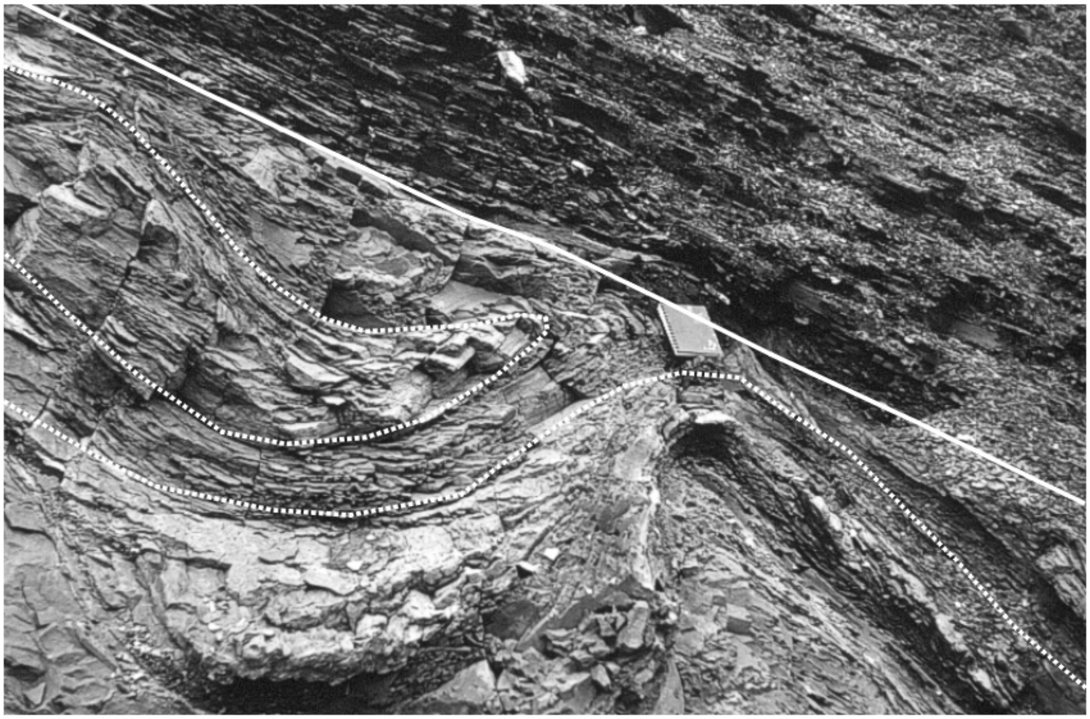

Figure 17. Truncation of folds, including refolded folds, by overlying undeformed strata at stop 4.

Table 1. Table of formations for the western Moncton Subbasin.

SYSTEM	STAGE		GROUP	FORMATION	LITHOLOGY
UPPER CARBONIFEROUS	WESTPHALIAN	D	PICTOU		
		C		SALISBURY	Red mudstones, siltstones, sandstones and conglomerates; minor thin coal seams
		B			
		A	CUMBERLAND	BOSS POINT	Yellow-grey quartzose sandstone and quartz-pebble conglomerate; minor red sandstone, grey and red mudstone, thin coal seams
	NAMURIAN	C			
		B			
		A			
LOWER CARBONIFEROUS	VISEAN		MABOU	UNDIVIDED UNITS	Red to grey polymictic pebble and cobble conglomerate; minor red sandstone
			WINDSOR	CLOVER HILL	Halite, argillaceous halite, anhdrite and claystone
				CASSIDY LAKE	Halite, argillaceous halite, sylvinite and anhydrite
				UPPERTON	Anhydrite and gypsum
				MACUMBER/ GAYS RIVER	Wackestone, packstone, algal boundstone; minor floatstone and intraformational breccia
	TOURNAISIAN		SUSSEX	HILLSBOROUGH	Yellow-grey to red polymictic conglomerate and sandstone; minor red mudstone
				WELDON	Red mudstone, siltstone and fine sandstone; minor grit and polymictic conglomerate
				ROUND HILL HAZEL HILL MEMBER	Grey polymictic conglomerate, grit and coarse sandstone HAZEL HILL: Grey conglomerate containing green-grey chert and marble clasts.
			HORTON	BLOOMFIELD	Red mudstone, siltstone and fine sandstone; minor grit and polymictic conglomerate
				ALBERT	Mostly grey feldspathic sandstone, mudstone, kerogeneous mudstone and shale, polymictic conglomerate; minor limestone.
				MEMRAMCOOK	Red to grey polymictic boulder conglomerates with minor sandstone and mudstone
UPPER DEVONIAN					
MID. DEVONIAN AND OLDER			BASEMENT COMPLEX		