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Interpretation of fracture and physiographic patterns in Alberta, Canada

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Abstract—Thousands of linear elements (joint traces, river trends and photolinears) have been identified and statistically analysed in the Province of Alberta, Canada, from the U.S. border to the Fort McMurray area. A statistical evaluation was performed on the data by fitting Dimroth–Watson distributions to groups of them. It is suggested that the joints represent shear surfaces formed in a neotectonic stress field whose maximum compression is oriented normal to the front of the Rocky Mountains, at least in the vicinity of that range. Further to the northeast, the stress trajectories swing to E–W and N–S directions. The river courses in Alberta do not align themselves with the joints and are presumably controlled by the general slope of the land towards Hudson's Bay. The photolineaments are features of uncertain origin and age.

INTRODUCTION

MEASUREMENTS of the orientations of various linear elements in Alberta have been reported in a series of papers (Babcock 1973, 1974a, b, 1975, Babcock & Sheldon 1976). These elements include joint traces, stream directions and photolineaments. Since these papers were published, statistical processing techniques have become available which are based on making best fits of theortical probability distributions to data sets on a sphere (Kohlbeck & Scheidegger 1977). These developments permit a reprocessing of the older data, as well as of additional measurements taken since the introduction of the new techniques. It is also now possible to attempt an interpretation of the results in the light of plate-tectonic theory.

EVALUATION PROCEDURE

The orientation data considered in this paper relate to planar surfaces. The orientation of a plane in space is given by stating the azimuth of maximum inclination and its angle with the horizontal. Linears visible on the surface of the Earth (e.g. photolinears or valley directions) have been taken to be traces of approximately vertical planes. To a set of such data, theoretical Dimroth–Watson distributions have been fitted. These are probability–density distributions of the type $A \exp(k \cos^2 \theta)$ where A is the amplitude, k a sharpness parameter and θ the deviation angle from the 'centre' of the distribution; the fixation of the latter requires two parameters: the azimuth N $\rightarrow$ E and the plunge angle. Computer programs exist for making best fits of up to four Dimroth–Watson distributions and calculating their parameters simultaneously; this is done by an elaborate function-minimization procedure which minimizes the sum of the squares of the deviations between observed and predicted data densities. The computing effort required for achieving this is considerable and makes use of iterative processes described by Kohlbeck & Scheidegger (1977).

In practice, it was found that, at most, three superposed distributions suffice for matching orientation data. Two of these represent near-vertical, one near-horizontal preferred orientations. The near-horizontal orientations refer to lithological factors and are, thus, uninteresting for structural interpretation. The data processed in this paper represent mainly steeply dipping planes; therefore, they can be satisfactorily approximated by two superposed Dimroth–Watson distributions. In the tables of this paper, I list for each region investigated the number of individual input data, the two preferred orientations with error and the angle between the two. In Alberta, and in some other parts of the world, this angle is close to 90°. If the features are brittle failure surfaces, the maximum compression (σ_1) should be contained in the lesser quadrant, the minimum compression (σ_3) in the larger one, the intermediate principal stress direction being parallel to the intersection line (the latter is near-vertical because the preferred orientations of the structural elements considered are near-vertical). However, inasmuch as the angles at the apices of the quadrants are near 90°, it is not usually possible to identify the smaller quadrant unequivocally. Nevertheless, in the tables, the σ_1 and σ_3 directions as calculated formally upon this assumption are also shown.

The interpretation of the fractures as brittle failure surfaces may be questioned. In the Mohr theory, fracture planes form an angle of only some 60° between each other, not nearly 90° as in Alberta. Thus, it may therefore be more reasonable to interpret the Albertan sets as shear (Lüders) surfaces (Scheidegger 1979).

The next question, of course, concerns the age of the structures investigated, and hence the stress history deduced from them. The world-wide experience of the author seems to indicate that joints and valley directions are, in a statistical sense, responses to the present-day stress field, whereas photolinears do not fit such a hypothesis. Because this is true generally, similar conditions may be expected to obtain in Alberta.

THE JOINTS

Data

A large number of joints have been investigated in many locations in Alberta from the U.S. border north to the Fort McMurray area. Typically, these joints occur in fresh outcrops of sandstones to shaly siltstones ranging in age from the Cretaceous to the present. In previous studies of the joints (Babcock 1973, 1974a, b, 1975), it was shown that a uniform pattern persists over an area extending from the Rocky Mountain foothills to the Saskatchewan border. The pattern also persists vertically through sections from the Upper Cretaceous to the Upper Pleistocene. Babcock's original data, which he kindly supplied, and some data taken and added in 1980, were subjected to the evaluation routine of Kohlbeck & Scheidegger (1977). For this purpose, 12 regions in the Province of Alberta have been identified (Fig. 1, Table 1). The joints available in each area were then evaluated statistically by the Kohlbeck–Scheidegger (1977) algorithm. The results obtained, following the general scheme of presentation explained in the last section, are shown in Table 2. For a better visualization of the results, it is customary to plot pole-density diagrams of the distributions of joint orientations. However, because most of the joints investigated are nearly vertical, we have drawn polar histograms instead (Figs. 2a–l). In Fig. 3, the preferred stikes of the joints are shown approximately in the centre of each of the 12 areas identified.

Interpretation

Using the idea, outlined in the previous section, that the maximum compression is contained in the lesser quadrant enclosed by the joints, one can infer principal stress directions in the 12 areas identified. Statistically, two sets of joints are dominant at every locality. It is appreciated that there are some subordinate sets, but because Babcock's data are the base of this study, it was not possible to subject these sets to an analysis. The result, obtained statistically, is that there are two, and only two, preferred joint orientations in each area. This being so, one can use the Mohr theory to identify maximum and minimum pressure directions. In terms of these principal stress directions, a remarkable uniformity becomes apparent throughout Alberta. This uniformity can be expressed as a gradual turning of the maximum compression from E–W in the northern plains to NE–SW (i.e. normal to the Rocky Mountain front) near the mountains. In another study (Scheidegger 1981) this orientation is maintained further to the west throughout the Rockies. A study of well break-outs by Bell & Gough (1979) indicates that, at the Rocky Mountain front, the maximum compressive stress acts NE–SW, that is in a direction in complete conformity with the conclusions found in this study. This matter will be discussed further after the evaluation of other orientation data.

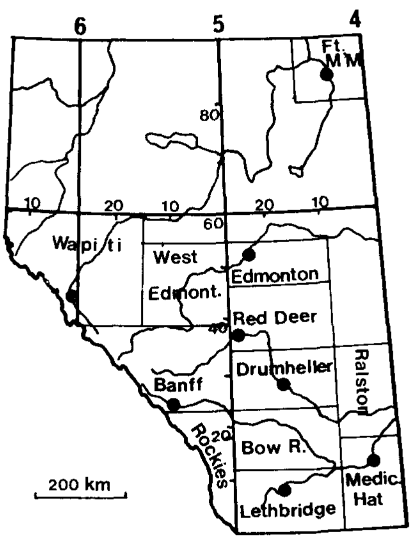

Fig. 1. Location of joint sampling areas in Alberta.

STREAM DIRECTIONS

Data

The next set of data which we consider are Albertan stream directions. Directions of river courses in six of the regions defined in Fig. 1 were measured, the procedure being to take the corresponding topographic maps (usually on a scale of 1:250,000), and to note the direction (i.e. the azimuth of the normal to each segment) of each unit length (usually 1 km) of river course. Thus, a weighted distribution for each region was obtained.

The results of the evaluations are given in Table 3 which also lists the number of individual river segments that were considered. In the Medicine Hat region this number is very large, because maps of scale 1:50,000, rather than 1:250,000, were used. The corresponding rose diagrams (of the normals to the trends) are shown in Figs. 4(a–f). The latter show that the many maxima are not very pronounced (e.g. Medicine Hat and Wapiti), although the computer, using parametric fitting of the theoretical distributions to a very large number of individual data points, came up with fairly narrow confidence (error) intervals.

Interpretation

By analogy with the procedure used in the analysis of joints, the principal stress directions were calculated according to the Mohr theory. The results which are shown in Table 3 were plotted in Fig. 5. Inspection of this figure shows that the river courses in the foothills are preferentially parallel and normal to the Rocky Mountain front. Further into the plains they run more N–S and

Table 1. Boundaries of regions (townships and ranges are inclusive)

	East	West	North	South
Ft. McMurray	4th Meridian	Range 12	Tp 90	Tp 80
Edmonton	Range 11	5th Meridian	Tp 55	Tp 47
West Edmonton	5th Meridian	Range 16	Tp 55	Tp 39
Wapiti	Range 17	BC Boundary	Tp 60	Tp 39
Red Deer	Range 11	5th Meridian	Tp 46	Tp 36
Banff	5th Meridian	BC Boundary	Tp 38	Tp 25
Drumheller	Range 11	5th Meridian	Tp 35	Tp 25
Ralston	4th Meridian	Range 10	Tp 35	Tp 18
Bow River	Range 11	5th Meridian	Tp 24	Tp 13
Rockies	5th Meridian	BC Boundary	Tp 24	Montana Boundary
Lethbridge	Range 11	5th Meridian	Tp 12	Montana Boundary
Medicine Hat	4th Meridian	Range 10	Tp 17	Montana Boundary

Table 2. Joints in the Alberta foothills. Dip(plunge) direction (azimuth clockwise from N) and angle with horizontal

Region	No.	Max. 1	Max. 2	Angle	σ_1	σ_3
Ft. McMurray	608	229 ± 1/86 ± 2	140 ± 0/90 ± 2	89	095/03	005/03
Edmonton	374	093 ± 4/90 ± 4	141 ± 2/89 ± 2	89	008/01	098/00
West Edmonton	882	028 ± 5/88 ± 3	129 ± 5/90 ± 3	78	259/02	169/02
Wapiti	1354	216 ± 2/90 ± 2	303 ± 5/84 ± 4	88	169/04	079/04
Red Deer	631	043 ± 4/90 ± 4	315 ± 2/87 ± 2	90	180/02	090/02
Banff	1044	071 ± 6/89 ± 6	155 ± 3/87 ± 3	84	023/01	293/03
Drumheller	1810	053 ± 2/90 ± 2	144 ± 2/89 ± 2	89	279/01	009/00
Ralston	900	067 ± 3/90 ± 2	158 ± 5/86 ± 4	89	292/03	022/03
Bow River	1719	066 ± 3/90 ± 2	156 ± 3/90 ± 2	89	111/00	021/00
Rockies	4363	088 ± 5/85 ± 5	351 ± 2/89 ± 1	83	219/04	309/03
Lethbridge	4708	066 ± 2/88 ± 1	161 ± 2/89 ± 1	85	294/02	204/01
Medicine Hat	2944	074 ± 2/90 ± 2	173 ± 2/89 ± 2	81	124/00	034/00

Table 3. Albertan stream directions (normals)

Region	No. of links measured	Max. 1	Max. 2	Angle	σ_1	σ_3
Edmonton	730	095 ± 08	173 ± 07	78	48/00	134/00
West Edmonton	913	023 ± 09	121 ± 06	82	72/00	162/00
Wapiti	1,477	042 ± 06	139 ± 06	83	91/00	001/00
Drumheller	1,128	006 ± 00	105 ± 00	81	56/00	146/00
Lethbridge	481	045 ± 16	135 ± 20	90	90/00	000/00
Medicine Hat	12,595	054 ± 04	145 ± 04	89	99/00	009/00

Table 4. Albertan photolineaments

Region	Max. 1	Max. 2	Angle	σ_1	σ_3
Ft. McMurray	146 ± 6	066 ± 3	80	16/00	106/00
Lethbridge	050 ± 1	138 ± 3	88	04/00	094/00
Medicine Hat	042 ± 2	146 ± 2	75	94/00	004/00

E–W. These trends are not the same as those of the joint sets in the corresponding areas. This is a condition which is not common elsewhere in the world, inasmuch as it has generally been found that surface joints and river trends are more or less parallel (cf. Scheidegger 1982).

PHOTOLINEAMENTS

The last set of data to consider are lineaments visible on air photographs. Such lineaments were identified by Babcock and his coworkers in connection with their studies of joints (see list of references in Introduction). I have taken the original numerical data and reprocessed them using the Kohlbeck–Scheidegger (1977) algorithm.

In order to make a comparison with the joint data, the province of Alberta was divided as shown in Fig. 1. Photogeological data were available for three areas; the Ft. McMurray, Lethbridge and Medicine Hat regions. The results of the numerical evaluation of the data are shown in Table 4 (the dips are now all 90°) the corresponding rose diagrams of the normals to the lineaments being given in Figs. 6(a–c).

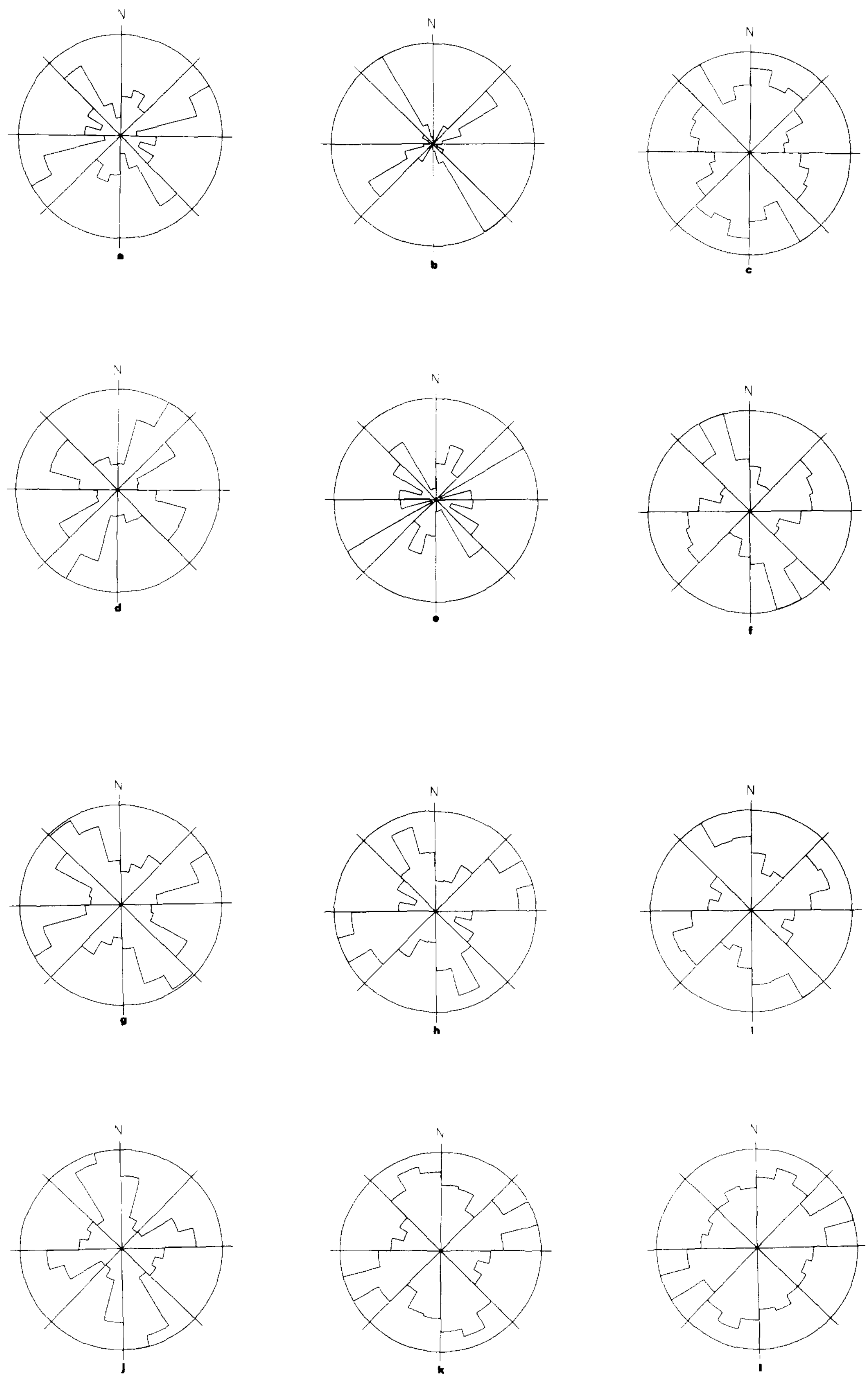

Fig. 2. Rose diagrams for poles to joints in Alberta. (a) Ft. McMurray. (b) Edmonton. (c) West Edmonton. (d) Wapiti. (e) Red Deer. (f) Banff. (g) Drumheller. (h) Ralston. (i) Bow River. (j) Rockies. (k) Lethbridge. (l) Medicine Hat.

I have again plotted the preferred directions of the inferred principal stresses on a map of the province (see Fig. 7). The limited number of results agree with those of the river courses, but not with those of the joints in the two southern areas (Lethbridge and Medicine Hat). In the Fort McMurray region, there is conformity between the joint orientations and photolineament orientations. River courses were not investigated in this region.

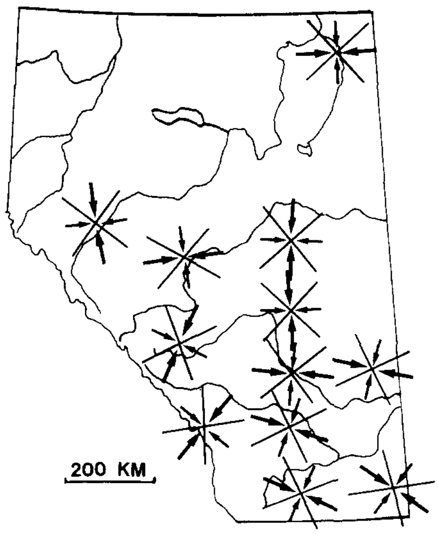

Fig. 3. Preferred joint orientations (lines) and inferred principal stress directions (arrows) deduced for the 12 areas of Alberta (see Fig. 1). Large arrows σ_1 (maximum compression), small arrows σ_3 (minimum compression).

DISCUSSION

It remains to interpret the conclusions reached from the field and office analysis in terms of plate-tectonic concepts. In this connection it should be noted that the interpretation of surface joints at outcrops as shear-type responses to the present-day neotectonic (intraplate) stress field has been well supported by the author's studies from all over the world (Scheidegger 1982). In the vicinity of the Rocky Mountains and in the southern part of the Province of Alberta, the joints strike preferentially N–S and E–W, indicating a maximum compression NE–SW, that is normal to the Rocky Mountain front. This orientation of the maximum compression is supported by investigations of well break-outs in the

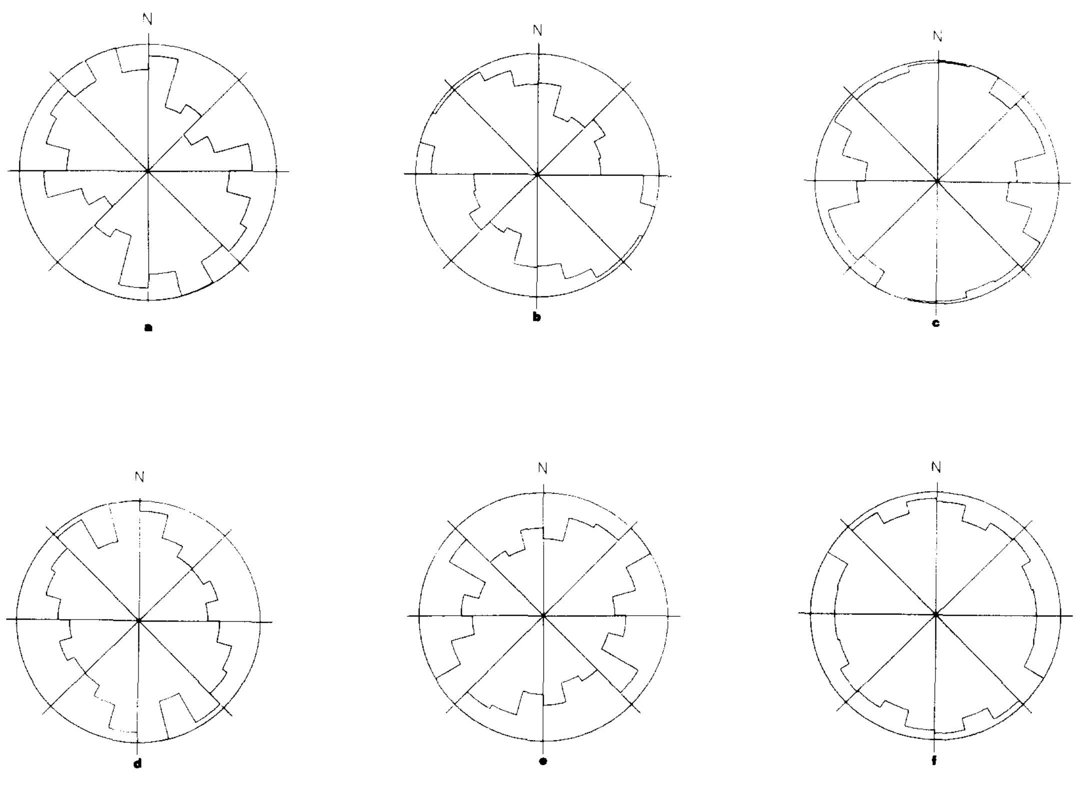

Fig. 4. Rose diagrams of river azimuths (normals to actual trends). (a) Edmonton. (b) West Edmonton. (c) Wapiti. (d) Drumheller. (e) Lethbridge. (f) Medicine Hat.

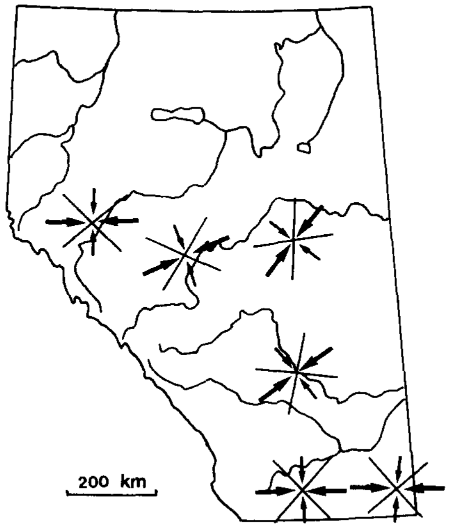

Fig. 5. Preferred river trends (lines) and inferred principal stress directions (arrows as in Fig. 3) in six areas of Alberta (cf. Fig. 1).

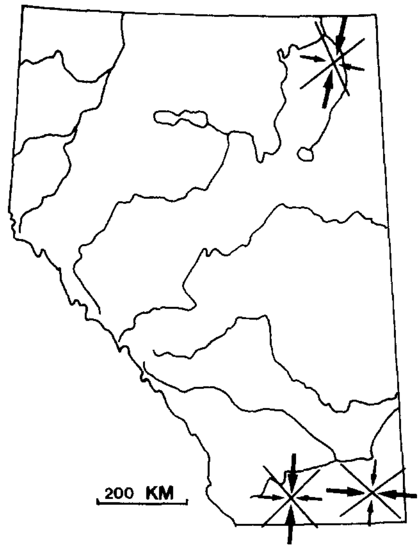

Fig. 7. Preferred orientations (lines) of photolinears and inferred principal stress directions (arrows, as in Fig. 3) for the 3 areas of Alberta defined in Fig. 1.

area (Bell & Gough 1979). The same orientation of the intraplate stresses (NE–SW compression) is prevalent throughout the continental United States (Haimson 1978) and in Southern Manitoba (Scheidegger & Turek 1978). It may be hypothesized, therefore, that the surface joints in Alberta are also the expression of a shear phenomenon in response to the intraplate neotectonic stress field.

Further to the northeast in Alberta, the stress trajectories swing to E–W and N–S directions, the joints striking NE–SW and NW–SE. The significance of this fact is not clear; the intraplate stress orientations might indeed be different in the Arctic from those in the mid-continental area.

Looking at the river courses, we note that they do not, as is generally the case elsewhere, align themselves with the joints. However, there is much scatter in the orientations and the regularity may be entirely conditioned by the general slope of the continent toward Hudson's Bay: the rivers simply following the steepest gradient, which is from SW to NE. The computer has then picked this direction as being prevalent and the direction normal to it as being background. Thus, two preferential directions SW–NE and SE–NW are obtained which are, however, meaningless in a tectonic context. Their interpretation as shear directions in a N–S and E–W directed stress field is, therefore, probably not justified.

Finally, regarding photolineaments, it should first of all be noted that these may be entirely different things in different areas: they may represent anything from recent faults to ancient lithological contacts. Thus, the lining-up of photolineaments with the joints in the Fort McMurray region is probably accidental. No correspondence between photolineaments and joints was found in the other two areas investigated (i.e. Lethbridge and Medicine Hat).

In summary, it may be concluded that the joints in southern Alberta can be interpreted as shear features related to the present-day neotectonic stress field. The river courses are presumably conditioned entirely by the

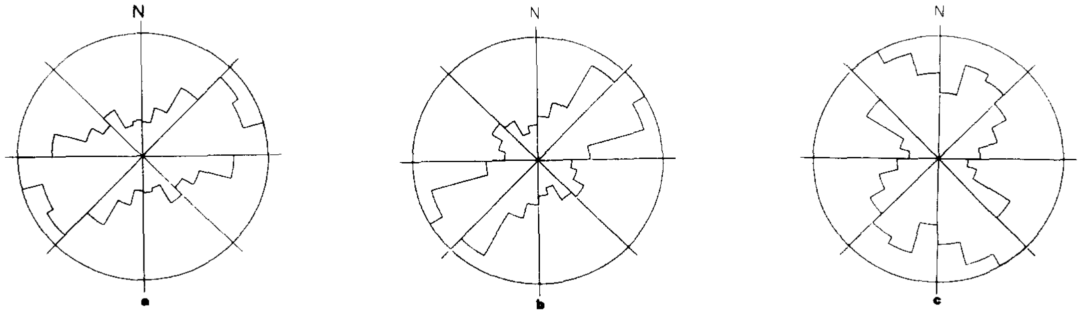

Fig. 6. Rose diagrams of azimuths (normals) of photolinears. (a) Fort McMurray. (b) Lethbridge. (c) Medicine Hat.

general slope of the region towards Hudson's Bay, and the photolineaments are features of uncertain origin and age.

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REFERENCES

Babcock, E. A. 1973. Regional jointing in Southern Alberta. *Can. J. Earth Sci.* **10**, 1769–1781.

Babcock, E. A. 1974a. Photolineaments and regional joints: lineament density and terrain parameters, South-Central Alberta. *Bull. Can. Petrol. Geol.* **22**, 89–105.

Babcock, E. A. 1974b. Jointing in Central Alberta. *Can. J. Earth Sci.* **11**, 1181–1186.

Babcock, E. A. 1975. Fracture phenomena in the Waterways and McMurray formations, Athabasca Oil Sands Region, Northeastern Alberta. *Bull. Can. Petrol. Geol.* **23**, 810–826.

Babcock, E. A. & Sheldon, L. G. 1976. Structural significance of lineaments visible on aerial photos of the Athabasca Oil Sands area near Fort MacKay, Alberta. *Bull. Can. Petrol. Geol. 24*, 457–470.

Bell, J. S. & Gough, D. I. 1979. Northeast–southwest compressive stress in Alberta: evidence from oil wells. *Earth Planet. Sci. Lett.* **45**, 475–482.

Haimson, B. C. 1978. The hydrofracturing stress measuring method and recent field results. *Int. J. Rock Mech. Min. Sci.* **15**, 167–178.

Kohlbeck, F. & Scheidegger, A. E. 1977. On the theory of the evaluation of joint orientation measurements. *Rock Mech.* **9**, 9–25.

Scheidegger, A. E. 1979. The enigma of jointing. *Riv. Ital. Geofis. Sci. Aff.* **5**, 1–4.

Scheidegger, A. E. 1981. Joint orientation measurements in Western Alberta and British Columbia. *Ann. Geofis. Roma* **34**.

Scheidegger, A. E. 1982. *Principles of Geodynamics*, 3rd edition. Springer, Berlin.

Scheidegger, A. E. & Turek, A. 1978. Joints in Eastern Manitoba. *Arch. Met. Geophys. Biokl.* **27A**, 381–389.