Geotectonic interpretation of measurements of joint orientations in the Muskoka region of the Canadian Shield

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SUMMARY. — A detailed survey of joint orientations was made in the Muskoka region of Central Ontario (Canada). Using a technique developed earlier, the principal present-day geotectonic stress trajectories were constructed for the area. The following results were obtained:

1) – The principal regional stresses run N-S and E-W. This corresponds to a fracture pattern which fits with the strike of the principal geographic features of the region, including the strike of the St. Lawrence valley.

2) – There is no correlation between the present-day joint system and older joints filled with pegmatite or quartz in the area, indicating that the orientation of the stress field has changed during geological history.

3) – There is no correlation between jointing and lithology. Recent joints are even visible in alluvial material.

4) – There is a small anomalous area which must be due to some local irregularity. It cannot be explained by lithology. The existence of such anomalies must be taken into account in regional surveys.

RIASSUNTO. — Uno studio dettagliato sugli orientamenti di giunti, è stato fatto nella regione Muskoka (Ontario Centrale - Canada). Usando una tecnica precedentemente sviluppata, sono state tracciate le direzioni principali geotettoniche attuali delle tensioni riguardanti la regione suddetta. Sono stati ottenuti i seguenti risultati:

1) – Le tensioni principali regionali corrono da N a S e da E a O. Ciò corrisponde al modello a frattura in accordo con l'orientamento delle principali caratteristiche geografiche della regione, ivi compreso quello della valle di St. Lawrence.

2) – Nella zona non c'è alcuna corrispondenza fra l'attuale sistema di giunti ed i giunti più vecchi riempiti di pegmatite o quarzo, che indichi un cambiamento nella storia geologica nell'orientamento del campo delle tensioni.

3) – Non c'è alcuna corrispondenza tra fratturazioni e litologia: giunti infatti, sono visibili anche in materiali alluvionali.

4) – Esiste una piccola zona anomala dovuta a qualche irregolarità locale: essa, infatti, non può essere spiegata dalla litologia. Comunque, in ricerche regionali, è doveroso prendere in considerazione l'esistenza di tali anomalie.

Fig. 1 – A joint in one of the investigated outcrops.

1. – INTRODUCTION

It is well known that most rock is jointed. Joints, as the term is understood here, are simply fractures or cracks; they are more or less clearly visible in any rock outcrop. (Fig. 1).

At a particular locality, the joints may present a picture of bewildering complexity. Nevertheless, if the orientations of the joint planes in an outcrop are plotted on a suitable diagram, one can often recognize preferred orientations which usually number 3. The three preferred orientations define the joint-parallelepiped; in favourable cases, this parallelepiped is recognizable at once in a fresh rock-cut (Fig. 2). In other cases, the preferred joint-orientations are not so immediately obvious and a statistical method has to be employed to determine them. In most cases, the three preferred joint orientations, defining the fundamental joint-parallelepiped, can be determined for a given locality.

Fig. 2 – Basic joint-parallelepiped (outcrop near Utterson Lake).

It may be reasonable to assume that joints have been produced by the geotectonic stress field. According to the usually accepted theory, they represent fracture surfaces inclined at an angle of 30°-45° towards the direction of greatest principal compression and containing the direction of the intermediate principal stress. Because of this fact, it is possible to determine the orientation of the stress field which produced the preferred joint-orientations at a given locality: two of the joint orientations will be identified with the two possible fracture surfaces in a triaxial stress state, the third is spurious; it completes the parallelepiped and is usually recognizable as a plane of layering, schistosity or gneissosity.

The above technique has already been employed by the writer to obtain the general course of the stress field in a test area of the Canadian Shield (Scheidegger 1975) (^{6}). It was found that the stresses were, roughly speaking, homogeneous over an area of about 10 × 4 km with the exception of a small area, which showed that the method of analysis employed is feasible.

However, the earlier study left many fundamental questions unanswered.

First, there is the question of the correlation between jointing and lithology. How indicative are the joints found in different strata of the times of formation of these strata?

Second, one often finds structural features, such as synclinal axes related to the orientation of the schistosity, etc., particularly in the Canadian Shield. How are the joint patterns affected by these structural features?

Third, thin sheet-like intrusions of pegmatite and quartz are often found which may simulate joint surfaces in outcorps. What is the relation of these to the other (non-intruded) joints?

Fourth, it has been found that there are spurious anomalous areas regarding the joint orientation in an otherwise largely homogeneous orientation field. Can these be more effectively delineated?

It is the aim of the present study to find answers to the above questions. For this purpose, the same area was again chosen in which the broad test-study had been made (Scheidegger 1975) (^{6}). Some answers were indeed found of which it is believed that they are not only valid for the Canadian Shield, but that they have a much more general significance.

2. – The region investigated

2.1. – *Geography*

As in the previous investigation (Scheidegger 1975) (^{6}), the area studied is in the vicinity of Three-Mile-Lake in the Muskoka Region of Ontario (lat. 45°10′N; long. 79°25′ W approximately). As against the earlier study, the area of investigation has been considerably extended to Lake Rosseau and Utterson Lake, and the number of outcrops visited has been substantially increased. Fig. 3 shows a section of the geologic map of the area (Hewitt, 1967) (³) with the outcrops visited (in 1974 and 1975) marked by circles.

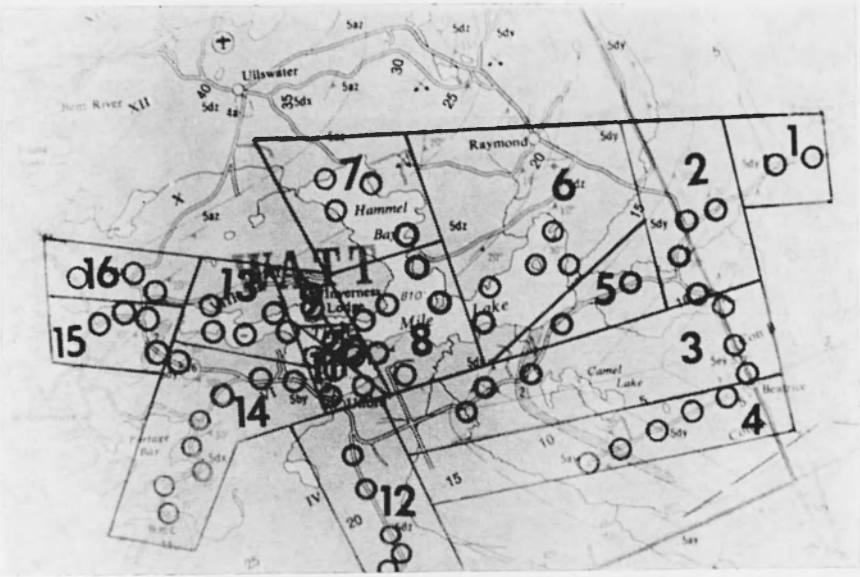

Fig. 3 – Section of geological map of area investigated (Hewitt 1967) (³) with outcrops visited marked by circles.

2.2. – *Petrology*

Inasmuch as an attempt was to be made to uncover possible relations between rock types and joint orientations, the region was visited by the writer with Dr. R. E. Smith of the University of Windsor, in order to identify the rocks.

Accordingly, the area is a part of the Grenville Province of the Canadian Shield. Radiometric ages of area rocks commonly yield a "*Grenville-age*" pf 950 ± 150 million years, but rock ages of 1035 to 1730 m.y. have also been found. The region, thus, contains re-worked rocks of an earlier age with the "*Grenville age*" being but the age of the latest recrystallization. The Grenville Province is now known to contain correlatives of rocks in the *"older"* provinces of the Shield, as well as a contribution, of *"new"* rocks dating from the time of the *"Grenville orogeny"*. (Wynne-Edwards, 1972) (7).

Fig. 4 – Most prevalent country rock: Migmatitic gneiss. Shore Portage Bay, Lake Rosseau, Ont.

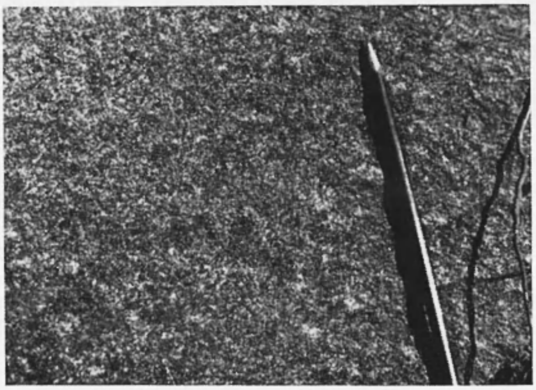

Fig. 5 – Hornblende-diopside gneiss. Shore Green Bay, 3-Mile-Lake.

The prevalent rock of the region studied, thus, is metamorphic. It is mostly layered and shows banded granitization; it is usually termed a migmatitic gneiss (Fig. 4). It is grey to pink in colour with whitish bands.

In some localities, which are, however, quite small in extent, one finds much earlier rocks which have been identified as hornblende-diopside gneisses and schists (Fig. 5). This rock has been mapped as "*metasedimentary*" by Hewitt (1967) (³). Related to this type are exposures of paragneiss, derived from impure sandstone.

In all the above rocks, frequent intrusion of pegmatite dykes and sills occur (Fig. 6, 7). On occasion, small areas of ultrabasic intrusive rocks (peridotite) are also encountered (Fig. 8) which become very friable when weathered.

Finally, in some areas of the region investigated the shield is overlain by Quaternary deposits (sands and gravel) which are being quarried. (Fig. 9). These also show jointing (Fig. 10).

Fig. 6 – Pegmatite dykes near Dinosaurland, Hwy. 516.

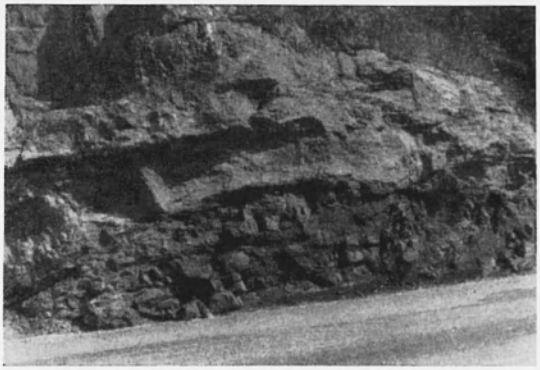

Fig. 7 – Dyke-fed pegmatite sill. Underneath sill there is strongly weathered hornblende-diopside gneiss (location as Fig. 5).

3.2. – *Paleotectonics*

The map of Hewitt (1967) (³) gives values for the strike and dip of the schistosity and/or gneissosity which, then, are interpreted in

Fig. 8 – Periododite ultrabasic intrusion. Shore of Long Bay, Lake Rosseau.

Fig. 9 – Sand quarry near Ufford.

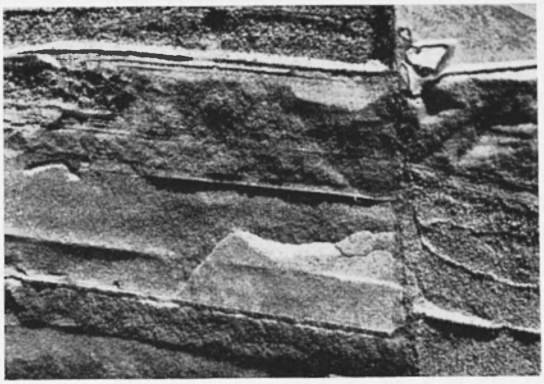

Fig. 10 – Joint in sand in quarry shown in Fig. 9.

terms of Grenville-orogenetic movements. In particular, a synclinal fold axis is noted running from Ufford through Camel Lake to Concession B near Beatrice on Hewitt's map (Fig. 3). A specific effort was made to ascertain the influence (if any) of this Grenville-caused tectonic element upon today's joint orientations. Furthermore, schistosity and gneissosity strike almost NNW near Utterson Lake and swing around by 90° to ENE north of Windermere. Again, a possible correlation of this switch in direction with jointing is of interest. It must be expected that the tectonic features indicated by Hewitt (1967) (3) are related to the Grenville orogeny.

3. – EVALUATION TECHNIQUE

As in the earlier study, we shall follow a technique developed mainly by Muller (1963) (4): For each joint plane measured, the *pole* is plotted on an equal-area projection of the *lower* half of a unit sphere. Then, the density of joints around a direction is determined by noting how many pole-points fall within a circle of diameter $d = D/\sqrt{n}$ on the plot where D is the diameter of the sphere in the equal-area projection and n the total number of pole-points in the diagram. The number is usually called the "*per-centage density*" (%) of pole points. Then, density-lines for equal percentage differences are drawn and the maxima are determined. Hopefully, there will be three such maxima so that the fundamental joint-parallelepiped is defined. This method, evidently, represents a nonparametric statistical procedure which is entirely independent of any preconceived ideas regarding the distribution of joint orientations around the mean orientations.

The exposition given above only relates to well-known facts. However, at this point, some remarks have to be made regarding the technique as it was actually applied by us in the field. Thus, an attempt was generally made to identify present-day fracture surfaces. These were particularly easy to identify in recent highway-cuts. It is believed that fresh fractures are indicative of the stresses acting to-day. Evidence of older joint-systems can be found everywhere. Thin pegmatite veins and dykes evidently also often form conjugate systems of fractures (Fig. 6). Unless a specific effort is contemplated to date and study such features which are presumably ancient, the veins will be ignored even if they happen to be exposed at a recent crack. The fresh fractures usually cut across any dykes and veins they encounter (Fig. 6), although on occasion, they may be deflected *en echelon* by the latter.

Furthermore, joints are sometimes not straight, but split up and assume their general orientation after a small distance. Evidently, this is also immaterial, as the deviations disappear in the density diagram. If basic joint-parallelepipeds (Fig. 2) or fracture niches were clearly recognizable at a location, an effort was made to measure 4-5 of these, yielding 12-15 measurements of joints which usually gave very consistent results, and the 3 preferred joint-orientations could immediately be identified.

When the three preferred joint orientations have been determined, a choice must be made as to which set of joints is assumed as "*spurious*" and which sets are assumed as representing conjugate fracture planes corresponding to the usual Coulomb-Mohr theory of fracture in a triaxial stress state. Generally, in our area, the steeply dipping joint planes had the appearance of fresh fractures, the more shallow ones were often seen to be connected with foliation or dyke-intrusions, corresponding to a "*standard state* [Anderson (1951)] (¹) *of incipient transcurrent fracture*" of the stress field. As indicated above, this stress field must be identified with the *present-day* geotectonic stress field if the *fractures* are recent. In a transcurrent type stress field, the *smaller* angle between the strike of the fracture planes encloses the maximum horizontal compression (P-direction). Thus, the P direction can be identified from joint-orientation measurements.

The above procedure makes use of the usual interpretation of rock joints as representing (at least incipient) shear fractures in a triaxial stress state. As of late, other joint-formation mechanisms have also been suggested, notably that of joints being extension fractures which would arise in a direction normal to the smallest principal compression (Price, 1966) (^{5}). Nevertheless, the sets of joints commonly from near-orthogonal systems over huge areas (see e.g. Babcock, 1973 (^{2}), for southern Alberta). Such near-orthogonal systems of joints cannot be explained in terms of an extension (uplift) mechanism, as has been pointed out by Babcock (1973, p. 1780, top) (^{2}), and must therefore be regarded as "*Anderson-type*" shear fractures, since this is the only alternative left at this time. Furthermore, inasmuch as the joints are also visible in Pleistocene material (see Figs. 9, 10), they cannot be the result of the release of "*frozen-in*" stresses either: thus the joints must be the expression of present-day geotectonic activity.

4. – RESULTS

The earlier study of the region in question yielded the result that the stress field which caused the fresh joints is homogeneous. The new measurements permit one to make much more detailed statements than before and, in fact, to plot the stress trajectories for the area.

For this purpose, the outcrops were assigned to 16 areas numbered 1 to 16 as shown in Fig. 3. For each of these areas, a combined joint density diagram was drawn and the pole maxima were determined. It was found that these corresponded in every case to 3 sets of joint-planes, one of which was subhorizontal, the other two were always nearly vertical. It was assumed that it is the vertical planes which are produced by the regional stresses. The reason for doing so is the fact that the near-horizontal fracture planes were recognizable as lithologically induced, so that only the near-vertical fractures could be stress-induced. It then follows that the largest and smallest principal stresses are horizontal; the largest compression should be enclosed by the *smaller* angle between the joint planes. However, since the angles between the preferred vertical joint orientations were often close to 90°, the identification regarding largest and smallest stress is uncertain. Nevertheless, the principal horizontal stress directions were determined in this fashion and plotted in Fig. 11 for the 16 areas. The heavy bar indicates the directions of the largest, the fine bar that of the smallest compression.

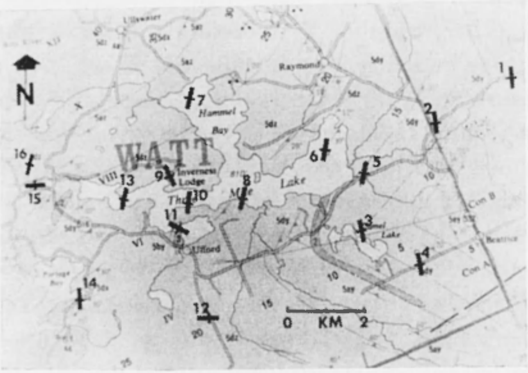

Fig. 11. – Principal horizontal stress directions in the regions under investigation. Numbers refer to the areas in Fig. 3; an heavy bar indicates the maximum, a thin bar the minimum compression direction. Underlying map by Hewitt (1967) (³).

Our inspection of Fig. 11 permits the following observations:

1) – The prevailing stress is a N-S compression. The stresses in areas 12 and 15 are rotated by 90°, but in view of the remarks made above, the identification of maximum and minimum compression is probably an error.

2) – There is no correlation between the present-day stress system and the tectonism indicated by gneissosity or schistosity. Thus, areas 2, 3 and 4 are located North of, on, and South of the geosynclinal axis respectively, but the stresses and fresh joints have the same orientations. Similarly, the schistosity turns by 90° between locations 1 and 14, but no change is seen in the joints.

3) – There is a stress anomaly between Ufford and Inverness (localities 11 and 9). One might suspect that there might be a relation between stresses and lithology, inasmuch as the map show "*metasediments*" in a part of this strip. However, an inspection of the outcrops in question showed that there are indeed hornblende-diopside gneisses and schists (Fig. 5) around Ufford, but such rocks were also found in area 2 (although they are not noted on Hewitt's map) where there is no stress anomaly. Furthermore, the rocks in area 9 are normal migmatitic gneisses, and this is within the region of the stress-anomaly. Thus, there seems to be no correlation between lithology and contemporary jointing and stresses.

4) – The detailed survey-results permit one to draw a stress-trajectory map of the area, as shown in Fig. 12. In the construction of this map, it has been assumed that the identification of maximum and minimum compression at locations 12 and 15 is erroneous. The plot of the trajectories shows the distortion of the more or less regular grid near Ufford.

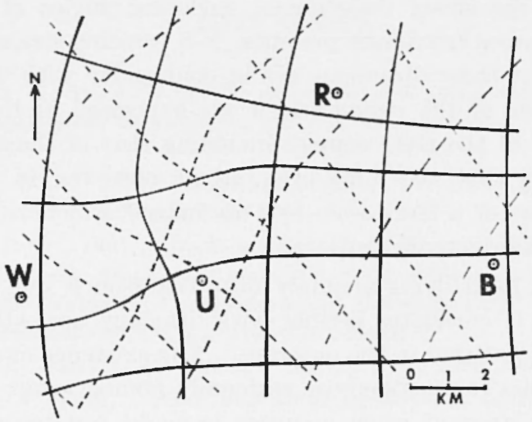

Fig. 12. – Stress trajectories (Solid lines) and preferred strike directions of vertical joints (dotted lines) in the region under investigation, W = Windermere, U = Ufford, R = Raymond, B = Beatrice.

5. – GEOTECTONIC INTERPRETATION AND CONCLUSIONS

After an evaluation of the measurements has been made, it is now possible to attempt a geotectonic interpretation of the results as well as to give answers to the general questions posed in the Introduction. Thus, one can make the following statements:

1) – The jointing investigated refers to the present-day tectonic stress field. An attempt was made to observe only "fresh" joints, not joints filled with pegmatite or quartz as these are evidently much older. The fresh joints do not correlate with either lithology or tectonic features seen in the orientation of gneissosity or schistosity which are presumably related to the Grenville orogeny. However, "fresh" joints are also visible in alluvial deposits (Fig. 10). The stress field producing the joints must therefore be post-Pleistocene.

2) – The main trend for the extremal horizontal principal stresses is NS and EW. Indications are that the NS direction corresponds to the maximum compression, but because the identification of the maximum pressure depends on the angle between the preferred joint planes which is usually close to 90°, the identification of the *maximum* compression direction as the NS-direction may be in error.

The preferred vertical fracture-orientations form a similar grid (Fig. 12) as the stress trajectories, enclosing angles of about ±40° with the presumed maximum pressure (N-S trending stress) trajectories. It is clear that these directions are in conformity with the main geomorphic trends of the region which are expressed in the orientation of the strikes of the river courses including that of the St. Lawrence. This indicates that the joint orientations observed in the Muskoka region are part of a large-scale system indeed which is, presumably, caused by plate-tectonic motions.

3) – The local stress anomaly near Utterson is due to some local irregularity. It correlates neither with lithology nor with schistosity or gneissosity patterns in the outcrops. The existence of such localized stress anomalies in an otherwise regionally homogeneous pattern must be taken into account when a survey is made, lest too small an area be chosen therefore.

4) – Inasmuch as the present-day joints cut clearly across evidently older joint systems, it is clear that joints can in time "heal" completely as far as the mechanical properties of the rock are concerned. If an effort were made to identify and date older joint systems, which evidently also formed conjugate fracture surfaces (see Fig. 6), a means could be obtained to trace the evolution of the geotectonic stress system during geological time. However, this would require a tremendous effort inasmuch as the assignment of particular fractures to particular systems is by no means easy to achieve. The present study concerned with present-day conditions shows, indeed, that the geotectonic stress field between Grenville and present times has not been constant.

ACKNOWLEDGEMENTS

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2118 in Figures 3 and 8 has been granted by Dr. E. G. Pye, Director of the Geological Branch, Ontario Dept. of Mines, Toronto. Dr. T. E. Smith of the University of Windsor has identified the rock-types in the outcrops visited. The author wishes to acknowledge his indebtedness therefor.

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