Structural Investigation Of Allochthonous Upper St. George Group Carbonates (Lower Ordovician) At Select Localizations In Western Newfoundland, Emphasizing The Potential Impact Of Deformation On Reservoir Quality.

William Jamison
Center For Earth Resources Research
Memorial University Of Newfoundland

EL# 92-103-01-EG
Release Date: December 31, 1997

List of Figures

Introduction

A three-week structural field investigation (23 Sept. to 15 Oct. 1991), plus subsequent thin-section analysis, of "autothonous" Ordovician carbonates was conducted for Mobil Canada Ltd. at four localities along the west coast of Newfoundland. This study has focused on the mesoscale deformational features that have developed within the upper portion of the Lower Ordovician St. George Group, with a particular view towards assessing the probable impact of this deformation on the reservoir characteristics of these lower Paleozoic carbonates in offshore/onshore western Newfoundland. These small-scale features are evaluated in the context of (1) the local/regional tectonic history, (2) position within larger-scale structures, (3) and the lithology of the involved rock units.

All of the lithologies can be very highly fractured, locally. Fractures are almost exclusively extension fractures, as opposed to shear fractures. The limestones also show evidence of very large amounts of pressure solution, occurring as a result of both burial diagenesis and tectonism. This has provided a source of calcite that has completely filled virtually all fractures with any measurable opening. Only in the northernmost study area, where almost complete dolomitization of the upper portion of the Catoche Formation has pre-dated the major phase of macro scale structural development, is calcite consistently absent in fractures. Though structural position and tectonic history are very important considerations for anticipating the relative intensity and orientation of the small-scale deformational features, lithology is the critical factor determining the impact of the deformation on reservoir quality.

General

The locations of the three areas of study (Fig. 1) are Cape Comorant, which is along the western shore of the Port au Port Peninsula; Table Mountain, which is located along the eastern margin of Port au Port Bay; Deer Cove, which is on the western shore of the Northern Peninsula, about 4km north of the community of Bellburns, and Norris Point Anticline, exposed in a roadcut about 5km east of the community of Rocky Harbor. Though the focus of the study is on mesoscale deformational features, a substantial amount of macroscale mapping has also been necessary to supplement the available structural map data. At all locations, the study has concentrated on deformation within the Catoche Formation, which has been identified by Mobil as the most promising reservoir rock in the St. George Group. At Table Mountain and Deer Cove, the study has extended slightly upsection into the overlying Aguathuna Formation, which is generally the uppermost formation of the St. George Group (Knight & James 1987, Knight et al. 1991). Locally the Aguathuna Formation is absent by virtue of nondeposition or by erosion at the St. George Unconformity (Knight et al. 1991). The Aguathuna Fm. appears to be absent at Cape Comorant. The Catoche and Aguathuna formations contain limestones, dolomitic limestones and dolostones in proportions that appear to vary considerably among the localities examined (Langdon 1992).

The Humber Zone of Newfoundland, which includes all of the localities visited, forms the western margin of the Appalachian Orogen in Newfoundland. It is the site of two phases of generally WNW contraction during the Paleozoic Period (Williams 1979), the mid to late Ordovician Taconic Orogeny and the Devonian Acadian Orogeny. The Taconic Orogeny has produced a strong tectonic telescoping of distinct facies within the lower Paleozoic sedimentary rocks: slope and basin facies have been thrust over their shelf facies counterparts. Those rocks interpreted to have been substantially transported during the Taconic Orogeny are termed "allochthonous", whereas those which were unaffected, or only mildly affected, by this first Paleozoic deformation are considered "autochthonous" or "para-autocthonous," depending on the relative effects of the subsequent Acadian deformation.

The St. George Group is regionally mapped as "autothonous" or para-autothonous," implying that it was essentially unaffected by the Taconic deformation. The structures observed at the four study sites have been interpreted as Acadian features Williams & Cawood (1989). However, I believe that there is also a significant imprint of the Alleghenian (Carboniferous) deformation at the southern two study locations (Cape Comorant and Table Mountain). This interpretation is derived from the meso- and macroscale structural features assessed during this study and the offshore seismic study of Langdon (1991). Evidence of the Alleghenian effects is well documented immediately to the south, in Bay St. George and the adjacent onshore region to the east (Knight 1983, Langdon 1991). These southern two study localities may simply be on the margin of the area affected by the Alleghenain deformation. This may be a very important consideration when extrapolating the results of this study, and also the "triangle zone" interpretations of the "Acadian" deformational front (Stockmal & Waldron 1990, 1991) to the north.

Though the St. George Group strata have not been physically transported during the Taconic Orogeny, this unit has been strongly affected by this tectonic event. Specifically, the St. George Unconformity is now interpreted to be the direct result of the uplift associated with the peripheral swell, which was advancing outboard of the early Taconic deformational front (Knight et al. 1991). The massive dolomite replacement occurring in the zinc mines at Daniel's Harbour (Cummings 1968) and at the Deer Cove outcrops is considered to be directly linked with the development of this unconformity and the relatively minor normal faults developing along the crest of the peripheral swell (Knight et al. 1991).

Deer Cove

Deer Cove is just north of Table Point, where a complete, structurally uninterrupted section of the Table Head Group is well exposed (Knight & James 1987). Stratigraphic continuity and exposure continues downsection through the Aguathuna and upper part of the Catoche formations between Table Point and Deer Cove (Fig. 2). Though this area provides the type section of the Aguathuna Formation, it was not clear to me exactly where the contact between the Catoche and the Aguathuna formations lay. I have tried to indicate on the locality map (Fig. 2) this formational contact based on the map of Knight (1985). The measured thickness of the Aguathuna Fm. is 62m (Knight & James 1987). From my structural, I estimate about the upper 120m of the Catoche Fm. is exposed at this location, which is roughly 3/4 of this unit (Knight & James 1987). These rock units are gently folded, but the specific character and age of this structuring is indeterminant.

There is major, penetrative dolomitization throughout most of the Catoche Fm. at Deer Cove. The dolomite consists of a tan to grey, finely crystalline (50-200m, see thin section descriptions) replacement dolomite, with more coarsley crystalline (500-1000m) white "saddle" dolomite occurring in varying patterns through the rock, described below. This saddle dolomite and the coeval sphalerite formation in the Daniel's Harbour area (Knight & James 1987), which is 16kms south of Deer Cove, are characteristic of Mississippi Valley type dolomitization. The existing map (Knight 1983) indicates a boundary between a limestone subunit of the Catoche Fm. stratigraphically below a dolomite subunit (see Fig. 2), but I find dolostones containing the saddle dolomite, as well as non-dolomitized thrombolitic limestones, below this indicated boundary. All indications are that the dolomitization front does not necessarily follow stratigraphic horizons.

Dolomitization within the Catoche has been recognized to be multigenetic (Haywick & James 1984). Certain of the history of the dolomitization is dramatically displayed in the outcrops in the uppermost portion of the Catoche Fm. at Deer Cove. Some beds of non-dolomitized thrombolitic limestone, a common primary lithology of the Catoche Fm. (Knight & James 1987), transition laterally and abruptly to a partially dolomitized lithology, with the replacement dolomite occurring throughout the thrombolitic framework while the matrix limestone remains unaltered. Nearby, the partially dolomitized thrombolitic limestone transitions to a pure dolostone, wherein the residual micritic limestone has been replaced by the coarsely crystalline saddle dolomite. The saddle dolomite has the appearance of vug-filling crystal growth forming an overall mottled rock tecture (e.g. Fig. 3 upper photo). In places the white dolomite produces a "zebra-rock" texture. The dolomitization fronts are very sharp and beautifully displayed on the clean outcrops within the surf zone. The dolomitization front locally follows a fracture zone, but generally does not follow the deformational features.

The saddle dolomite can also occur within the fractures of pseudo- breecia (Cummings 1968). These fractures form in a very polygonal network, with much stoping of fragments of the country rock into the fracture spaces (Fig. 3 lower photo). These pseudo-breecia fractures have the erratic geometry of collapse fractures, as opposed to the planar, aligned fracture configurations more typical of tectonic fractures. However, planar extensional fracture systems filled with the saddle dolomite are also common in the Deer Cove outcrops (Fig. 4). The various rock textures associated with the saddle dolomite occurrences may be partly controlled by the initial rock texture. The mottled or zebrarock distribution of the coarse white dolomite may be restricted to thrombolitic boundstone units, whereas the pseudo-breecias and planar extension fractures occur in beds with a homogenous, uniform crystal size. The planar fractures are best developed in the more finely crystalline beds, but do form in all Catoche lithologies.
It was my initial inclination to interpret these planar fractures as tectonic and subsequent to the other expressions of saddle dolomite development. However, several characteristics of these fractures can be explained more easily with the interpretation that they are synchronous with the final phase of dolomitization: (1) the fracture walls (Figs. 4 upper photo, 5 upper photo, 6) do not have the sharp boundaries common to filled tectonic fractures (c.f. thin section photos of fractures in limestone in following sections), (2) these filled fractures are cut by a system of unfilled extension fractures (Fig. 4 lower photo), and (3) the filled planar fractures do not cleanly cut through other saddle dolomite textures (e.g. Fig. 3 lower photo).

A recent article (Knight et al. 1991) relates the development of the St. George Unconformity and the development of the above described saddle dolomite textures to a peripheral swell associated with the initial phases of the Taconic Orogeny. A peripheral swell is a zone of slight arching and uplift that develops foreland of a convergent tectonic front. It occurs as a viscoelastic lithospheric response to the downward flexure of the plate margin beneath the advancing, stacked thrust sheets. In concept, the zone of the peripheral swell will move progressively in a foreland direction as the collisional front advances. Knight et al. (1991) suggest that the pseudo- breccia textures (and I would add the planar, filled extension fractures) are associated with small-displacement, NE-trending normal faults that developed during the arching of the peripheral swell. This NE orientation fabric is also observed in some of the planar fractures filled with the saddle dolomite (see Fig. 11). The NF, fault trend is slightly oblique to current mountain front (and coastline) of western Newfoundland. Based on my field observations in the Deer Cove area, I would endorse this interpretation of genesis and timing.

Post-dolomitization, tectonic deformation is evident in outcrop and thin section in the form of unfilled extension fractures (Figs. 4 lower photo, 7), small displacement faults with associated breccia/gouge zones (Figs. 5 lower photo, 8, 9), and minor pressure solution seams. The small displacement faults are fairly minor in terms of distribution and effect, but they are the most unequivocally tectonic structures found in this area. They are very important inasmuch as they appear to be linked genetically to the unfilled extension fractures, thus providing some temporal control on the latter features.

The unfilled extension fractures are very planar features, and they occur in one or two very systematic sets (e.g. Fig. 7 upper photo) at most outcrop locations (Fig. 10). They always occur at high angels (>75') to bedding (Fig. II). These fractures would be termed joints by virtue of these geometric characteristics. There are several recurring fracture trends through the Deer Cove study area (Fig. 10), but there is not a consistent fracture pattern encompassing this area. Systematic trends appear to be related more to specific stratigraphic units than to a regional pattern or to structural position. This is, in fact, a fairly common characteristic of joint systems. Average joint spacing at the measurement stations range from 5 to 20 cm. Though fracture spacing is smaller at some locations (e.g. Fig. 7 lower photo), it can also be much larger (e.g. 50 cm or greater). On the weathered outcrops, fracture widths appear to reach several mm's or cm's (Fig. 7 upper photo), but this appears to be very much an artifact of weathering. In many areas I find that these ostensibly very wide fractures are the result of preferential weathering along hairline fractures. I am inclined to think that these joints are all originally hairline fractures. Thus they may not provide major reservoir permeability enhancement, despite some of the outcrop appearances.

The small-displacement faults are best developed in the vicinity of "f" on the fracture map (Fig. 10). Most are strike-slip, and the fault orientations and displacements consistently indicate a ESE-WNW s1 orientation. Some of these faults transition into swarms of unfilled, hairline extension fractures of essentially the same orientation. The measured joint patterns in the vicinity of these small faults are also developed with the same orientation fabric. The corresponding orientation patterns between the small faults and the hairline extension fractures suggests they are genetically associated, comtemporaneus deformational features. I assume that these mesoscale features, and the macroscale doming, are Acadian structures, but they could also simply have developed during the waning phases of the Taconic Orogeny. The small faults consistently offset all features containing the coarsely crystalline, white, "saddle" dolomite (Fig. 8 lower photo). The maximum displacement on any of these faults is about 2m, and most have a displacement of 10cm or less. The associated brecciated gouge zone can be several cm's wide (Figs. 5 lower photo, 8 upper photo). The gouge zone consists of physically comminuted dolomite, reduced to a general grain size of about 10m (Figs. 5 lower photo, 9). Within the gouge zone are very thin, anastomosing zone of extremely fine grained ultraclasite (Fig. 9). Similar gouge zones in porous sandstones serve as local barriers, or baffles, to fluid flow, producing an overall reduction to the bulk reservoir permeability.

A very few pressure solution features (stylolites) were noted in outcrop in the dolostones at Deer Cove. In thin section they are observed to be fairly common along the boundaries of contrasting crystal size domains. In outcrop, the stylolites are at high angles to bedding, implying that they are tectonic (as opposed to burial digenesis) features. Some solution seams occur along the gouge zone boundaries, indicating that pressure solution was active syn- or post-fault movement.

Table Mountain

Table Mountain anticline is mapped as a major N-S anticline, segmented by some secondary NNW-SSE faults (Williams 1985). This is somewhat misleading, as only the west-dipping flank of the inferred fold is in evidence. A major normal fault runs along the eastern side of the mountain, removing any evidence of the major hinge and east flank of the anticline. This situation is depicted in cross-section A-A' accompanying the map of Williams & Cawood (1989). There are some minor fold hinges associated with the secondary, cross-cutting faults. Williams & Cawood (1989) map the Table Mountain structure as a basement-cored hangingwall anticline of a thrust that overrides a Taconic melange, suggesting that it is an Acadian structure. Stockmal and Waldron (1991) also interpret this as a basement-cored structure, based on existing seismic data along Fox Island River, just north of Table Mountain itself.

Along the southern half of Table Mountain, Cambrian through Ordovician planar strata dip 20' to 30' to the WNW (see Fig. 15 upper photo) and exhibit very minimal mesoscale deformation. It appears that these strata have simply been translated and rotated above the relatively strong granitic basement core of the fold without undergoing significant internal deformation. Towards the southern end of the mountain, the strike of these strata swings toward the west, but there is still little evidence of secondary structures or mesoscale deformation. In contrast, in the central and northern portion of Table Mountain (Fig. 12) there is fairly substantial mesoscale deformation. This deformation is distinctly related to the NNW- SSE trending secondary faults and associated structures.

These cross-trending faults, etc., do not have an obvious structural association with the main Table Mountain Anticline. I prefer to interpret these secondary features, and the swing in bedding strike in the southern part of Table Mountain, to be a manifestation of dextral shearing along fault(s) that run E-W along the north margin of Bay St. George. Although such faults have not been mapped, they have been inferred from potential field (e.g., Kilfoil 1988) and seismic data (Langdon 1991), and they have been interpreted to be Alleghenian features associated with the formation of the Carboniferous basins south of this study area. I interpret the NNW-SSE trending cross-faults to be sinistral strike-slip faults, transitioning into N-S trending thrusts and compressional folds at their western terminations (Fig. 13). This suite of structures accompanies and accomodates the structural rotation and the minor axial extension that is inherent in this simple shear deformation (Jamison 1991). These sinistral strike-slip faults have the orientation and sense of slip of R'-shears in relation to the E-W dextral strike-slip zone.

Tectonic mesoscale deformation on Table Mountain is concentrated around these interpreted "Alleghenian" structures. In the area of my more detailed structural mapping (Fig.12), only the upper portion of the Catoche Fm. and the Aguathuna Fm. crop out. Slightly north of this map area, east of the community of Point au Mal, an exposure through one of the N-S trending, presumely Alleghenian folds (Fig. 14) was accessed. Roughly the upper half of the Catoche Fm. is exposed in this fold, which is referred to in the following as the Point au Mal fold.

Away from these "Alleghenian" features there is remarkable little mesoscale deformation, with the exception of bedding-parallel pressure- solution in some of the limestones that probably occurred during burial diagenesis. For example, in Smelt Brook (Fig. 15 upper photo), where there is almost complete exposure of the entire St. George Group, the only indication of tectonism is the bulk rotation of these strata. Where fractures do occur, they are widely spaced (usually >25cm), hairline fractures, with no consistency of orientation (Fig. 15 lower photo). The lithology of the St. George Group formations at Smelt Brook is described in detail in the companion report of Langdon (1992).

The Catoche Fm. consists of interbedded limestones, dolostones, and dolomitic limestones. Thrombolitic boundstones appear to be the dominant rock type of the Catoche Fm at Table Mountain. Very commonly, dolomite occurs as finely crystalline replacement dolomite of the thrombolitic framework while the matrix micrite remains limestone (Fig. 16 upper photo). The distribution of dolomite can vary, however. Some beds in the Catoche Fm. are completely dolomitized, and some of the thrombolitic limestones appear to have undergone no dolomitization. Nowhere on Table Mountain did I note the white, coarsely crystalline "saddle" dolomite that was so prevalent at Deer Cove. The Aguathuna Fm. consists of interbedded micritic limestone and dololaminites. Both lithologies commonly show evidence of algal lamination (Fig. 16 lower photo).

Extension fractures and pressure-solution seams (stylolites) are the dominant forms of mesoscale deformation throughout the Table Mountain study area. Solution seams are particularly common in the limestones. In the dolostones and dolomitic limestones, solution seams are rarely evident in outcrop, though they are observed in some of the thin sections. Pressure solution is a much more active process in calcite than in dolomite, and rates of pressure solution are particularly high in lime rnicrites (e.g. Rutter 1976), which seems to be prevalent throughout the St. George and Table Head Group limestones. Pressure solution in the limestones may occur both as a digenetic and a tectonic process.

Though most of the fractures observed on Table Mountain appear to be tectonic, there are some very non-systematic fractures (Fig. 17) that probably pre-date deformation. In the limestones, these occur as non- systematic networks of extension fractures that link, and are probably contemporaneous with, bedding-parallel solution seams (Fig. 17 upper photo). Both the solution seams and the fractures are, in this case, probably the result of burial diagenesis. Most of these fractures terminate against the solution seams. In the dololaminites, irregular fracture networks (Fig. 17 lower photo) may be the product of dessication and/or dolomitization of the algal-laminated limestones. In both of these cases, the fractures have a small but discernible fracture width (<~1mm) and, in both lithologies these fractures are infilled with twinned calcite. The development of the calcite twins signifies that the calcite fill is pre- or syn-tectonic. I infer that the fracture-filling calcite in both lithologies is supplied by the burial digenesis solution seams. Twinned calcite spar also appears to be filling all the interpelletal pore space in the limestones.

The tectonic fractures usually form at high angles to bedding and occur along one or two dominant orientations at any particular outcrop location (Figs. 18 upper photo, 20). There is no evidence of a regionally consistent fracture pattern (Figs. 19,20), nor is there any pattern within the collected data that I feel easily relate to structural style or structural position. Only within the Point au Mal do the fractures and small faults form with a fabric easily related to the larger-scale structure. All of the mesoscale features that are clearly related to the fold development are essentially strike-parallel to the fold axis. This includes faults in the forelimb and fractures in the backlimb (Fig. 14). Though not shown in these data, there is also a strong development of fractures dipping at low- angles to bedding (Fig. 18 lower photo) and pressure solution seams at high angles to bedding (both features still strike-parallel to the fold axis) in the lower exposed beds in the Point au Mal fold (Fig. 14 photo). All of these fractures occur throughout the fold at a moderate to high intensity. They are overprinted by a low-density set of fractures at high angles to the fold axis.

Fracture intensity is extremely variable. It is common to observe strong differences in the fracture intensity in adjacent limestone and dolostone lithologies, with the dolostones consistently exhibiting a much stronger fracture development than the limestones or the dolomitic limestones (Fig. 18 lower photo). Certain of this variation in fracture intensity is only apparent, resulting from the very different weathering characteristics of the different carbonate lithologies, discussed further, below. However, there can also be extremely strong and bona fide differences in fracture intensity in nearby outcrops (Fig. 21), with the high-intensity fracturing usually related to a fold hinge or a small fault zone.

Joints (systematic, planar fractures) are observed in the limestone units (Fig.22 upper photo), but they are a relative rarity. I think most of these joints are probably hairline fractures (Fig. 22 lower photo) that have separated during weathering of the outcrop. The opened hairline fractures in these limestones, and in the dolostones at Deer Cove, have no plumose or other surface markings that can be used to establish that these definitely are extension fractures (Kulander et al. 1990). In thin section these fractures are still extremely narrow and appear to be calcite filled. Most of the fractures in the limestones display measureable extension (as much as several mm's) and typically have a slightly irregular surface configuration (Fig. 23 upper photo). A few shear fractures (microfaults), with displacements of mm's or less, were noted in the forelimb of Port au Mal fold (Figs. 14, 23 lower photo, 25 upper photo). Virtually all of the fractures in the limestones that have undergone any extension are completely filled with calcite (Figs. 24, 25, 26). This includes dilatant jogs along the shear fractures (Fig. 26 upper photo; these shear fractures also contain a very narrow gouge zone consisting of cryptocrystalline calcite).

Pressure-solution seams generally form perpendicular to the local principal compressive stress direction. If the solution seams are parallel to bedding, it is often difficult to establish whether they are diagenetic or tectonic, and in the Table Mountain area, most of the solution seams in the limestones are bedding-parallel. It is my impression that they initiated as a result of burial diagenesis but were progressively active syn- and/or post tectonism. The latter assessment is established by the fact that many of the solution seams cut through tectonic fractures and distort the calcite fill within the fractures (Fig. 26 upper photo). If the solution seams are at high angles to bedding, they are most certainly tectonic. I find the latter grouping to be common in the limestones in the Port au Mal fold. The solution seams within the dolostones and dolomitic limestones generally have an irregular configuration, commonly following fractures or the boundaries of the dolomitized thrombolites (Fig. 26 lower photo). I infer the pressure solution in the latter lithologies to be primarily tectonic.

The existence of the fracture fill makes these fractures very difficult (more accurately, impossible) to recognize on the weathered surface of the limestones. Because of this, most of the fracture orientation data from the

Table Mountain area (Figs. 19, 20) have come from the dolomites. I also conclude that collecting fracture intensity data in outcrop from the limestones is a meaningless exercise. Outcrops of limestone that have no discernible mesoscale deformation (according to my field notes) have been found, from thin section inspection, to have an extremely intense fracture network, with fracture spacings of 1 to 2 mm (Fig. 24). In all samples from Table Mountain that have been inspected in thin section, the calcite filling the fractures has a blocky texture, and there is no obvious preferred crystal fabric of the filling calcite, nor is there any suggestion of a recurring crack-seal fracture growth. Rather, it appears that there was, for each fracture, a single episode of fracture opening, followed by complete calcite filling of the fracture. All of the calcite-filled fractures show evidence of moderate to strong calcite-twin development for crystal sizes down to ~5mm. The very fine-crystalline fracture fillings (occurring in comparably narrow fractures) are probably twinned as well; it is just very difficult to recognize in conventional thin section inspection. This general occurrence of twinning in the calcite fill indicates that the fractures were filled during tectonism, probably very soon after the formation of the fractures. The very high activity of pressure solution in in these micritic limestones provides a virtually limitless supply of calcite in solution in the formation water to immediately fill the fractures.

The only fractures that are not syntectonically filled with calcite are hairline fractures in the dolostones, which can develop with a very high density in some of the dololaminites of the Aguathuna Fm. (e.g. Fig. 21 lower photo). Unfortunately, these fractures are probably not connected to any porous lithologies, nor do they provide a fracture porosity due to the fact that they have an infinitesimal fracture width. The wider fractures in the dolostones are filled with calcite because they are always close to some calcite-sourcing solution seams in this intercalated-limestone/dolostone section. If there were a thick section of dolostone, wide fractures could potentially develop without immediate infilling with calcite, especially if there were intercalated shales to act as barriers to the calcite-saturated fluids. I don't believe that there is a enough pressure-solution in the dolomite itself to provide a significant source for fracture cement fill.

Cape Comorant

The Cape Comorant study area lies just south of the community of Mainland, and the Mainland syncline (Williams & Cawood 1989). The existing level of structural mapping on the Port au Port Peninsula appeared to be inadequate to provide a reasonable framework for any detailed studies. Fortunately, an updated map of the peninsula (Fig. 27) is in press (Waldron & Stockmal 1991). The Cape Comorant study area (Fig. 28) is in the foreland hangingwall of the "triangle zone" structure (see Fig. 38) postulated by Stockmal & Waldron (1990, 1991), an area I have referred to as the "backthrust wedge" (Jamison, in review). This triangle zone interpretation will be discussed following presentation of the study area data. The Aguathuna Formation is locally absent in western Newfoundland due to the St. George Unconformity (Knight & James 1987, Knight et al. 1991). Though there are no published stratigraphic sections of the lower Ordovician in this area, it appears that the Aguathuna Fm. is, in fact, absent in the Cape Comorant area. Thus, the Table Point Fm (a micritic limestone) of the Table Head Group lies directly on the Catoche

Fm. There are some algal laminated limestones and dolostones, similar to the Aguathuna lithologies observed at Table Mountain, present in the Cape Comorant study location, but they are intercalated with the thrombolitic boundstones that identify the Catoche Fm. These thrombolitic boundstones occur as limestones, dolostones and dolomitic limestones, as at Table Mountain, but their relative abundance in the Catoche section is notably less that at Table Mountain, apparently being replaced by the algal- laminated lithologies. The coarse crystalline saddle dolomite observed at Deer Cove was found nowhere in the Cape Comorant study area.

There are several NE-SW trending faults within this study area, with dextral separations ranging from several tens of meters to several hundred meters (Fig.28). As these faults maintain a consistent trend while crossing terrain of considerable topographic relief, they must be very steep faults. These faults are parallel to and have the same sense of offset as both the Alleghenian Long Range fault bounding the Carboniferous subbasins of SW Newfoundland (Knight 1983) and the Alleghenian faults in the central part of the Port au Port peninsula (e.g., the faults intersecting the south shore of the peninsula near Sheaves Cove; Fig. 27). Consequently, I am inclined to interpret these NE-SW faults in the Cape Comorant area as Alleghenian dextral strike-slip faults.

My mapping through this area also defines several intermediate-scale folds and flexures, with axes trending NE to ENE, in both the Table Point and Catoche formations. In only one location is there actually a reversal in bedding dip direction across these features. In general, these are simply secondary flexures in a generally NNW-dipping panel of rock (Fig.28). By virtue of their orientations and the associated fracture patterns, described below, I believe these flexures are not associated with the strike-slip faults described above. However, there are no cross-cutting relationships to establish relative timing.

On the mesoscale, bedding-parallel pressure-solution seams are extremely abundant (Fig. 29) throughout the limestones of the Catoche Fm. and the overlying Table Point Fm. It appears that the solution seams are particularly abundant in limestone units that contain identifiable algal laminations, which are much more common in the Catoche section at this location than at either Table Mountain or Deer Cove. Algal-laminated limestones with strong bedding-parallel solution seams are even more common through the Table Point Fm. (which appears to be entirely limestone). There is clear evidence both in outcrop and in thin section that many of these bedding-parallel solution seams were active both before and after the development of extensional fractures.

Extensional fractures are quite common in outcrops north of the main strike-slip fault. South of this area, there is little apparent fracture development. The strongest development of fractures that I observed was in steeply dipping, interbedded limestones and dolostones of the upper Catoche Fm. (Fig. 30 upper photo) in the steep limb of one of the secondary folds. In the weathered extremities of the outcrop, these fractures are all open, creating a very rubbly outcrop appearance. However, on fresher surfaces, fractures were either closed (but unfilled) hairline fractures in dolostone (Fig. 30 lower photo) or extended but calcite-filled fractures in both limestones and dolostones (Fig. 31 upper photo). As noted at Table Mountain, very highly deformed limestones (Fig. 31 lower photo) commonly appear to be undeformed on weathered outcrop due to a lack of mineral and weathering differential between country rock vs. fracture filling cement.

In hand samples and on protected surfaces, a moderate (5 to 15 cm fracture spacing) to high (<~2cm spacing) fracture density was almost always evident north of the main strike-slip fault, but fracture orientations could not be measured. Fracture orientations could generally be measured only in dolostones and in dolomitic limestones (Fig. 32 upper photo). Most fractures are oriented at high-angles to bedding, though in some of the very highly deformed outcrops there is also a fracture system at low angles to bedding. In thin section, the fractures at low angles to bedding are observed to post-date the high-angle fractures and most of the solution seams (e.g. Figs. 31 lower photo, 35 upper photo). Fracture data, which come from different structural positions and bedding units, evidence a very consistent fracture fabric (Figs. 33, 34). These fractures can have associated solution seams at high-angles to bedding (Fig. 32 lower photo), which indicate these extension fractures developed due to a NW-SE bedding-parallel maximum compression (s1). At one location, tension gashes developed in a micritic limestone (Fig. 35 upper photo) indicate the same s1-direction. The fractures occurring at low-angles to bedding may also reflect this same s1-direction.

Calcite-cement in the extension fractures always occurs with a blocky texture and without a preferred crystal fabric. There is no evidence of a crack-seal fracture history. Most of the calcite in the fracture fill is moderately to strongly twinned. A noteable exception is the fill of the tension gashes in the limestones (Fig. 35). The fractures themselves can be several mm's wide (Fig. 35 upper photo) and contain fragments of the wall rock fracture cavities (Fig. 35 lower photo). The coarse, blocky calcite cement in these fractures is untwinned or only mildly twinned. This would suggest that the cement developed very late in the deformational history of the area (Fig. 36 lower photo). Some of the solution seams at high angels to bedding have clearly been active after the fracture fill was emplaced (Figs. 36, upper photo). The triangle zone interpretation shown in Fig. 37 (Stockmal & Waldron 1991) was presented at the recent Lithoprobe East transect meeting in St. John's. Their section B-B' (Fig. 37) goes directly through the Cape Comorant study area. They offer these cross-sections as "balanced" but still preliminary. I believe this more recent interpretation, which incorporates their recent mapping on the Port au Port peninsula (Waldron & Stockmal 1991) is significantly different from the much cruder version offered earlier (Stockmal & Waldron 1990), which was based on vintage seismic data.

Stockmal & Waldron (1991) interpret the triangle zone structure (Fig. 37) to be an Acadian feature. The complexity of the faulting and associated structures within the backthrust wedge results from superposed deformation (Fig. 38), produced by a late (but still Acadian), easterly shift of the active backthrust of the triangle zone (also termed the upper detachment) to the Red Brook Detachment (RBD). Note that the Red Brook Detachment, which has very little stratigraphic throw in outcrop (Fig. 27), serves as a fairly large-displacement fault in their interpretations. I believe they recognize the high-angle, NE-SW trending faults in the central part of the Port au Port peninsula to be Alleghenian, although these are depicted in their diagram (Fig.38) as "late" Acadian.

The variation in bedding strikes through the Cape Comorant area is interpreted (Stockmal & Waldron 1991) as a NW-plunging antiform developed over a lateral ramp in the triangle zone backthrust (upper detachment). Their mapping in this area around Cape Comorant appears to follow existing structural mapping, though they do supply some additional bedding orientation data. They apparently do not recognize the the NE-SW dextral strike-slip indications I have mentioned above, and map two of them as east-transporting thrust faults, part of the early deformation in the backthrust wedge of the triangle zone. The NE to ENE trending folds and the fracture trends that I have mapped in the Cape Comorant area are very compatible with the triangle zone interpretation of Stockmal & Waldron (1991). This backthrust wedge portion of the triangle zone can have quite strong internal deformation (e.g. MacKay 1991). In fact, the triangle zone interpretation provides a good explanation for the relatively strong internal "Acadian" deformation here, vs. the very minimal internal deformation in the "Acadian" structure at Table Mountain. I believe, however, that they have created an unnecessarily complex structural configuration and deformational history for the area (Figs. 32, 33) by interpreting the strike-slip faults in the Cape Comorant area as thrusts.

Norris Point Anticline

The Norris Point anticline was examined briefly to establish the character of deformation in autothonous carbonates lying slightly hinterland of the Appalachian deformational front. Though this structure is mapped (Williams & Cawood 1989) as an overturned anticline in undivided Cambro-Ordovician platformal sediments, the outcrop consists of an upright anticline-syncline pair, with fold asymmetry indicating vergence to the west. The lithologies (only a few tens of meters of section are exposed here) consist of laminated dolostone, some dolomitic thrombolitic limestones (remniscent of the Catoche lithologies seen elsewhere) and some grainstone limestones (possibly indicating a more distal facies of these units). There is no evidence of the coarse-grained saddle dolomite.

Locally through the outcrop area there is a mild to moderate cleavage developed in both the dolostones and limestones (Fig. 39 upper photo). The cleavage orientation is distinctly not axial planar to the folds, and is overprinted by extensional fractures (calcite-filled), which do appear to be related to these upright folds. There is also a suggestion of isoclinal folding in some of the limestones that pre-dates the development of the anticline- syncline pair. Overall, the mesoscale features suggests two phases of deformation, presumably Taconic and Acadian, with the isoclinal folding and cleavage developing during the first event, and the larger scale folds and extension fractures developing subsequently. Major sets of en echelon tension gashes and some large plastic strains in the limestones (Fig. 39 lower photo) are associated with the second period of deformation. Certain of the operative deformation mechanisms of both events (Fig. 39; solution cleavage in the dolostones, incipient recrystallization in the limestone) indicate that deformation conditions were approaching greenshist facies temperatures.

Summary & Conclusions

The structures investigated at both Table Mountain and Cape Comorant appear to consist of Alleghenian deformation superposed on Acadian structures. The Acadian orogeny has created the main structural features, whereas relatively secondary faults, folds, and associated mesoscale features were produced during the Alleghenian deformation. These Alleghenian features are probably associated with the development of Bay St. George at that time, and thus may not persist much further north from these areas. The superposed deformation creates some unconventional structural associations. Only by separating the two suites of deformation can a reasonable assessment of the structural style of the Acadian deformational front be made. Even after separation of structural events is made, however, the view of the Acadian structural style is still quite different at Table Mountain vs. Cape Comorant .

At Table Mountain, the exposed westerly dipping forelimb of a basement-cored anticline displays remarkably little internal deformation. At Cape Comorant, in contrast, the broad northwesterly dipping panel of essentially the same lithologies displays considerable secondary folding as well as a moderate to strong development of mesoscale deformation. I believe that the triangle zone interpretation for the Appalachian mountain front (Fig. 38, Stockmal & Waldron 1991) offers a credible rationale for this difference, though I find two aspects of the interpretation troublesome. First, their interpretation involves a crystalline basement core to the triangle zone, and I am unaware of any other area where a basement-cored triangle zone has been documented. Second, it is quite conceivable that the entirety of the deformation in the backthrust wedge of the "triangle zone" is actually Alleghenian, related to an inferred E-W dextral shear zone bounding Bay St. George on the north. This carries the implication that the "triangle zone" feature may be restricted to the northern rim of Bay St. George. If, however, seismic data further to the north indicates that the "triangle zone" persists, I would suggest that the model offered by Stockmal & Waldron (1991) provides a reasonable interpretational guideline (once the more likely Alleghenian features are removed).

Where mesoscale deformation of the Catoche Fm. occurs, it consists predominantly of extension fractures and solution seams. Moderate to high fracture intensities can occur in all lithologies (limestones, dolostones, and dolomitic limestones). These fractures are usually developed at high angles to bedding and occur along one or two well defined trends at any given exposure. The only location where the fracture patterns define a regionally persistent trend is in the Cape Comorant area, where the fractures (and solution seams) indicate NW-SE layer-parallel compression (which fits well with the triangle zone interpretation). The limestones within the Catoche, and adjoining, formations are highly prone to pressure solution by virtue of their mineralogy and their very fine grain size. The dolomite evidences only a modest amount of pressure solution.

Though much of the pressure solution in the limestones probably occurs in association with burial diagenesis, it continues through the period(s) of tectonic deformation. Because this pressure solution is placing so much calcite in solution in the formation waters, extension fractures in the limestones, and in dolostones intercalated with micritic limestones, are completely filled with calcite cement soon (not immediately) after they have opened. Primary pore space in the pelletal limestones is also filled with calcite spar cement. Only hairline extension fractures in the dolostones seem to be exempt from this infilling, probably due to the lack of circulation of fluids through these cracks.

The incursion of the calcite cement into the thicker dolostone seems to be fairly restricted, as is suggested by the fact that no calcite cement was observed in the thick Catoche dolostones at Deer Cove. This last observation may simply be due to the fact that permeability in these particular dolostones is poor due to the pervasive infill of saddle dolomite. According to Langdon (1992), the better permeability and porosity occurs in the dolomitized boundstones that have not been affected by the saddle dolomite emplacement. As there are no thick units of such dolostones in the locations I examined, I cannot assert that they will also escape the influx of calcite cement, but I would guess that they would.

I conclude that the most critical factor determining the effects of deformation on reservoir quality is the lithology of the carbonates at the inception of deformation. Unless relatively thick sections of the carbonate are completely dolomitized prior to deformation, the occurrence of calcite cement driven by pressure solution in the micritic limestones will occlude primary pore space and tectonically induced extension fractures. All of the dolomite that I have seen appears to pre-date Acadian deformation. The emplacement of the saddle dolomite (seen only at the northernmost study area, Deer Cove) in the early phases of the Taconic orogeny (Knight et al 1991) appears to be the the last phase of dolomitization. It is clearly overprinted by deformation that is probably Acadian, but could even be the main phase of Taconic deformation.

The absence of significant internal deformation in the forelimb of the Acadian Table Mountain fold could be viewed negatively, as it implies very little potential for fracture-enhancement of reservoir permeability. However, in light negative value of tectonically driven pressure solution, this lack of internal deformation may help preserve what reservoir enhancement has occurred strictly by dolomitization in the Catoche FM. where it consists of intercalated dolomites and limestones.

A massive dolostone sequence has developed in the Catoche FM. at Deer Cove as a result of Mississippi Valley type dolomitization. Tectonic deformation of this section has produced small faults with mechanically comminuted, low-porosity gouge, and also extension fractures which do not have a calcite-cement fill. Knight et al. (1991) suggest that this particular phase of dolomitization is concentrated along NE-SW trending faults, which project into the offshore south of Daniel's Harbor due to the slight obliquity between this fault trend and the coastline. Though this suggests a potential exploration trend for the desired dolostone, this particular phase of dolomitization may not actually produce an associated enhancement of reservoir porosity because it has deposited massive infill of saddle dolomite in contemporaneous vugs and fractures.

William R. Jamison

References

Cumming, L.M. 1968. St. George-Table Head disconformity and zinc mineralization, western Newfoundland. Can. Min. & Metal. Bull., 61, 721-725.

Haywick, D.W. & James, N.P. 1984. Dolomites and dolomitization of the St. George Group (Lower Ordovician) of western Newfoundland. In current research, Part A. Geol. Surv. Can., Paper 84-1A. 531-536.

Jamison, W.R. in review. The mechanical stability of the triangle zone: the backthrust wedge. Can. J. Earth Sci.

Kilfoil, G.J. 1988. An integrated gravity, magnetic and seismic interpretation of the Carboniferous Bay St. George Subbasin, western Newfoundland. M.Sc. thesis, Memorial University of Newfoundland, 172 p.

Knight, I. 1983. Geology of the Carboniferous Bay St. George Subbasin, western Newfoundland. Newfoundland Dept. Mines & Energy Memoir, 1, 358 p.

Knight. I. 1985. Geology map of Bellburns (12I/5,6), Newfoundland. Nfld. Dept. Mines & Energy, Min. Devel. Div., Map 8563.

Knight, I. & James, N.P. 1987. The stratigraphy of the Lower Ordovician St. George Group, western Newfoundland: the interaction between eustasy and tectonics. Can. J. Earth Sci., 24,1927-1951.

Kulander, B.R., Dean, S.L. & Ward, B.J., Jr. 1990. Fractured core analysis: interpretation, logging, and use of natural and induced fractures in core. AAPG Methods in Exploration Series, 8, 88p.

Langdon, G.S. 1991. Recent research related to new opportunities for exploration in the Carboniferous of western Newfoundland and nearby areas (poster). C.S.P.G. Ann. Conv., Calgary.

Langdon, G.S. 1992 in prep. Porosity and permeability in the upper St. George Group carbonates of western Newfoundland. Report for Mobil Canada Ltd.

MacKay, P.A. 1991. A geometric, kinematic and dynamic analysis of the structural geology at Turner Valley, Alberta. PhD thesis, University of Calgary: 138.

Stockmal, G.S. & Waldron, J.W.F. 1991. Balanced cross sections through the Appalachian structural front, Port au Port Peninsula, western Newfoundland (ex. abs.). 1991 Lithoprobe East Transect Meeting, St. John's.

Stockmal, G.S. & Waldron, J.W.F. 1990. Structure of the Appalachian deformation front in western Newfoundland: Implications of multichannel seismic reflection data. Geology, 18, 765-768.

Waldron, J.W.F. & Stockmal, G.S. 1991 (in press). Mid-Paleozoic thrusting at the Appalachian deformation front, Port au Port Peninsula, western Newfoundland. Can. J. Earth Sci., 28.

Williams H. 1979. Appalachian orogen in Canada. Can. J. Earth Sci., 16,792-807.

Williams, H. 1985. Geology, Stephenville map area, Newfoundland. Geol. Sur. Canada Map 1579A, scale 1:100,000.

Williams, H. & Cawood, P.A. 1989. Geology, Humber Arm Allochthon, Newfoundland. Geol. Sur. Canada Map 1678A, scale 1:250,000.

Thin Section Notes

WN-16 (Deer Cove): Pure dolomite. This section contains one of the minor fault gouge zones, which varies in width in the hand specimen from ~1 to 4 cm. The gouge zone consists of cataclasized (comminuted) dolomite reduced to ~10m, with thin anastomosing seams of ultracataclasite developed throughout the width of the gouge zone. Some pressure solution seams developed along boundaries of dissimilar crystalline size domains, and some solution seams developed along boundary between the gouge zone and the country rock. Minor twin development in both the medium and fine crystalline fraction of the country rock.

WN-17(Deer Cove): Pure dolomite. Very similar to WN-20, except that there is no fracture development and there is some very minor twin development in the coarser fraction.

WN-20 (Deer Cove): Pure dolomite. Very fine crystalline (50-200m) grounclmass with medium crystalline (500-1000m) dolomite filling vugs and fractures (veins). The walls of the fractures are not sharp, suggesting that they may be pre- or syn-dolomitization. There are some voids remaining in the vugs, which may be an artifact of section preparation (check hand specimen). There are some significant pressure solution seams, which appear to follow contacts between differing grain size domains. These solution seams are at high angles to the fractures, but do not cross them, though it does appear as though there may be some incipient solution seam development within the vein crystals at one seam crossing. No twinning anywhere in the section, nor any suggestion of crystal lattice distortion by other crystal plastic mechanisms. Within the finer crustalline fraction it appears there may incipient but pervasive grain boundary solution.

WN-35 (Table Mountain): Micritic limestone with some dolomitic (thrombolitic) inclusions. Extremely strong fracture development, with orthogonal trends (high and low angle to bedding). Overall fracturing forms a grid with ~1mm fracture spacing. Fractures seldom >.1mm wide, commonly much narrower. There is strong solution seam development, somewhat chaotic in orientation. This irregularity of stylolite orientation is also noted in outcrop. Certain of the fractures appear to have a direct genetic association with the solution seams, terminating with there wide ends at the seams, tapering to a narrow tip 1 to 2 mm from the seam. Very finely crystalline dolomite inclusions are encased by solution seams. Some of the fractures at low angles to bedding appear to have very small shear displacement and thin gouge development, juxtaposed with minor pockets of spar infill along the mildly undulating fracture surface. There is a (late) development of a non-sutured solution seam along the gouge of these shear fractures. All fractures are filled with gouge or with calcite spar, and all calcite spar is twinned. There is one step of about 2mm between adjacent shear fractures that is filled with the development of very closely spaced extension fractures in a releasing step configuration.

WN-44 (Table Mountain): Micritic pellatoidal limestone. Section contains major bedding-parallel solution seams. There is one major fracture (~.8mm wide) perpendicular to bedding, with a host of minor fractures more oblique to bedding. All fractures are completely filled with calcite spar, as are the voids between micrite pellets. There are quite a number of dolomite rhombs scattered through the groundmass, and there are some globular inclusions of very fine crystalline dolomite, which I suspect may be the dolomitized expression of the framework thrombolites. These dolomite inclusions are surrounded, but not intruded, by solution seams. The calcite in the large fracture is blocky, and at one point a single optically continuous crystal fills the entire fracture width. The calcite fill in this fracture is strongly twinned throughout, and crystals are exceptionally twinned and distorted at intersections with solution seams. Some of the fractures at low angles to bedding have only minor twin development, even at intersections with solution seams. These relationships are pretty strongly suggestive of superposed deformational events, which could be different phases of a single deformational process, but could also be distinct deformational (tectonic) events.

WN-50 (Cape Comorant): Micritic pellatoidal limestone. Strong development of bedding parallel solution seams, with intense extension fracture development at high angles to bedding/solution seams. Fracture spacing ~2mm. Maximum fracture width in the section is 1mm, normal width is ~.1mm, and some fractures appear to be hairline even at 20x magnification. All fractures are completely calcite filled. The fracture-filling (vein) calcite spar has a blocky texture and does not appear to have any preferred crystal orientation. There is no suggestion in the vein fill of a crack-seal mechanism for fracture growth. There are some fractures developed at low angles to bedding that appear to post-date the high-angle to bedding fractures. Twinning is common in all calcite down to a crystal size of ~5m, which includes most of the fracture- filling calcite and also calcite spar growing in the voids between micrite pellets. Solution seams developed along bedding appear to both pre- and post-date the fractures which are at high angles (~75o) to bedding, though the suture teeth are parallel to the fractures, suggesting that most of the solution is probably associated with (contemporaneous with) the development of the high-angle-to-bedding fractures.

WN-53 (Cape Comorant): Micritic pellatoidal limestone from area of tension gash development. Fractures are 1+mm wide, and some have a breecia-like appearance, with stoping of country rock fragments into the fracture. Fracture width and geometry are quite variable (variations in fracture width are directly linked to extension of a fracture with an irregular geometry. There is only a very low and scattered twin development within the fracture-filling calcite spar (which has a blocky texture), and there are no stylolites within the section, though some were seen in outcrop.

WN-59 (Table Mountain): Micritic limestone with only a minor development of hairline fractures, at high angles to bedding. My note indicate that this is a thin limestone intercalated within cryptocrystalline dolostone (probably Aguathuna Fm.). There is some coarse crystalline calcite filling what were probably irregular fracture voids (possibly primary dessication fratures). There are some minor gypsum nodules along what appears to be a primary sedimentary seam (possibly dolomitic) at margin of section. Some solution seams are developed along and parallel to this sedimentary seam. The spar calcite is extremely highly twinned and the crystals are flattened suggesting shortening parallel to bedding. There is no indication of solution or fracturing associated with this shortening event.