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# Joints, tensile strength and preferred fracture orientation in sandstones, New Brunswick and Prince Edward Island, Canada

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The orientations of tensile fractures in Upper Devonian, Carboniferous and Lower Permian sandstones of southern New Brunswick and Prince Edward Island show correlation at the submicroscopic scale of microcrack alignments, the macroscopic scale of joints, and the megascopic scale of airphoto lineaments. Planes of minimum tensile strength and planes of preferred fracture, induced in visibly unfractured sandstone test-samples by line-loading and point-loading tests, are identified as microcrack alignments. The joints and airphoto lineaments have microcrack alignments parallel to them, but not all microcrack alignments are represented at the macroscopic and megascopic scales.

Deformed Carboniferous sandstones east of Saint John have two prominent orthogonal joint systems with microcrack alignments parallel to the four joint sets. The airphoto lineaments are parallel to only three joint sets. Southeast and northeast striking joints in one orthogonal system are tentatively interpreted as planes of extension and release respectively, related to the direction of compression during the Variscan-Appalachian orogeny. The other orthogonal system, with joint sets striking close to 010° and 100°, is interpreted as post-Triassic in age, possibly related to the presently acting crustal stresses in eastern North America.

Il y a correspondance dans les grès du Dévonien supérieur, du Carbonifère et du Permien inférieur du sud du Nouveau-Brunswick et de l'île du Prince-Edouard entre l'orientation des fractures de tension à diverses échelles: microscopique — alignement des microfissures; macroscopique — diaclases; et mégascopique — linéaments observés à partir de photographies aériennes. On reconnaît comme alignements de microfissures les plans de force de traction minimale et les plans de fracture préférentielle occasionnés par des essais de charges linéaires et ponctuelles sur des échantillons types de grès préalablement exempts de fractures apparentes. Bien que parallèlement aux diaclases et aux linéaments on retrouve des alignements de microfissures, ce ne sont pas tous les alignements de microfissures qui s'expriment aux échelles macroscopique et mégascopique.

A l'est de Saint-Jean, les grès déformés du Carbonifère possèdent deux systèmes distincts de diaclases orthogonales accompagnés d'alignements de microfissures parallèles aux quatre ensembles de diaclases. Les linéaments observés sur photographie aérienne ne sont parallèles qu'à trois ensembles de diaclases. On interprète provisoirement les diaclases de direction sud-est et nord-est dans l'un des systèmes orthogonaux comme, respectivement, des plans d'extension et de relâchement reliés à la direction de compression durant l'orogenèse varisque-appalachienne. Des orientations se rapprochant de 010° et 100° caractérisent l'autre système orthogonal qui serait d'âge post-triasique et peut être relié aux forces de tension contemporaines agissant sur l'écorce terrestre dans l'est de l'Amérique du Nord.

[Traduit par le journal]

## INTRODUCTION

Although the rock occurring between joints is often assumed to be unaffected by fracture, there have been a number of studies demonstrating that fractures, at a much smaller scale than joints, do exist in the seemingly unfractured rock. For example, correlation between joints and microfabric has been described in sandstone by Reik and Currie (1974), and in quartz diorite by Swolfs *et al.* (1974). Microcrack alignments may exist either parallel or perpendicular to the maximum principal stress direction(s) of the geological past (Lajtai and Alison 1979). Preliminary comparison of microcrack alignments and jointing

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(Lajtai and Alison 1979) nas indicated that joints have microcracks running parallel to them, but not necessarily all microcrack alignments become joints.

The main purpose of the present investigation has been to establish a correlation between tensile fractures occurring at the submicroscopic (microcrack alignments), macroscopic (joints), and megascopic (airphoto lineaments) scales. Joint orientations have been measured in the sandstones of five predominantly terrestrial formations in southern New Brunswick and Prince Edward Island (Fig. 1), ranging from Upper Devonian to Lower Permian in age. Microcrack alignments in oriented, visibly unfractured sandstone test-samples have been compared with the strikes of subvertical (75-90° dipping) joints in the flat-lying Pictou Formation and the gently dipping Perry Formation (mainly undeformed rocks of Williams 1978, see Fig. 1), and in the folded, thrust-faulted and locally

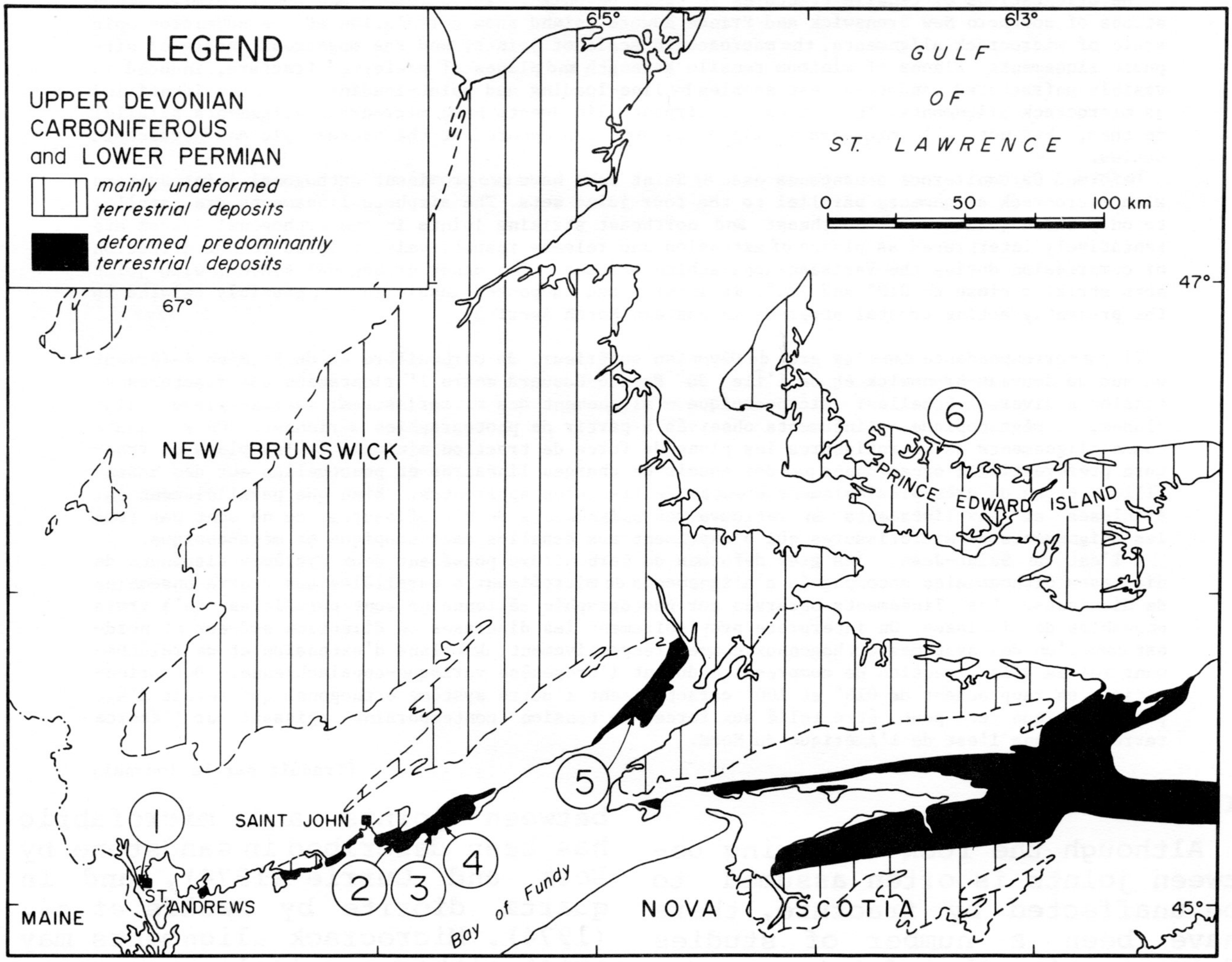


Fig. 1 - Location map of sandstone formations investigated. Locality 1 - Perry Formation; 2 - Balls Lake Formation; 3 - McCoy Head Formation (Emerson Creek); 4 - McCoy Head Formation (Gardner Creek); 5 - Boss Point Formation; 6 - Pictou Formation. Areas of mainly undeformed and deformed Upper Devonian, Carboniferous and Lower Permian rocks are based on Williams (1978).

cleaved Pennsylvanian Boss Point and McCoy Head Formations (deformed rocks of Williams 1978). Airphoto lineaments have previously been established (Naing 1976, Naing and Lajtai 1977) east of Saint John in southern New Brunswick.

Two methods for identifying preferentially oriented microcracks in rocks are the point-loading and the line-loading (Brazilian) tests. The first produces a preferred fracture orientation which corresponds to the plane of minimum tensile strength, and the second determines the tensile strength for any plane (McWilliams 1966, Lajtai and Alison 1979, Lajtai 1980); minima on the tensile strength distribution curve identify the azimuths of the microcrack alignments.

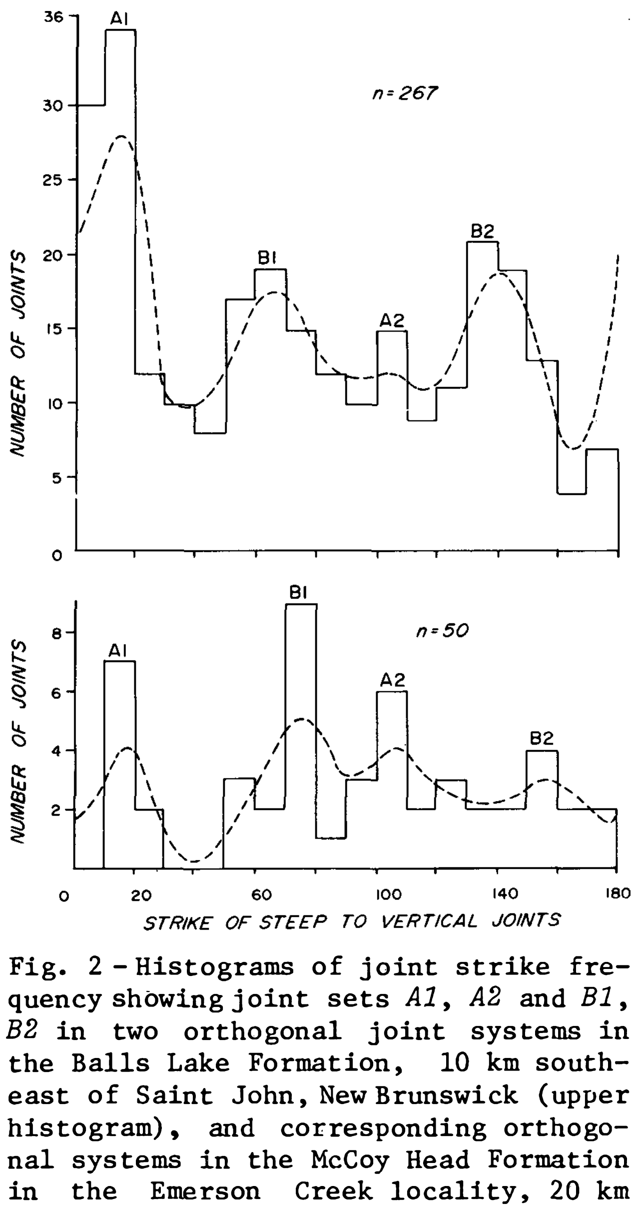


Fig. 2 - Histograms of joint strike frequency showing joint sets *A1*, *A2* and *B1*, *B2* in two orthogonal joint systems in the Balls Lake Formation, 10 km southeast of Saint John, New Brunswick (upper histogram), and corresponding orthogonal systems in the McCoy Head Formation in the Emerson Creek locality, 20 km east of Saint John (lower histogram). Broken lines are smoothed distribution curves.

Fracture tests were made on sandstone samples from flat-lying or gently dipping (0-15° dip) beds in four of the formations investigated. Discs of sandstone, prepared by slicing core drilled perpendicular to bedding in the samples, were loaded along the axis of the disc in the point-loading tests and along diametral planes in the line-loading tests. The discs were 22.9 mm in diameter and 7.9 mm thick. Thin sections of the sandstone test-samples show no preferred orientation of constituent grains or grain boundaries, and the fractures produced during the tests are assumed to represent microcrack alignments.

The fracture planes produced in both tests were perpendicular to bedding. In the point-loading tests, the results were plotted as frequency histograms (Figs. 3,4,6 and 8) with the number of fractures counted for each 10° interval of azimuth. Smoothed distribution curves are shown on the same figures. In the line-loading tests, the tensile strength was computed at 10° azimuth intervals and displayed to show variations of tensile strength with azimuth in relation to the strike of joints and preferred fractures.

Correlation of results between the two tests is unequivocal only if the distribution of tensile strength as a function of orientation is unimodal, in which case the peak of the preferred fracture orientation curve or histogram corresponds to the trough on the tensile strength distribution curve. In most rocks, however, there is more than one microcrack alignment and therefore the tensile strength distribution curve may have more than one minimum. This condition, however, may not be reflected by the preferred fracture distribution unless the tensile strength belonging to each microcrack alignment is of the same order of magnitude. Therefore secondary or tertiary microcrack alignments can only be detected with any reliability by the line-loading technique (Lajtai and Alison 1979, Lajtai 1980).

*Joint Terminology*

In descriptive classification, joints have been divided into *systematic* and *nonsystematic* joints (Hodgson 1961, Nickelsen and Hough 1967). Systematic joints are planar or broadly curving, occur in sets which cut across other joints and are commonly perpendicular to bedding. Nonsystematic joints are curviplanar and terminate against other joints and bedding planes. In the present investigation, systematic and nonsystematic joints have been distinguished only in the Pictou and Perry Formations.

*Presentation of Data*

Joint orientation data for the sandstone formations investigated are presented in histogram form (Figs. 2,3,4,6 and 8) showing the number of joints striking within each 10° azimuth interval. A smoothed distribution curve is displayed on each histogram, drawn according to the formula

$$b' = [a + 2b + c]/4$$

where $b'$ is the smoothed frequency for each azimuth interval, $b$ is the unsmoothed (actual) frequency for the same interval, and $a$ and $c$ are the unsmoothed (actual) frequencies for the two azimuth intervals adjoining the $b$ interval. The same smoothing formula has also been applied to the orientation data for preferred fracture. Smoothing of the orientation data emphasizes only the major trends and consequently may eliminate the minor but nonetheless geologically significant trends. For this reason we present both the smoothed and the unsmoothed (actual) orientation data.

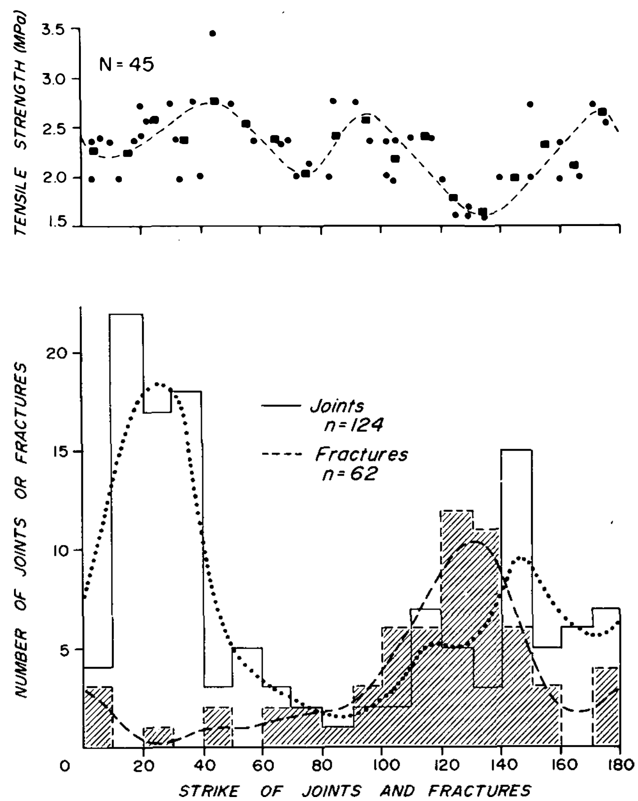


Fig. 3 - Joints, preferred fracture orientation and tensile strength in the flat-lying Pictou Formation near Cavendish, Prince Edward Island. Solid circles are individual tensile strength measurements, solid squares are averages per ten degree azimuth interval. In the histogram, the smoothed distribution curve for joint strikes is a dotted line, and that for preferred fracture azimuths is a broken line. Preferred fracture orientation correlates approximately with the strike of the 145° (nonsystematic) joints. The tensile strength minimum at 075° has no joint equivalent.

## JOINTS, TENSILE STRENGTH AND PREFERRED FRACTURE ORIENTATION

### *Balls Lake Formation*

Mississippian(?) sandstones, siltstones and conglomerates (Balls Lake Formation, Alcock 1940, part of the "Mispek Group" of Hayes and Howell 1937 and the "Mispeck Group"

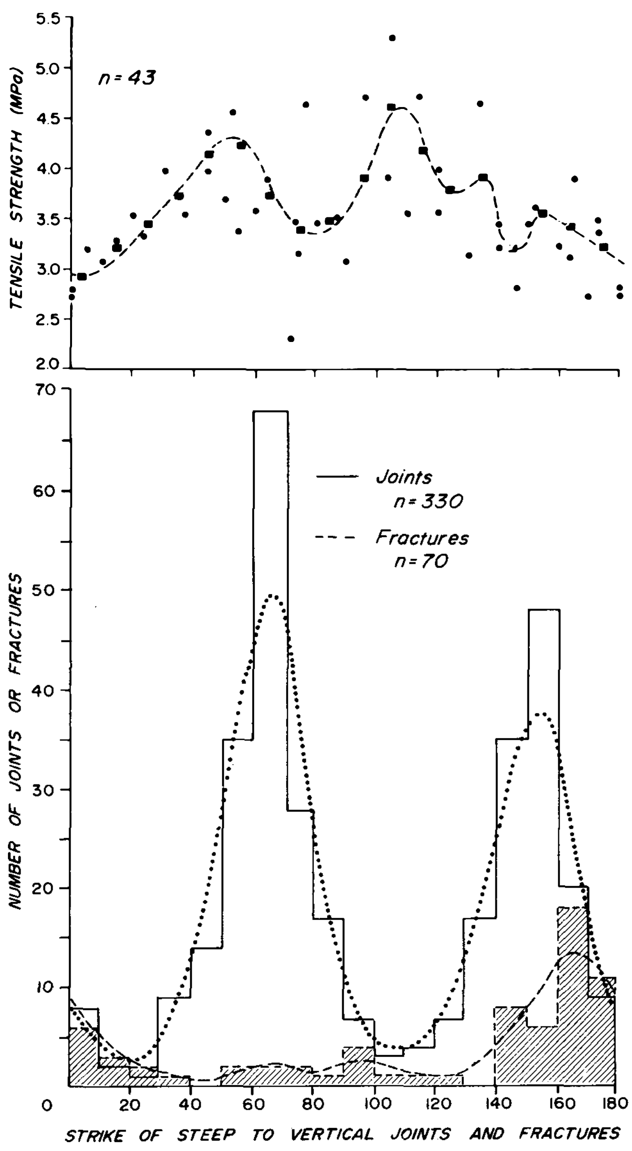


Fig. 4 - Tensile strength (above), preferred fracture orientation and joints (below) in the Perry Formation on the St. Andrews Peninsula and Minister Island, New Brunswick. Orthogonal joint sets strike 065° and 155°. Symbols as in Figure 3.

of McCutcheon, fig. D-2, *in* Ruitenberg *et al.* 1979) in the Mispec Bay area, 10 km southeast of Saint John, are deformed, with gently to moderately inclined $S_1$ and $S_2$ cleavages, and asymmetrical $F_2$ folds, trending mainly northeast (Ruitenberg *et al.* 1975, 1979). The Mispec Group ranges up to Westphalian B or C (Rast *et al.* 1978, McCutcheon *in* Ruitenberg *et al.* 1979), indicating a late Westphalian or younger age for the deformation, ascribed to the Variscan-Appalachian orogeny (Rast and Grant 1973).

Joints in the Balls Lake Formation along the coast and inland near Mispec Bay (Fig. 1, locality 2) show two orthogonal systems, designated *A* and *B*, with joint sets striking 015° and 105° designated *A1*, *A2*, and joint sets striking 060° and 140° designated *B1*, *B2* (Fig. 2). Bedding is mostly gently inclined, locally subhorizontal. The joints are vertical or steep (75° to subvertical dips).

### *McCoy Head Formation, Emerson Creek locality*

Joints in gently dipping Pennsylvanian sandstone beds (McCoy Head Formation, Hayes and Howell 1937) on the coast southeast of Emerson Creek, 20 km east of Saint John (Fig. 1, locality 3), show two orthogonal systems with joints striking 015° and 105° (*A1*, *A2*) and 075° and 155° (*B1*, *B2*), similar to those in the Balls Lake Formation (Fig. 2).

### *Pictou Formation*

Joints striking 025° and 145° are prominent in flat-lying sandstone beds near Cavendish on Prince Edward Island (Fig. 1, locality 6) which form the youngest beds of the Pictou Formation, dated as Lower Permian (Barss and Hacquebard 1967). The joints are not orthogonal; the dihedral angle of about

60° is compatible with a shear origin. However, the two sets of joints are unlikely to be conjugate shear fractures; the 025° joints are systematic and the 145° joints are nonsystematic, and neither set shows surface features compatible with a shear origin. The weak joint orientation peaks at 055° and 115° (Fig. 3) are orthogonal to the dominant 025° and 145° trends, suggesting that two orthogonal joint systems may be present in the Pictou Formation.

The Pictou Formation (Fig. 3) has a single preferred fracture orientation around 130°, correlating approximately with the 145° (nonsystematic) joints. The tensile strength distribution curve has three troughs. The minimum corresponds to the 130° preferred fracture orientation, the intermediate one at 075° has neither joint nor preferred fracture orientation equivalents, while the trough at 010° may correlate with the 025° (systematic) joints.

*Perry Formation*

Upper Devonian sandstones dip gently southeastward on the St. Andrews peninsula and Minister Island (Fig. 1, locality 1) in a thick homoclinal sequence of red conglomerates, sandstones and siltstones, with some interbedded basalts (Perry Formation, McKenzie and Alcock 1960, Rhoades 1963, Cumming 1966, Schluger 1973). Joints strike 065° and 155°, constituting an orthogonal system (Fig. 4).

The 065° joints, which dip steeply (75 - 90°) north-northwest perpendicular to bedding, are systematic joints. They are planar and cut across the 155° joints. The 065° joints also persistently cut through pebbles, cobbles and boulders of igneous rocks in pebbly sandstones and conglomerates. Plumose structures are present sporadically on the 065° joint surfaces (Fig. 5).

The 155° joints are nonsystematic joints. They are curviplanar, varying up to 25° in strike and dip from the mean 155°/vertical attitude. The 155° joints mostly deflect around pebbles, and plumose structures are lacking. The 155° joints commonly terminate against the 065° joints (Fig. 5).

A diabase dyke which crosses the St. Andrews peninsula and the north end of Minister Island (Rhoades 1963) trends 065° parallel to the systematic joints. Columnar jointing is present in the 11 m thick dyke; the columns plunge south-southeast at 5-15°, indicating that the dyke contacts have a steep north-northwest dip similar to that of the 065° joints. The frequency of the 065° joints in the Perry Formation increases over 500 m approaching the dyke and the closest (5 to 30 cm) spacing occurs in sandstone on either side of the dyke. The 155° joints in the sandstone continue through the dyke and cut the columns. The age of the dyke based on the composition and freshness of the mineral assemblage is Late Triassic or Early Jurassic (Pajari, G.E., Jr., oral comm. 1981).

The Perry Formation has a strong preferred fracture orientation at about 170° which is subparallel to the north-south tensile strength minimum (Fig. 4). The nearest joint trend at 155° is probably unrelated. It is more likely that the minor preferred fracture trend (unsmoothed distribution) at 145°, confirmed by a minor low in tensile strength, is the microcrack alignment corresponding to the 155° joints. The 080° major trough on the tensile strength distribution curve may correlate with the 065° joints, but the major trough at N-S does not clearly correlate in

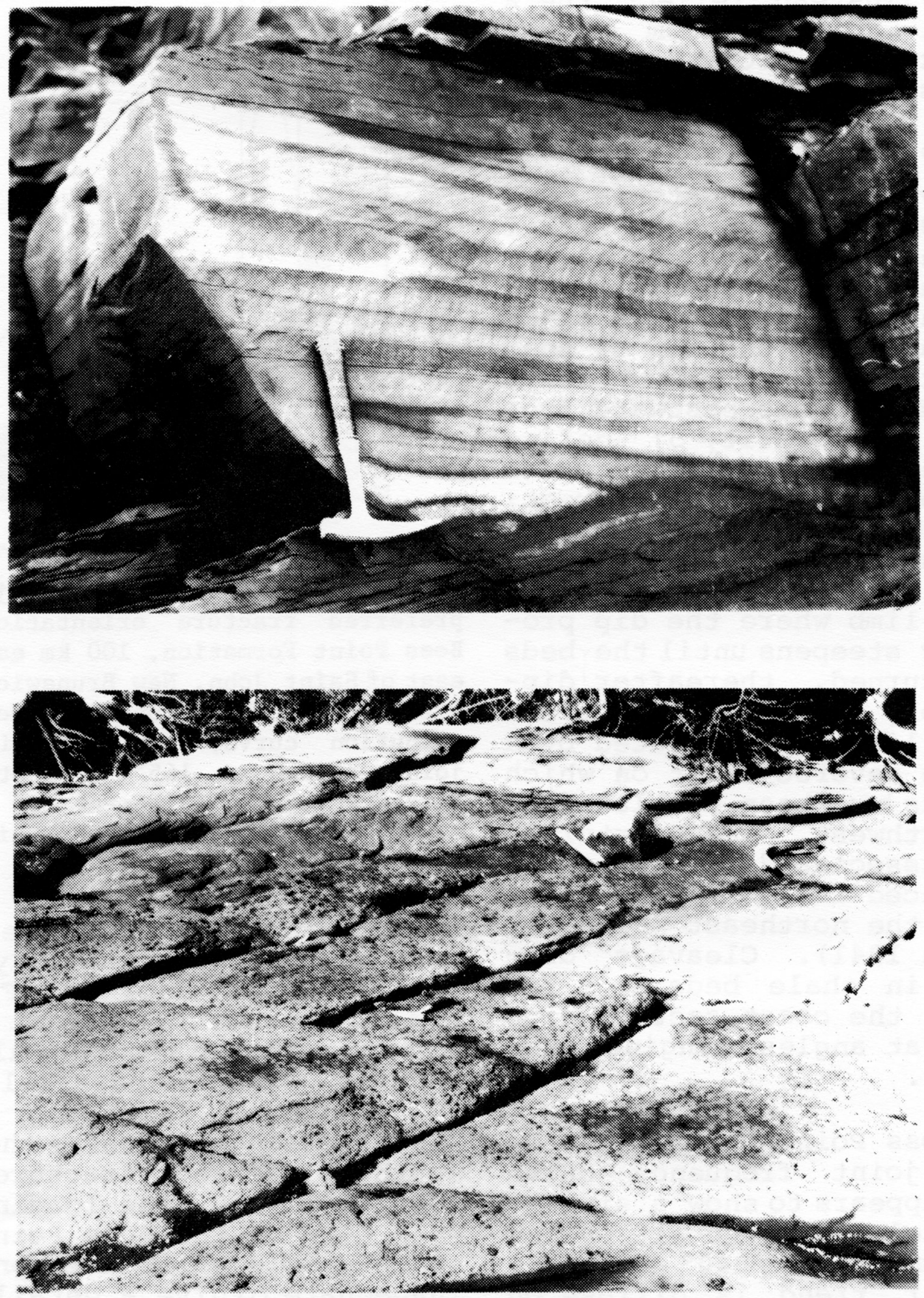

Fig. 5 - Joints in the Perry Formation, Minister Island, New Brunswick. Plumose markings on systematic joint surface striking 065°, north end of island (upper photograph). Orthogonal joints exposed on a gently dipping sandstone bed surface, west side of island; 155° joints (parallel to hammer handle) terminate against 065° joints (lower photograph).

orientation with the 155° joints; the 080° and N-S tensile strength minima may instead reflect the *A* orthogonal joint system of the Balls Lake and McCoy Head sandstones east of Saint John.

*Boss Point Formation*

Pennsylvanian sandstones and shales 100 km east-northeast of Saint John (Boss Point Formation, Flaherty and Norman 1941) are deformed by northeast trending major folds. Changes in the dip of bedding continuously exposed for 3 km along the coast eastward from Alma (Fig. 1, locality 5) define a major asymmetrical syncline verging toward the northwest; the dip of bedding changes from gentle southeastward in the northwest limb to northwestward in the southeast limb where the dip progressively steepens until the beds are overturned, thereafter dipping steeply southeastward. The southeast limb is truncated by a high angle reverse fault on which older rocks have been displaced up to the northwest. The overturned beds and associated reverse fault can be traced for at least 10 km inland to the northeast (Flaherty and Norman 1941). Cleavage, discernible in shale beds at a few places in the coast section dips southeast at angles ranging from 20° to 75°.

In the Boss Point Formation, the smoothed joint frequency curve (Fig. 6) appears to show a single, approximately orthogonal system with joints striking 040° and 120°; the latter trend is diffuse on the histogram, and may represent two sets of joints striking at 110° and 135°. The 135° set would then be nearly orthogonal to the 040° joints. The smoothed joint frequency curve also shows a weak joint trend at 165°.

The Boss Point Formation has a strong preferred fracture alignment at 030°, approximately parallel to the 040° joints (Fig. 6), and has a weaker alignment at 005°. A weak preferred fracture alignment is also present parallel to the 135° joints. Smoothing of the distribution eliminates the north-south preferred fracture alignment. Only 20 line-loading tests were done on the Boss Point sandstone sample which are considered inadequate to give a detailed tensile strength distribution.

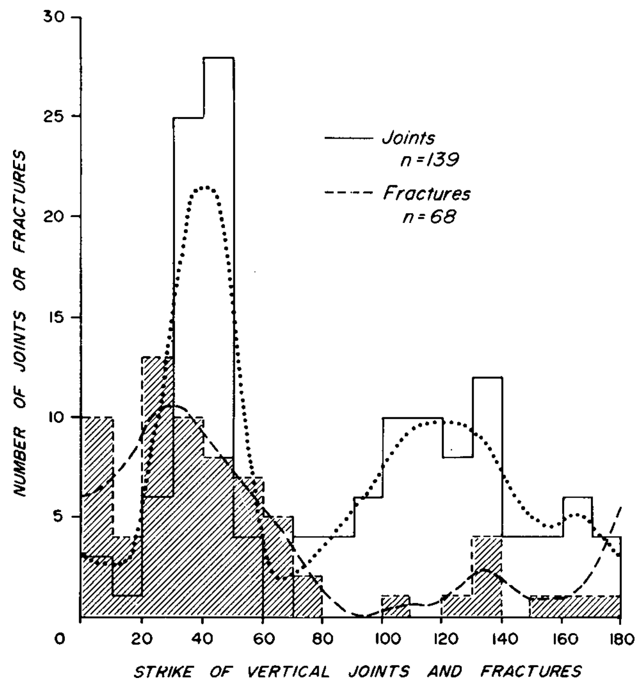


Fig. 6 - Histograms showing joints and preferred fracture orientation in the Boss Point Formation, 100 km east-northeast of Saint John, New Brunswick. Joints strike 040° and 120° on the smoothed distribution curve, and there is a minor joint strike at 165°. The strong preferred fracture alignment is approximately parallel to the 040° joints. Symbols as in Figure 3.

*McCoy Head Formation, Gardner Creek locality*

Pennsylvanian sandstones and shales of the McCoy Head Formation east of Gardner Creek, 25 km east of Saint John (Fig. 1, locality 4),

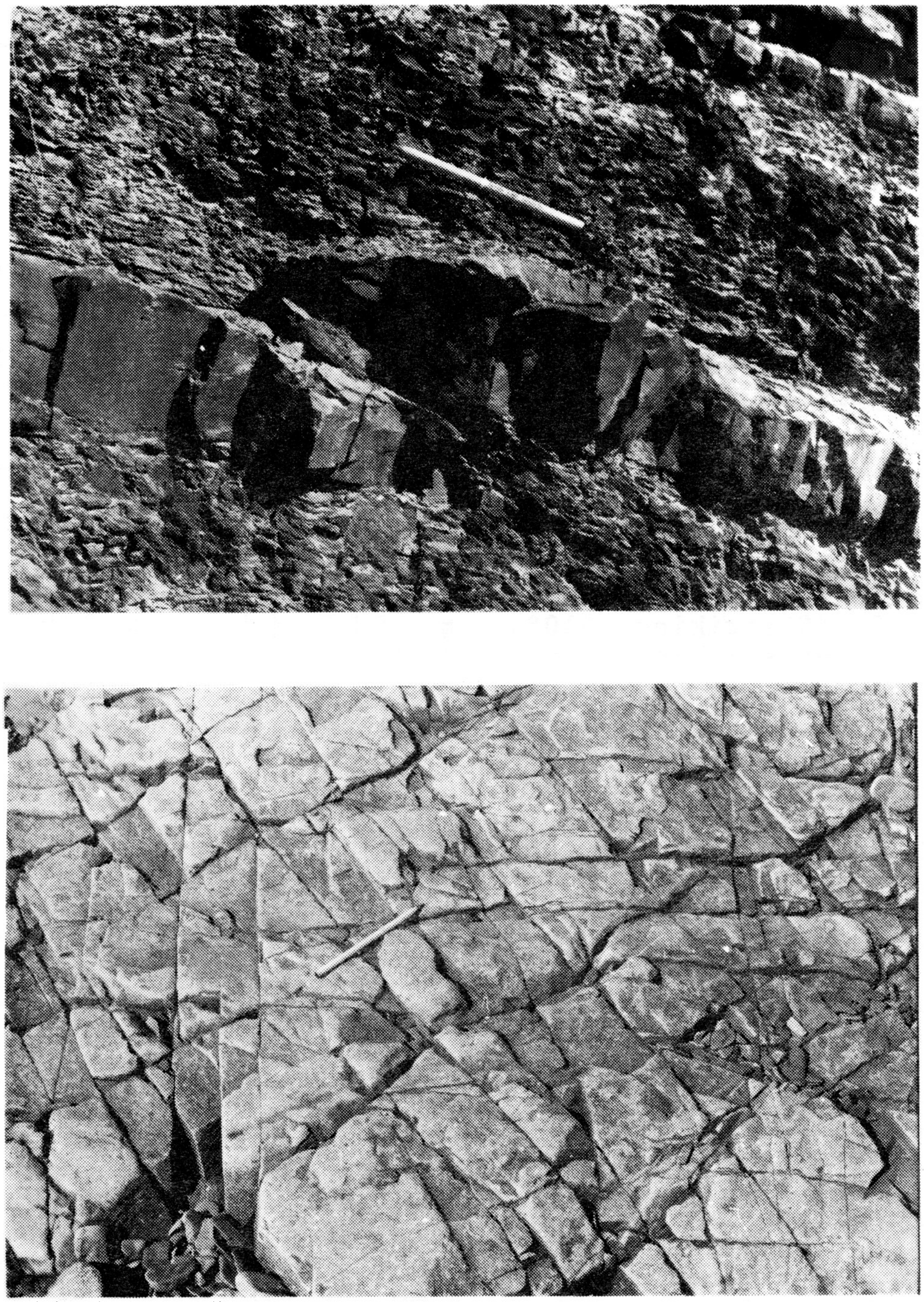

Fig. 7 - Structures in the McCoy Head Formation, coast east of Gardner Creek, New Brunswick. Sandstone bed is displaced 20 cm up to the northwest (left) on a low angle reverse fault (upper photograph). Joints in two orthogonal joint systems exposed on a gently dipping sandstone bed surface strike 017° (parallel to pen), 045°, 100°, and 135° (lower photograph).

appear more deformed than in the Emerson Creek locality. Beds have been displaced up towards the northwest on small scale thrusts (Fig. 7). Slickensides plunge southeast at 20° to 35° on the thrust surfaces, and cleavage parallel to the thrust planes is locally developed in the shales. The thrusts are deformed by northeast trending folds which verge toward the southeast. Bedding is gently inclined in the long limbs of the asymmetrical folds, and is subvertical or overturned southeastward (dipping steeply northwest) in the short limbs.

Joints measured in the McCoy Head Formation along 800 m of coastal outcrop east of Gardner Creek show two orthogonal systems (Fig. 7) designated *A* and *B*, with joint sets *A1*, *A2* striking 010°, 100°, and *B1*, *B2* striking 045°, 135° (Fig. 8).

A visibly unfractured sandstone block from gently inclined bedding in the McCoy Head Formation received the most comprehensive testing. Instead of spreading the tensile strength tests at 10° intervals over the 0-180° azimuth range, multiple tests (15 tests each) were made for selected orientations derived from information on jointing and preferred fracture orientations. Although the standard deviation of the results was found to be fairly large, azimuths of tensile strength minima parallel to each joint trend of the two orthogonal systems are apparent (Fig. 8). The azimuths of the lowest tensile strength minima correlate with the *A1* and *B1* joint sets of the two orthogonal systems.

The smoothed preferred fracture orientation curve (Fig. 8) shows correlation of preferred fracture with the *A1*, *B1* and *B2* joint sets, but not clearly with the *A2* joint set. It should be noted that point-loading tests, resulting in

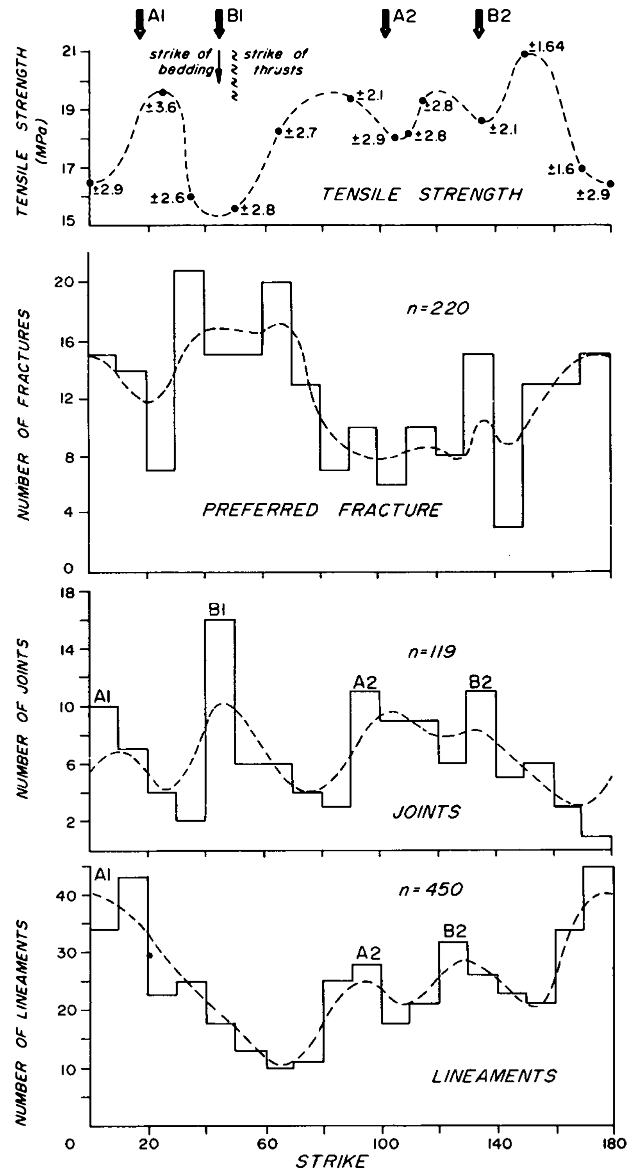


Fig. 8 - A comparison of trends displayed by tensile strength, preferred fracture, joints and airphoto lineaments in the McCoy Head Formation east of Gardner Creek, New Brunswick. Solid circles are means of 15 individual measurements. Standard deviations are shown for each mean. The solid arrows are the strikes of the joints in the two orthogonal joint systems in the outcrop shown in Figure 7 (lower photograph). There is a tensile strength minimum parallel to each joint set, but the strongest minima correlate with the joint sets *A1*, *B1*. There is no lineament trend parallel to the *B1* joints. Broken lines are smoothed distribution curves.

the determination of a preferred fracture orientation, can be effective in defining only the plane of minimum tensile strength (Lajtai and Alison 1979). For the three sandstones (Pictou, Perry, and McCoy Head at Gardner Creek) for which both point- and line-loading data are resented, the lowest tensile strength was measured across the plane of strongest preferred fracture orientation. Peaks of lower order on the preferred fracture orientation diagram may also be significant. For the McCoy sandstone, the two major and the one minor peak all correspond to minima in tensile strength. However, not all minima in tensile strength have corresponding preferred fracture peaks, e.g., *A2* of the McCoy Head Formation (Fig. 8), the 080° minimum in the Perry Formation (Fig.4), and the 075° minimum in the Pictou Formation (Fig. 3).

AIRPHOTO LINEAMENT TRENDS

A remarkable feature of the *B* orthogonal joint system is that the strong *B1* joints and parallel microcrack alignment do not produce lineaments identifiable by aerial photograph studies (Fig.9, after Naing and Lajtai 1977). The Balls Lake Formation has strong lineaments parallel to the *A1*, *A2* and *B2* joints, but no lineament is identifiable parallel to the *B1* joints (Fig. 9). The McCoy Head Formation shows a similar lineament distribution curve (Fig. 9), although there is also a weak lineament parallel to the *B1* joints in the unsmoothed distribution histogram (Fig. 8). The Boss Point Formation has lineaments trending approximately parallel to the 165° minor joints (*A1* lineament trend) and to the 120° joints (*B2* trend), and possibly to the *B1* joints (*cf.* Figs. 6 and 9); the *A2* lineament trend is missing.

The average length of the line-

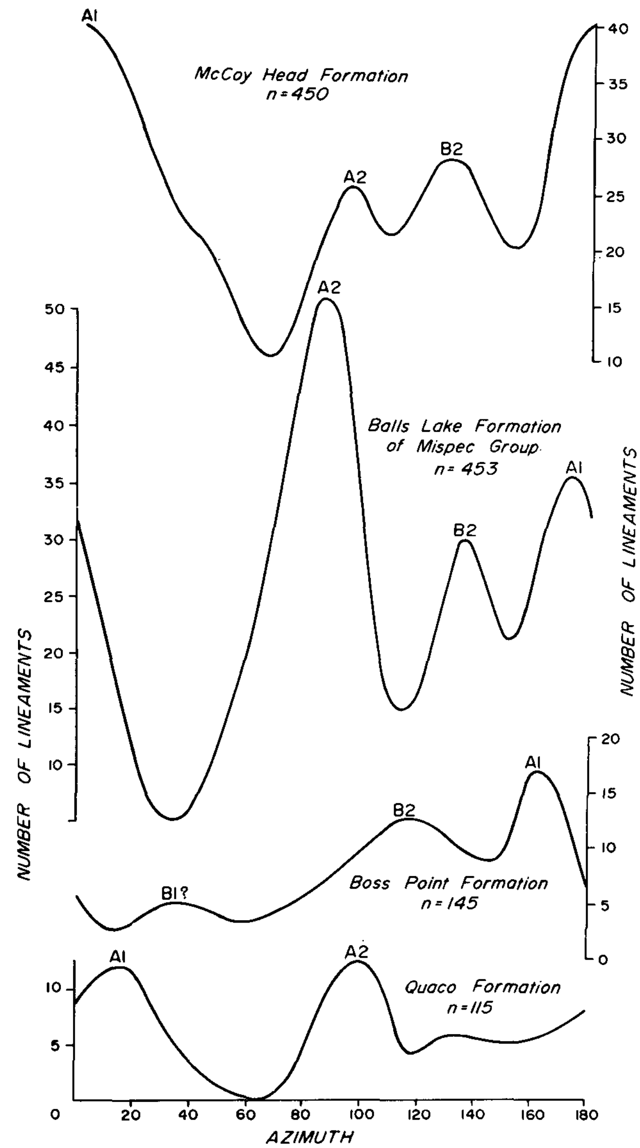


Fig. 9 - Airphoto lineament trends in four formations. The top three formations were affected by the Variscan-Appalachian orogeny. The *A1*, *A2* and *B2* lineament trends correlate approximately with the strike of corresponding joints in the Balls Lake and McCoy Head Formations (Figs. 2 and 8), but a lineament parallel to the *B1* joints is missing. The Triassic Quaco Formation shows lineaments parallel only to the *A* orthogonal joint system. (After Naing and Lajtai 1977).

aments is about 1.5 km, and therefore it would appear that where lineaments are lacking, the microcracks have grown only to joints of outcrop scale. The *B1* joints appear to be unique in lacking lineaments. Although both joint sets of the orthogonal joint system *A* are represented at the megascopic scale of lineaments in Precambrian to Triassic rocks in the region east of Saint John (Fig. 10), the 100° (*A2*) trend is the more prominent.

The investigation supports the view that tensile fracture originates at microscopic or submicroscopic stress concentrations and may grow in size to reach the macroscopic scale of joints (Lajtai 1977) or even the megascopic scale of lineaments. While earlier formed fractures propagate, new microfractures nucleate and grow con-

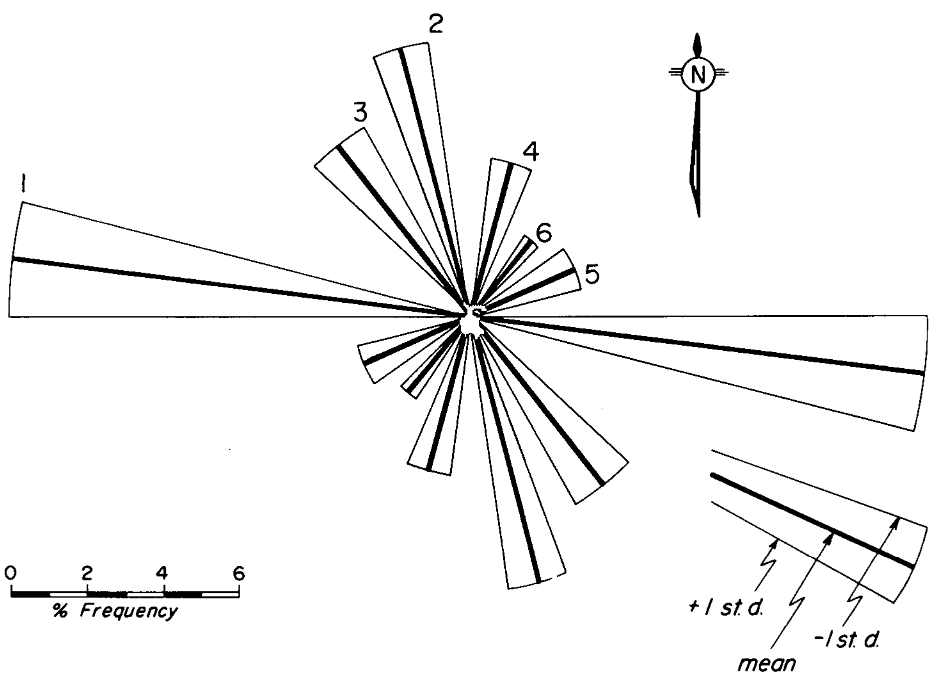


Fig. 10 - Airphoto lineament trends in the region east of Saint John, New Brunswick (after Naing 1976). The compilation includes all rocks.

## DISCUSSION AND CONCLUSIONS

The orientations of joints, tensile strength minima, preferred fractures and airphoto lineaments show close correlation in the McCoy Head (Gardner Creek) sandstone which received the most comprehensive testing, and they show correlation in the other sandstones investigated (Table 1): Microcrack alignments identified by the tensile strength minima and preferred fracture orientations are not always represented by joints or lineaments, but joints and lineaments are represented by microcrack alignments.

tinuously between them. Consequently, lineaments and joints should have a microcrack alignment parallel or subparallel to them. This is indeed the case in the sandstones in the present study. On the other hand, not all microcrack alignments have joint or lineament equivalents (e.g., there is no joint trend corresponding to the 075° tensile strength minimum in the Pictou Formation on Prince Edward Island, and northeast trending lineaments are lacking in the Carboniferous formation east of Saint John).

Nickelsen and Hough (1967) interpreted the approximately orthogonal systematic and nonsystematic joints in the Carboniferous rocks of the Appalachian Plateau of Pennsylvania, designated the *fundamental joint system*, as developing through a single cycle of coaxial tectonic loading and unloading. The systematic joints, which strike approximately perpendicular to the axial direction of the folds, formed early during tectonic loading while the nonsystematic joints, which strike nearly parallel to the axial direction of folds, are later release-type fractures.

The two types of joints in the fundamental joint system represent the load-parallel tensile fracture of rock mechanics terminology, termed *load-parallel* joints herein, and the load perpendicular release, or relaxation, fracture (extension fracture of Griggs and Handin 1960), termed *release* joints herein. The terms *load-parallel* and *release* specify the macroscopic field of stress existing at the time of formation of the joints. The actual stress responsible for both load-parallel and release joints is a tensile stress acting locally around submicroscopic Griffith cracks and flaws (Lajtai 1977).

The mechanism of release joint formation is similar to that involved in load-parallel joints insofar as fracture nucleation and growth would take place from microscopic stress concentrations and would proceed in an essentially compressive macroscopic stress field albeit an extensional one (i.e. decreasing compression). It is probable that the most effective parameter producing a release joint is the tensile residual stress (Friedman 1972, Lajtai 1977, Stringer and Lajtai 1979), localized in the cement of a sandstone and there growing in relative intensity as the original tectonic compression slowly relaxes.

The absence of plumose structures on the nonsystematic or release joints of Nickelsen and Hough (1967, p. 614, p. 626) suggests that release joints form very slowly. They noted (*ibid.*, p. 614) that whereas systematic joints are common in fresh outcrops, nonsystematic joints commonly do not appear in the high walls of strip mines until after several months or a year of weathering.

## *PERRY FORMATION ORTHOGONAL JOINTS*

In addition to joints formed as a result of tectonic compression and its subsequent relaxation, a third type of joint results from tensional stress (Nickelsen and Hough 1967), associated with crustal extension and more specifically with the bending of strata, i.e. flexures associated with

TABLE 1

| | PICTOU FORMATION | | | PERRY FORMATION | | | BOSS POINT FORMATION | | | McCOY HEAD FORMATION (Gardner Creek) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Joints (S, systematic; N, nonsystematic) | 025° (S) | - | 145° (N) | 065° (S) | 155° (N) | - | 040° | 120° | (165°) | 010° | 045° | 100° | 135° |
| Tensile strength minima | ?010° | 075° | 130° | ?080° | 145° | 180° | 040° | | | 000° | 045° | 105° | 135° |
| Preferred fractures | - | - | 130° | - | (145°) | 170° | 030° | 135° | (005°) | 000° | 050° | ?115° | 135° |
| Airphoto lineaments | | | | | | | (040°) | 120° | 160° | 000° | - | 100° | 135° |

Summary of trends of joints, tensile strength minima, preferred fractures and airphoto lineaments in sandstones of the Pictou, Perry, Boss Point and McCoy Head (Gardner Creek) Formations. Trends in parentheses indicate minor peaks, and question-marks *indicate possible correlative trends. Dashes indicate that correlative trends are absent.*

vertical movement in the crust (draping across basement faults, diapiric rise of magma or salt), or warping of a sedimentary basin (Price 1974). Such joints are termed *tensile* joints herein. Again, the adjective (tensile) specifies the macroscopic stress field. In load-parallel, release and tensile joints, the individual tensile fracture nucleates from a submicroscopic stress concentration at a microcrack. The extension of a single microcrack to a macroscopic joint would depend primarily on the large-scale stress field (as opposed to the microscale of microstress concentration).

*ORTHOGONAL JOINT SYSTEM B*

In the Boss Point and McCoy Head (Gardner Creek) Formations, there is a consistently strong northeast trend of preferred fracture orientation (Figs. 6 and 8), and in the McCoy Head sandstone the plane of minimum tensile strength trends northeast (Fig. 8). The tensile strengths (20 tests) computed for the Boss Point sandstone ranged from 5 to 10 MPa; the lowest value occurred at azimuth 040°, again corresponding to the northeast (*B1*) direction. The sandstone test-sample from the Pictou Formation on Prince Edward Island shows a strong southeasterly preferred fracture orientation (Fig. 3) unlike any of the other formations. In older (Upper Pennsylvanian) Pictou Formation sandstone at Fredericton, New Brunswick, 250 km to the west, however, northeast trending preferred fractures (Lajtai and Alison 1979, fig. 11) may correlate with the *B1* joints in the Balls Lake, McCoy Head and Boss Point Formations.

The northeast trend of *B1* joints, tensile strength minimum and preferred fracture in the Carboniferous sandstones east of Saint John are parallel to the trend of folds and thrusts formed by northwest-southeast compression during the Variscan-Appalachian orogeny. In model tests designed to simulate tectonic loading during cementation and subsequent unloading, the plane of minimum tensile strength and strong preferred fracture orientation was found to be the plane of release; load-parallel microcracks may form during the loading cycle or possibly during relaxation (Lajtai and Alison 1979). In the Carboniferous sandstones investigated, by analogy, the northeast striking tensile fractures would represent the plane of tectonic relaxation; the southeast striking tensile fractures would be parallel to the direction of tectonic compression (or relaxation).

The southeast striking joints of the orthogonal joint system *B* in the Carboniferous sandstones east of Saint John are tentatively interpreted as load-parallel joints and the northeast striking joints as release joints, related to northwest - southeast compression and relaxation respectively during the Variscan-Appalachian orogeny. A difficulty with this interpretation is that during folding and thrusting the bulk stresses would produce vertical extension, whereas the subvertical load-parallel joints imply northeast-southwest axial extension. However, axial extension, indicated by wrench faulting, may result from continued tectonic compression after the folding and thrusting stage of orogeny (Dewey 1969). North-northeast trending, left lateral wrench faults are present in the deformed Carboniferous rocks west of Saint John (Grant, R.H., oral comm. 1981) and possibly in the Gardner Creek area (map 21H: 5E, Ruitenberg *et al.* 1975). Axial extension may also occur before folding and thrusting in orogeny; Nickelsen (1979) interpreted vertical northwest-southeast trending joints, which pre-date cleavage in folded Pennsylvanian sandstones, as extension joints that developed during the inception of layer-parallel shortening under the northwest-southeast compression of the Allegheny orogeny. The load-parallel joints may, therefore, have formed under compression during an axial extension phase of the Variscan-Appalachian orogeny; the release joints resulted from relaxation of the northwest-southeast compression.

The orthogonal joint system in the Perry Formation is similar in orientation to the orthogonal system of northeast and southeast striking joints (the *B* system) of the Balls Lake, McCoy Head and Boss Point Formations. However, there is no preferred fracture parallel to the 065° joints (Fig. 4). Furthermore, the 065° joints in the Perry Formation appear to be associated with intrusion of the Late Triassic – Early Jurassic dyke, and the 155° joints are interpreted as post-intrusion in age; both joint sets apparently post-date the Variscan-Appalachian orogeny. During the Late Triassic, the dominant tectonism involved crustal extension perpendicular to the Appalachian trend (Rodgers 1970). The 065° joints in the Perry Formation in the St. Andrews area may therefore be tensile joints. The origin of the 155° joints and their orthogonal relationship to the strike joints is uncertain.

*ORTHOGONAL JOINT SYSTEM A*

The orthogonal joint system *A* cannot be attributed to any identifiable tectonic event. Nevertheless, it is present in most of the rocks studied. Both joints and lineaments trending approximately 010° (*A1*) and 100° (*A2*) are well defined in the Balls Lake and McCoy Head rocks, and *A1* and *A2* microcrack alignments are present in the McCoy Head Formation at Gardner Creek (Fig. 8). In the Boss Point Formation, the lineament trend at 160°, the weak joint trend at 165°, and the unsmoothed preferred fracture distribution at 005° (Fig. 6) suggest the existence of the *A1* trend; the unsmoothed 110° joints (Fig. 6) suggest an *A2* trend, but 100° (*A2*) lineaments appear to be absent (Fig. 9). Strong microcrack alignments in the 170° (approximately *A1*) orientation exist in the Perry Formation (Fig. 4), and north-south preferred fracture has been identified in the Pictou (Fredericton) sample (Lajtai and Alison 1979). In the 100° (*A2*) direction, no significant microcrack alignments exist in either the Perry or Pictou Formation sandstones.

The fundamental joint system *A* is interpreted as post-Triassic in age. The bimodal distribution of lineaments in the Triassic Quaco Formation (Fig. 9), adjacent to the McCoy Head Formation, clearly suggests correlation with the *A* system; lineaments corresponding to the *B* system are absent. There is evidence that supports a relatively young age for the *A* system. *In situ* strain measurements in the Potsdam sandstone, northeast of the Adirondacks, suggest that the upper crust of eastern North America is in a state of horizontal compression, the average direction of compression being at 102° (Engelder and Sbar 1976). Focal mechanism solutions of earthquakes suggest that presently the maximum principal stress in most of eastern and central North America is east-northeast (Sykes and Sbar 1973), and this stress is tentatively related to the presently active driving mechanism of plate tectonics. The strongest trend of lineaments east of Saint John in southern New Brunswick is 097±7° (Fig. 10, and Naing and Lajtai 1977).

A fundamental joint system is the product of a complete loading and unloading (release) cycle, and therefore development of a stress release fabric (microcrack alignment, joint and lineament), such as the north-south *A1* trend, requires the rocks to be in an unloaded condition, separated from stresses deeper in the crust. Although there is no physical evidence for uncoupling of the sandstones investigated from the stressed part of the crust, we note that at one of the five sites measured by Engelder and Sbar (1976), the maximum principal stress direction was at 018°, approximately at right angles to the 102° direction. This suggests that at this site the rock has indeed been released from the 102° compression.

The north-south *A1* trend is marked by strong preferred fracture orientation, low tensile strength, and weak lineament trend, similar to the *B1* trend which marks the release plane of the Variscan-Appalachian stress field. This would suggest that the *A1* joints are release joints and the *A2* joints are load-parallel joints.

The investigation indicates that correlation of tensile fracture at all scales (microcracks, joints and lineaments) can distinguish between load-parallel and release joints. When all three scales of structure are indentified in a sandstone and the tectonic stresses are known from separate structural evidence, there appear to be certain characteristic features. The strongest microcrack alignment, as defined by both tensile strength and preferred fracture studies, occurs along the release joints. Although microcrack alignments exist parallel to load-parallel joints as well, they appear to be weaker than those associated with release joints. In contrast, lineaments are more numerous in the load-parallel joint direction.

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