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Tectonically deformed pillow lava as an indicator of bedding and way-up

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Abstract—Often the outlines of tectonically deformed lava pillows cannot be used to give directly the true bedding and way-up directions. Where the pillows are strained homogeneously, with moderate total strains, certain procedures allow the determination of the true bedding and way-up directions. Where the strain history has been coaxial, these are: the use of pillows fortuitously parallel with a principal extension direction and graphical restoration of pre-tectonic pillow shapes to fix true bedding directions. Furthermore, use may be made of special pillow shapes with flat bases or multiple cusps, even where the strain history has been noncoaxial. With total strain ratios > 4.5, heterogeneous strain often occurs and it may not be possible to determine the true bedding and way-up directions.

INTRODUCTION

PILLOW lavas are important for the determination of way-up and also for the determination of bedding in otherwise massive volcanic sequences. This is so in many terrains and is especially the case in Archaean greenstone belts. Borradaile & Poulsen (1981) have already shown that pillow selvages can provide an easy-to-use strain marker. They suggested also that caution should be applied in determining bedding directions and way-up directions from distorted pillows. This problem is examined here more closely.

Most of the ensuing discussion uses concepts of homogeneous strain. The effects of homogeneous strain were simulated by computational means using formulae presented by Ramsay (1967, chapters 3 and 5) and the results were presented by automatic graph-plotter. However, the author's qualitative observations over four field summers supported by strain analysis permit some final comments on the effects of heterogeneous strain.

For the purposes of computation, a model is used of a natural pillow before straining (Fig. 1). The essential parts of the model are: (1) an elliptical outline, (2) a line parallel to the initial long axis (equivalent to bedding) and (3) a line joining the centre of the ellipse with a point corresponding with the cusp.

A line parallel to the initial long axis marks bedding. This line continues to track bedding after straining but it will be shown later that it then usually differs in orientation from the long axis of the strained pillow model. A perpendicular to this line, pointing away from the side of the pillow with the cusp, always gives the way-up or top direction.

Although the cusp-to-centre line of the model indicates the way-up direction in the pre-strain state, this is not so in the strained model. During straining this line tracks the stratigraphic thickness direction (Schwerdtner 1978), see Fig. 2. That is, it records the direction in which the tectonically modified, stratigraphic thickness should be measured to allow a simple restoration of the original stratigraphic thickness from any available strain data. This direction may approximate to the structural facing direction of the folds (Borradaile 1976) under suitable circumstances (see Fig. 2).

The study has involved using this model of an undeformed pillow with varying shape; ratios of long:short axes of 3:2 and 4:1.5 were used. These are reasonable approximations of the shapes of Archaean lava pillows which show little evidence of strain at the Steel River, Jackfish and Schreiber localities on the North Shore of Lake Superior, Ontario.

COAXIAL AND NONCOAXIAL STRAIN HISTORIES

During a coaxial strain history, successive increments of the principal extensions are added parallel to the same material lines in the body. That is, the successive finite strain ellipses at a point may remain parallel to some line of reference fixed in the material.

We know that increments of principal extensions are not added along the same material direction in many natural strain histories (e.g. Durney & Ramsay 1973, Means 1976, Ramsay 1967). For this reason the effects of both coaxial strain histories and some probable noncoaxial strain histories have been examined.

COAXIAL STRAIN OF PILLOW LAVA

The effects of coaxial strain on pillow lavas have been studied by transforming the geometric model of the pillow and graph-plotting the results. As an initial illustration the model of the pillow has been chosen with

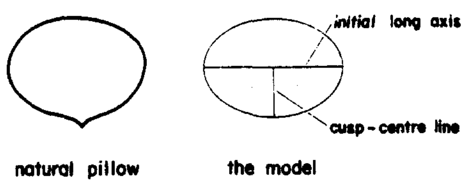


Fig. 1. An idealised natural lava pillow before straining and the geometric model of it which is used in this paper.

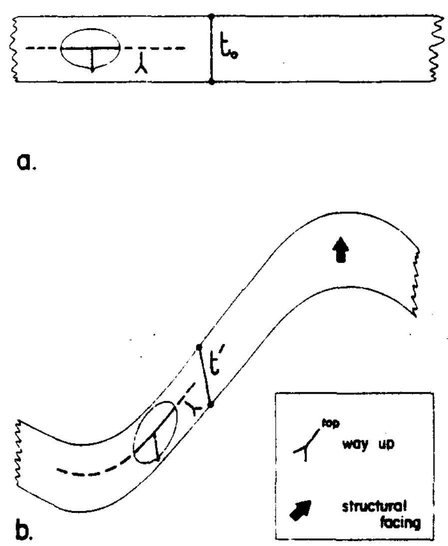


Fig. 2. (a) Undeformed bed with idealised pillow. The cusp-to-centre line of the pillow gives the younging direction. (b) Deformed bed with idealised pillow. The cusp-to-centre line of the pillow now tracks the 'stratigraphic thickness' direction, t'. This may approximate to the structural facing direction. The simple younging direction is no longer perpendicular to the long axis of the pillow in the general case, but, by definition, it remains perpendicular to bedding.

an axial ratio of 3:2. The range of possible different initial orientations of the pillow has been considered, from being perpendicular with the extension direction, through to parallel with the extension direction.

The results of the transformations are indicated in Fig. 3 for strains through to a total-strain ellipse with ratio 9.31:1.

It may be noted from the figure that two symmetrical cases arise, where the pillow's initial long axis is either perpendicular or parallel to the principal extension direction. For this reason, it would be possible to identify the bedding orientation and the way-up direction from such a deformed pillow if one could be certain that the natural deformation was indeed coaxial and homogeneous. Where the initial pillow is oblique to the extension direction the effects of progressive strain are more complex. In those instances, the imaginary lines which define the bedding direction, and the cusp-centre line, rotate towards the extension direction whilst the younging direction rotates away from the extension direction. The outline modelling the pillow changes shape so that its new long axis, at any stage, is differently oriented from the bedding direction.

The bedding-direction line rotates much more slowly towards the extension or x-direction than do the successive long axes of the pillow outlines. This is shown in Fig. 4. The effect is more noticeable for pillows that initially make a large angle with the extension direction. With high strains the bedding direction, the long axis of the pillow outline and the cusp-to-centre line do eventually approach one another (see Fig. 3.)

The practical importance of this is that from a natur-

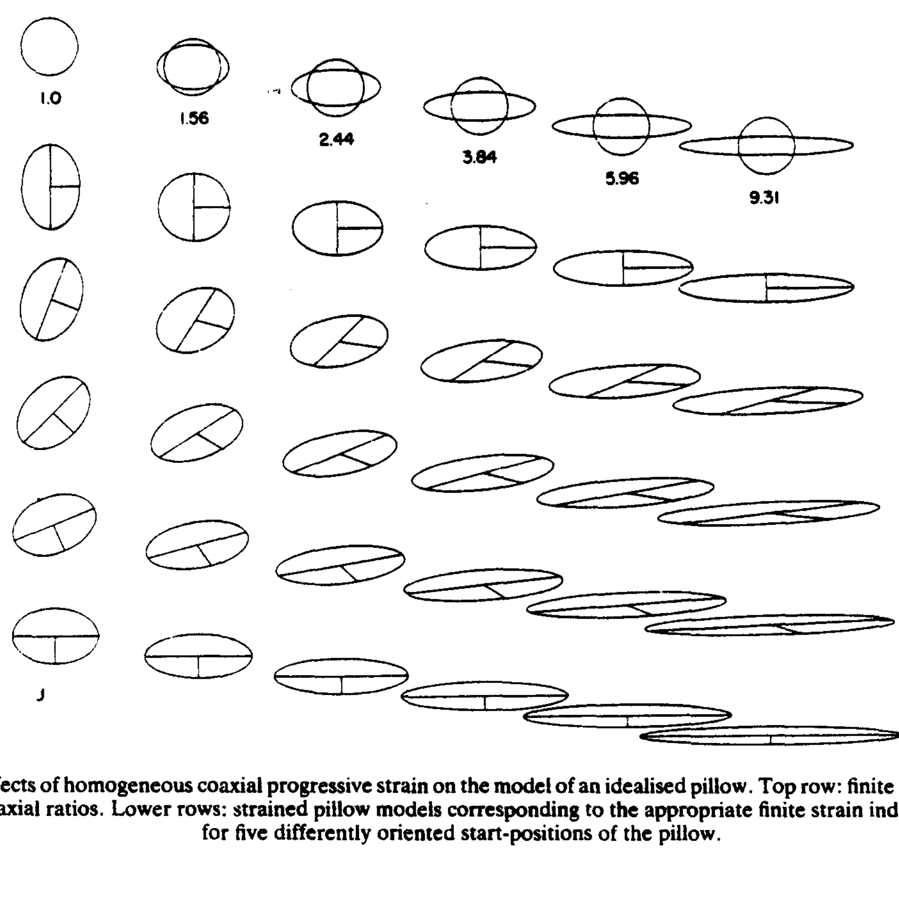


Fig. 3. Effects of homogeneous coaxial progressive strain on the model of an idealised pillow. Top row: finite strain ellipses with their axial ratios. Lower rows: strained pillow models corresponding to the appropriate finite strain indicated above, for five differently oriented start-positions of the pillow.

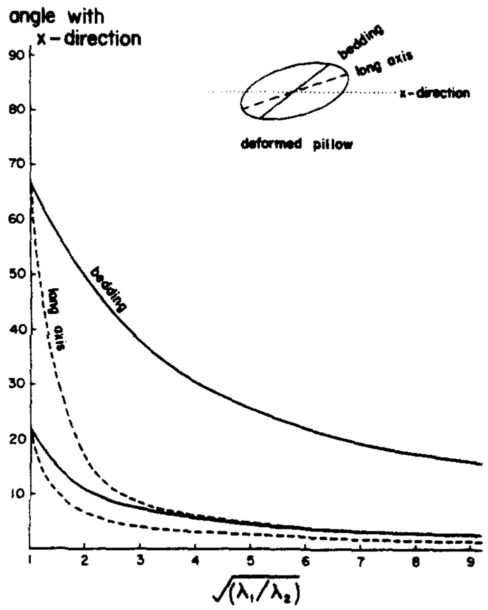


Fig. 4. The changes in angle between the true bedding direction and of the long axis of the strained pillow with respect to the extension direction. Homogeneous coaxial strain history.

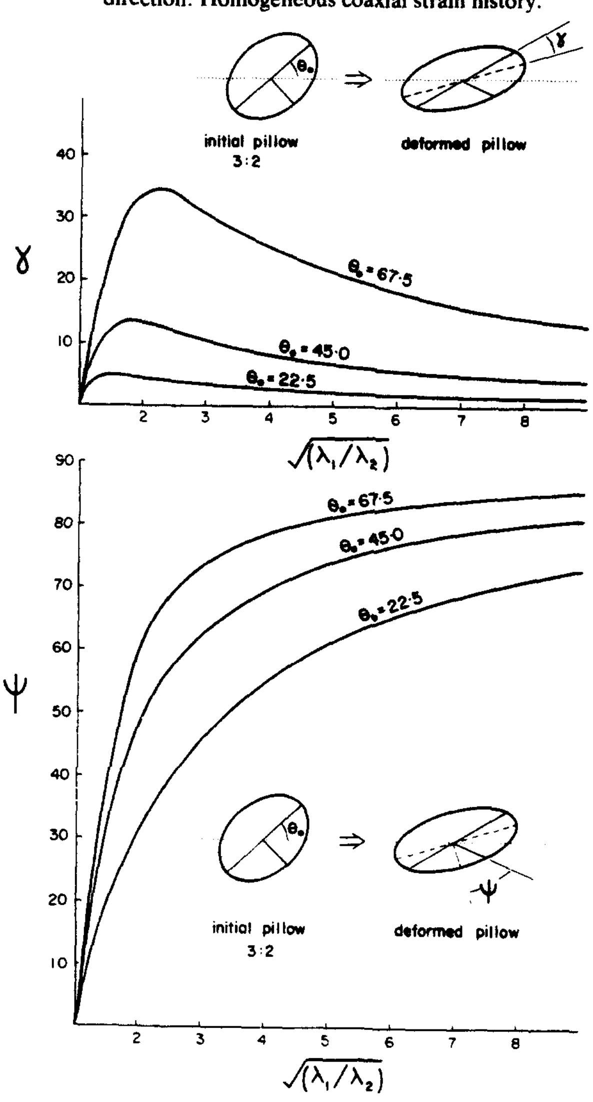


Fig. 5. Initial pillow ratio 3:2. γ, the discrepancy between bedding and the long axis of the strained pillow. ψ, the discrepancy between the stratigraphic thickness direction and the short axis of the pillow. Shown for different start-attitudes of the pillow model in progressive homogeneous coaxial strain.

ally deformed pillow it is not easy to infer either the bedding direction or the simple younging direction which is perpendicular to it. A common procedure is to take the long axis of a deformed pillow to represent the bedding direction and to assume the short axis is the younging or way-up direction. How reliable is this procedure?

Let us examine the discrepancy γ, between the long axis of the strained pillow and the line which tracks bedding. In the upper part of Fig. 5 the inset sketches indicate the initial model of the pillow and the strained pillow. The value of γ depends on the initial angle, θ_0, of the pillow with respect to the extension direction and it depends also on the amount of strain. For a pillow making $\theta_0 > 45°$ with the extension direction the discrepancy between the apparent 'bedding' direction (given by the elongation of the deformed pillows) and the true bedding direction, reach maxima for strain ellipse axial ratios of 2:1 to 3:1. At these commonly observed strains the strained pillows give their most misleading impression of the bedding direction, being in error by >15° for pillows which initially made >45° with the extension direction.

In the undeformed state, the younging direction is perpendicular to the long axis of the pillow. This is not

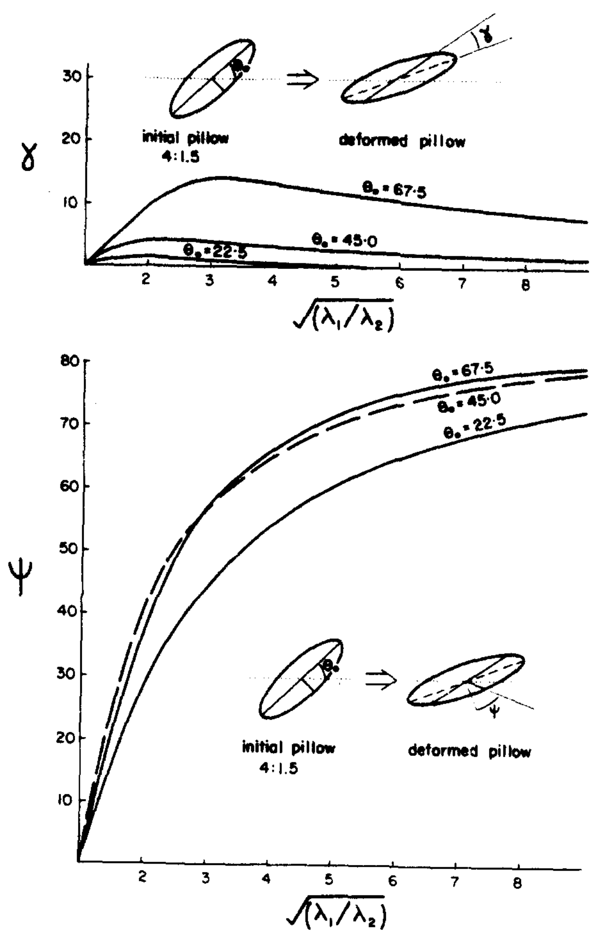


Fig. 6. Initial pillow ratio 4:1.5. γ, the discrepancy between bedding and the long axis of the strained pillow. ψ, the discrepancy between the stratigraphic thickness direction and the short axis of the pillow. Shown for different start-attitudes of the pillow model in progressive homogeneous coaxial strain.

the case, however, where the pillow is deformed. The simple way-up direction is always perpendicular to the true bedding direction (see Fig. 2). Therefore, the discrepancy between the simple way-up direction and the short axis of the deformed pillow (sometimes mistaken as the way-up direction) also has the value γ.

The stratigraphic thickness direction (t' in Fig. 2b) is given by the new position of the cusp-to-centre line. It makes an angle ψ with the short axis of the strained pillow (see inset in lower part of Fig. 5). ψ thus records the discrepancy between the shortest dimension of a strained pillow (sometimes mistaken as both a younging direction and a stratigraphic thickness direction by analogy with the pre-strain state: Fig. 2a) and the actual stratigraphic thickness direction. ψ becomes large at even quite modest strains as shown by the lower part of Fig. 5.

Further tests have been performed using a model of a pillow with axial ratio 4:1.5 (Fig. 6).

The discrepancies between the apparent and true bedding directions are quite small for $\theta_0 < 67.5°$. However, the discrepancies ψ between the short axis of the pillow and the stratigraphic thickness direction are >30° for strain states with strain ellipse axial ratios >2.

From the foregoing, it is apparent that younging and bedding directions are not simply given by the shape of a pillow once it has been strained. However, the arguments so far have been limited to coaxial strain histories. The more complex cases of noncoaxial strain are considered below.

NONCOAXIAL STRAIN OF PILLOW LAVA

In the previous section, the shape of the original pillow and the attitude of the original pillow with respect to the extension direction were the variables affecting the shape of the strained pillow. In this section, we shall consider only pillows with initial axial ratios of 3:2 but there is the added complication that the incremental strain ellipses change position with respect to some material reference line during the deformation. Thus the end result will depend also on the initial position of the incremental strain ellipse, the rate of rotation of the incremental strain ellipse and the final attitude reached by the incremental strain ellipse. For simplification the author used histories in which the incremental strain ellipse rotates by equal angles with each increment. The angles concerned were 4.5° and 2.25°. The incremental strain ellipse applied at each state had an axial ratio of 1.04 or 1.08.

In the first group of tests, the initial increments of strain were 90° away from the final increments. In other words, τ, the total rotation of the incremental strain ellipse with respect to the initial position of some material reference line, was 90°. Three interesting cases arise:

(a) first increment perpendicular to bedding,
(b) first increment inclined (at 45°) to bedding and
(c) first increment parallel to bedding.

Each of these is indicated in sketch-inset against the graphs of Fig. 7. The incremental strain ellipses rotate through τ while the finite strains accumulate in a non-linear fashion from strain ellipse ratios, $\sqrt{(\lambda_1/\lambda_2)} = 1.04$ (the first increment) to 3.89 (after the last increment). The horizontal graph axis shows both values of τ and the measure of strain applicable to all three cases.

What happens to our indicators of bedding and way-up under such conditions of non-coaxial strain? Again, γ indicates the discrepancy between bedding and pillow long axes. This has the same value as the discrepancy between the simple younging direction and the pillow short axis. ψ indicates the discrepancy between the stratigraphic thickness direction (the cusp-to-centre line) and the pillow short axis.

The first case (Fig. 7a) corresponds to initial tectonic shortening parallel to bedding. Beyond a rotation of the extension direction of only 20° (at which point the finite strain ellipse has a ratio 1.58), $\psi > 55°$. The indication of bedding and apparent younging is misleading to a different extent however. γ peaks after the principal incre-

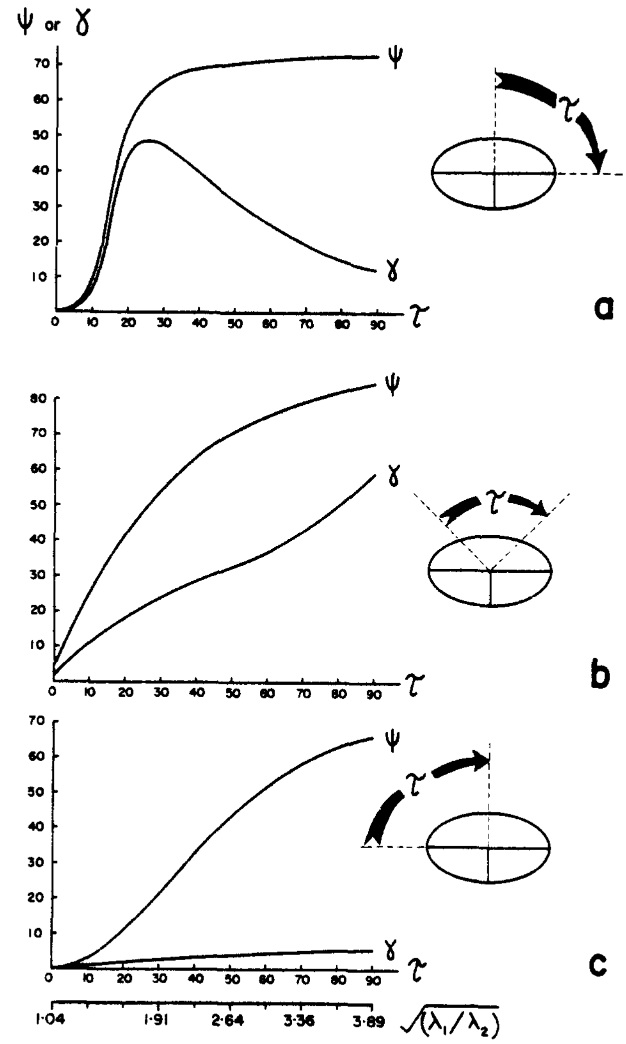


Fig. 7. The changes in γ and ψ during noncoaxial strain histories. The initial pillow ratio is 3:2. The inset sketches show the model of the pre-strain pillow, and the broken lines indicate the first and last orientations of the long axis of the incremental strain ellipse. τ indicates the sense of the 90° rotation of the incremental strain ellipse.

mental extensions have rotated between 20 and 30°, and thereafter the true bedding direction becomes closer to the pillow elongation.

Where the initial extension direction is oblique to the pillow shape and to bedding, (Fig. 7b), the pillow's morphology, both as an indicator of bedding in the deformed state and as a way-up indicator, becomes steadily worse with advancing strain.

In the third case, perhaps less likely in most tectonic schemes, the initial increments of extensions are applied parallel to bedding. The long axes of the strained pillows remain close to bedding; even with a finite strain ellipse axial ratio of 3.89, $\gamma \simeq 6°$. However, the stratigraphic thickness direction departs further and further from the short axis of the pillow as strain advances, with $\psi = 65°$ at the end of the strain history.

The noncoaxial strain histories studied so far involve a considerable rotation of the incremental strain ellipse, with $\tau = 90°$. More often a smaller rotation would be expected and the above studies have been repeated with $\tau = 45°$ (Figs. 8 and 9). Four situations arise here and these are presented in the order which corresponds to the probability of their occurrence in nature.

The most probable situation is one in which the first increments of extension are perpendicular to bedding (Fig. 8a). In this case the apparent younging and bedding directions rapidly depart from the true directions, discrepancies γ peaking at modest strain ellipse ratios of $\simeq 1.8$ The angle between the stratigraphic thickness direction and the pillow short axis, ψ, rapidly approaches 70° after a few increments of strain.

Where the initial increment of extension is oblique (here at 45°) to the pillow's initial long axis, two paths may be followed (Figs. 8b or c). In one, the 'rotation' of the incremental strain ellipses is away from the bedding direction (Fig. 8b) in the other the rotation (Fig. 8c) is towards the bedding direction. The results are not dissimilar. In both cases the discrepancy, γ, between the short axis of the pillow and the true younging direction and between the long axis of the pillow and the true bedding direction is quite small during the strain history shown. However, the discrepancy ψ between the stratigraphic thickness direction and the short axis of the pillow increases steadily during deformation.

In the final case, possibly less likely to occur in nature, the early increments of extension are parallel to the true bedding direction and 'rotate' steadily away from this material line (Fig. 8d). The result is that the long axis of the pillow remains a good estimate of the true bedding direction and its short axis remains a good estimate of the way up direction (γ remains <5° throughout the strain history). Nevertheless, the stratigraphic thickness

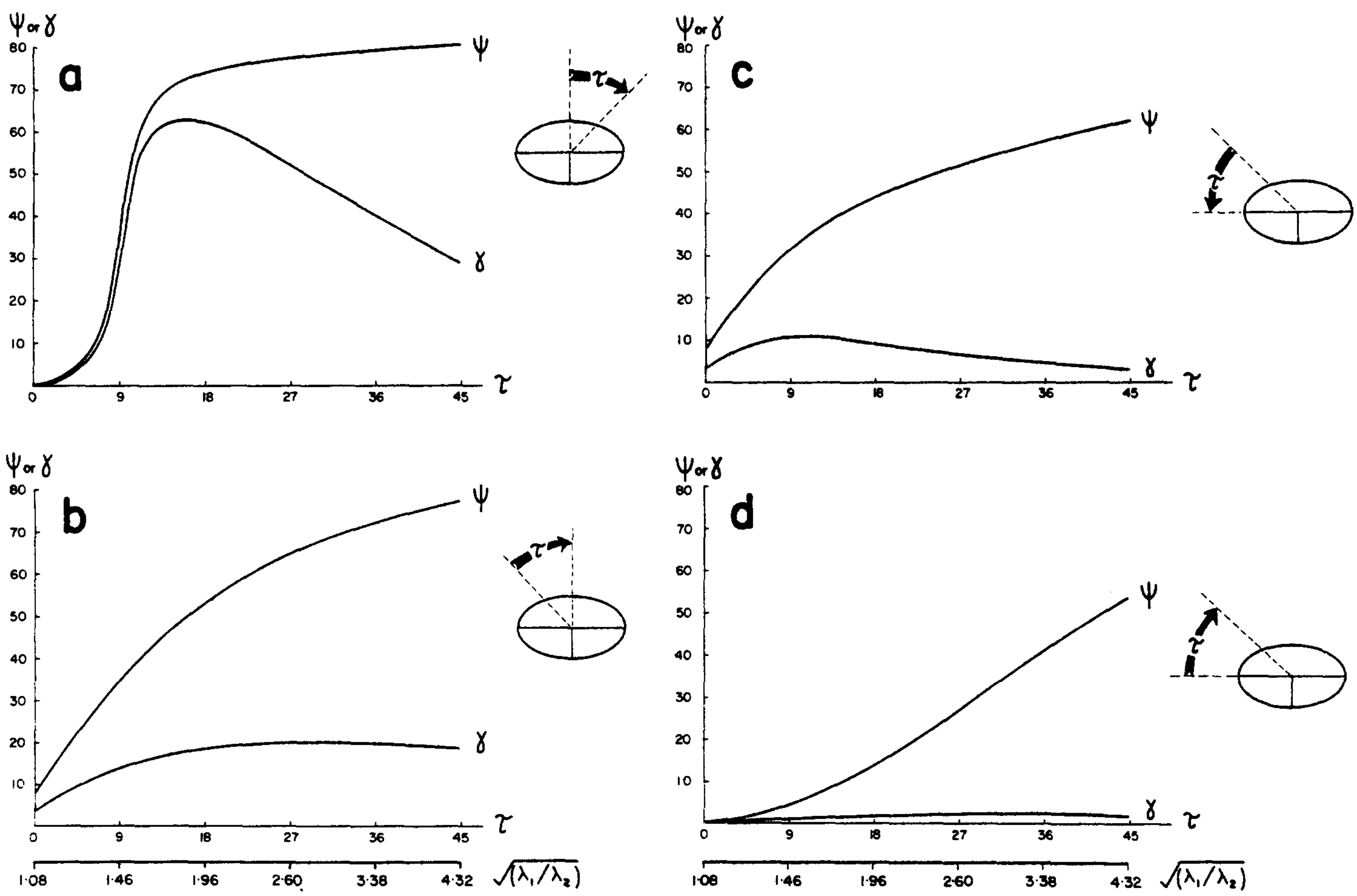


Fig. 8. The changes in γ and ψ during noncoaxial strain histories. The initial pillow ratio is 3:2. The inset sketches show the model of the pre-strain pillow, and the broken lines indicate the first and last orientations of the long axis of the incremental strain ellipse. τ indicates the sense of the 45° rotation of the incremental strain ellipse.

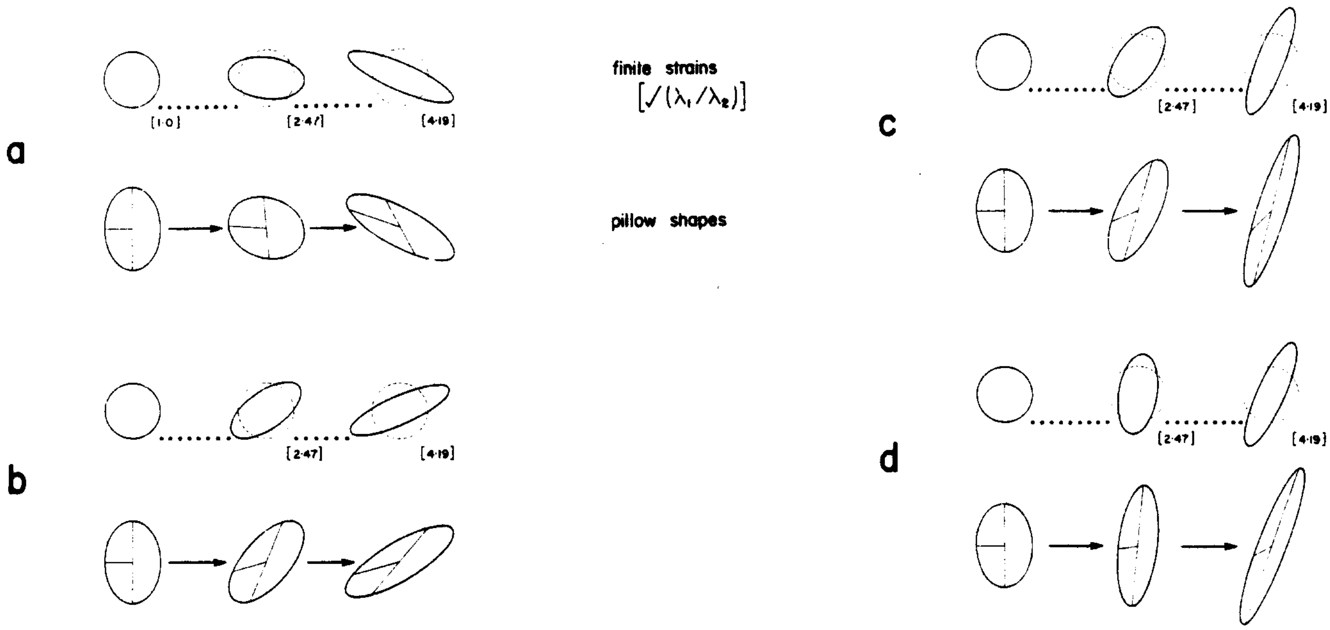


Fig. 9. The effects of noncoaxial homogeneous strain on the model of the idealised pillow. In each case, a–d corresponding to Fig. 8(a)–(d), the pillow shapes are plotted together with the appropriate finite strain ellipse. The initial, middle and total finite strain ellipses are shown in the upper rows. The total strain ellipse has an axial ratio of 4.19 in each case and the incremental strain ellipse rotates by 45° in each case with the senses shown in the corresponding part of Fig. 8.

direction moves steadily away from the short axis of the pillow as shown by the regular increase of ψ with progressive strain.

Selected pillows and strain ellipses from these four strain histories are sketched directly from the graph-plotter output in Fig. 9.

FIELD EXAMPLES OF DEFORMED PILLOW LAVA

A natural example of deformed pillow lava is shown in Fig. 10, and in detail in Fig. 11. Here the strain is approximately homogeneous, as indicated by selvage-thickness variations, and the strain history may have been approximately coaxial. Furthermore, the symmetry of the pillows (Fig. 11) and the thickened portions of selvages indicate that the strain ellipse is parallel to the long axes of the deformed pillows. In this simple and special case, corresponding to the lowermost, symmetrical, example in Fig. 3, the long axes of the deformed pillows are indeed a bedding indicator and the younging direction is perpendicular to the pillow long axes.

More usually asymmetric pillows occur and from these it is not so simple to determine bedding or younging (Fig. 12), even if a coaxial strain history is assumed.

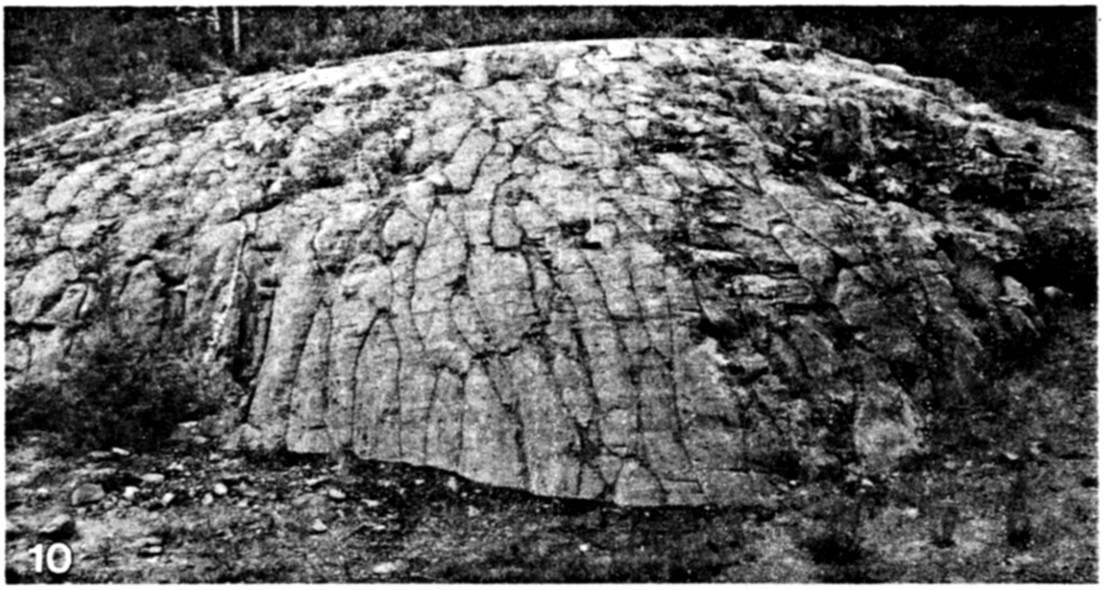
However, if sufficient data on selvage thicknesses can be collected it may be possible to graphically remove the effects of homogeneous strain from the pillows' outlines. In Fig. 13(a), the shapes of some deformed pillows are sketched, together with the appropriate strain ellipse, and the attitude of the schistosity trace, S–S. Removing the strain by graphical means produced the geometry shown in Fig. 13(b). In this restoration bedding has been located by broken lines. The broken lines from Fig. 13(b) may then be transposed back onto Fig. 13(a) to indicate the true bedding orientation in the deformed state.

One type of naturally occurring pillow which can minimise error in defining the bedding and younging directions is the pillow which shows multiple cusps. An example is shown in Fig. 14. Here, amongst inverted lava, a large pillow in the centre has draped over several smaller, older pillows. As a result the larger pillow shows more than one cusp. In this way, a better indication of the 'older' side of the pillow is given. Some pillows with flat bases may similarly be recognised in the deformed state. The flat base records the 'older' side of the pillow and also acts as a bedding marker.

HETEROGENEOUS STRAIN

The models studied and the natural examples cited so far concern situations in which the strain is homogeneous. In the natural examples the author has studied, the assumption of homogeneous strain is usually reasonable where the ratio of the strain ellipse axes on the surface of observation is <4.0. Above this strain value (as determined from selvage thickness variations) the pillow outlines start to show signs of heterogeneous strain. The first indication of this is where the termini of pillows become pear-shaped (Fig. 15). In some cases re-entrant portions of the pillow outlines also become folded (Fig. 16).

Ultimately, the pillows become crescent-shaped, or



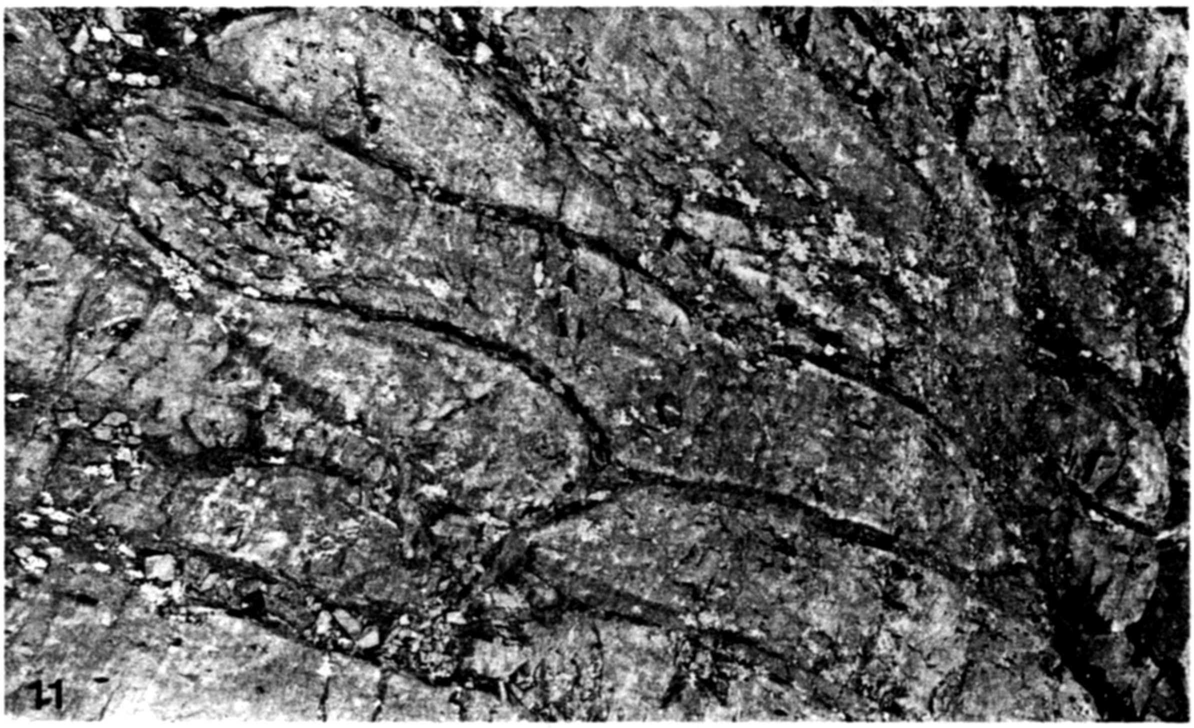


Fig. 10. General view of Archaean pillow lava in the Shebandowan Belt, Superior Province of the Canadian Shield.

Fig. 11. Close-up of outcrop shown in Fig. 10.

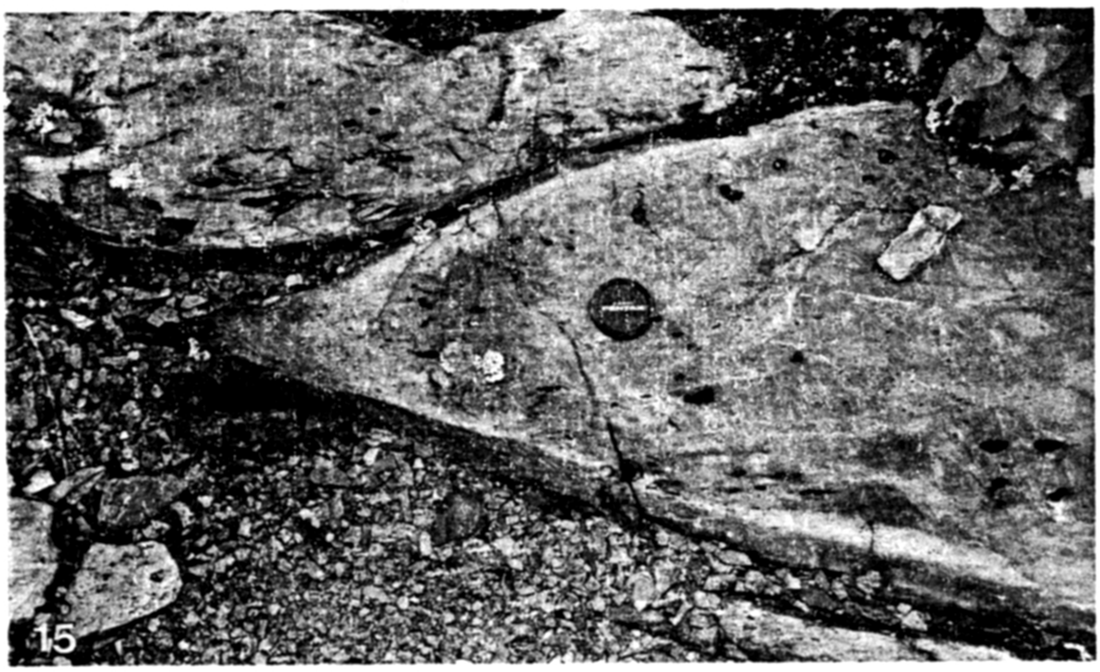
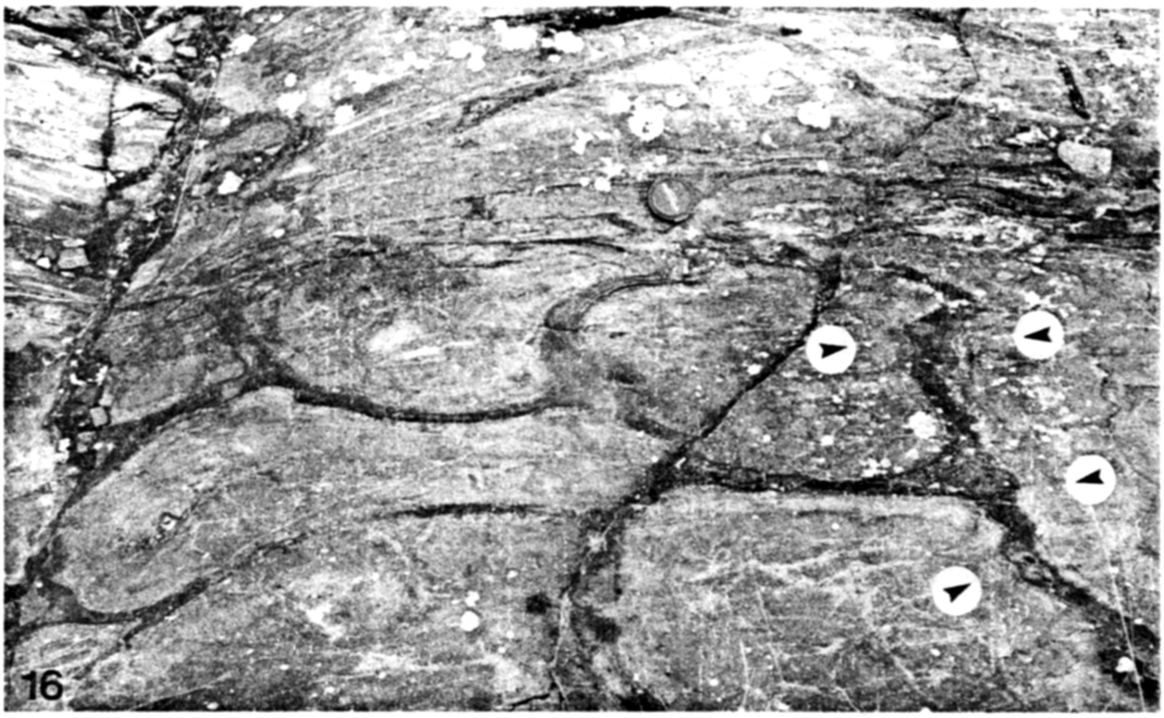


Fig. 12. Asymmetrical, deformed lava pillow, Archaean Shebandowan–Wawa Belt, Canadian Shield.

Fig. 15. Pear-shaped termination of a pillow from the Archaean Shebandowan belt.



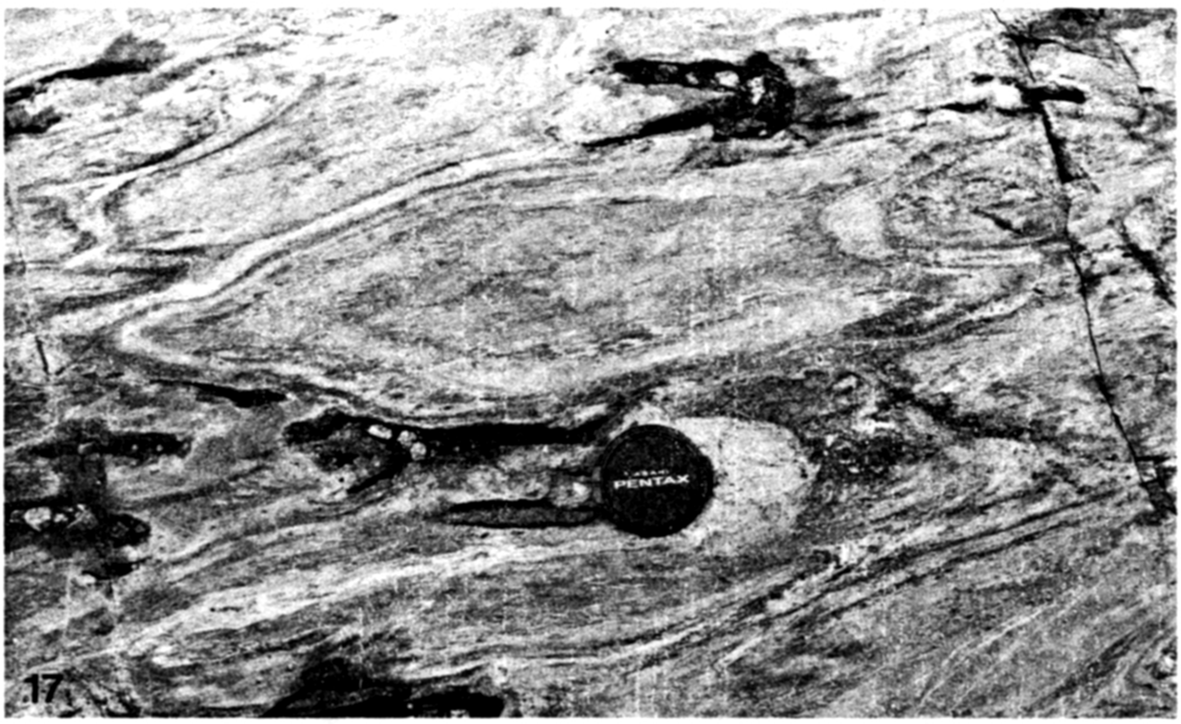


Fig. 16. Heterogeneously strained Archaean pillow lava from the Wabigoon Belt. Note folding of the pillow outlines indicated by arrows.

Fig. 17. Heterogeneously strained, 'molar-tooth' lava pillow from the Archaean Wabigoon Belt.

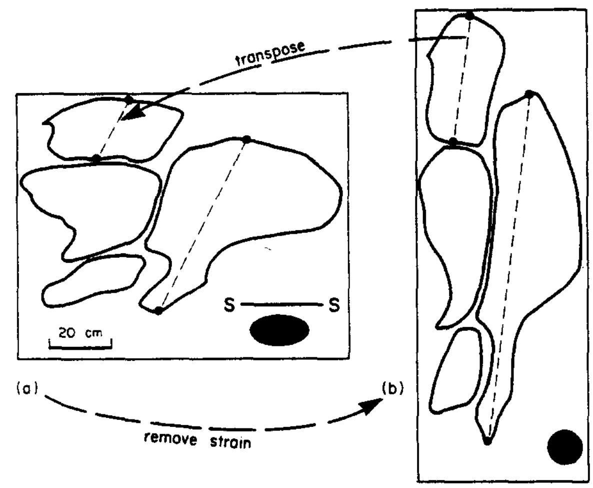


Fig. 13. (a) Field sketch of deformed pillow lava outcrop, Archaean Shebandowan–Wawa Belt, Canadian Shield. The ellipse indicates the strain, determined from pillow selvages, and S–S indicates the schistosity trace. (b) The same group of pillows after graphically removing the strain. The bedding direction in this de-strained state is given by the long axes of the pillows as indicated by the dashed lines. These lines may then be transposed to the deformed state in (a) to indicate the true orientation of bedding in the outcrop.

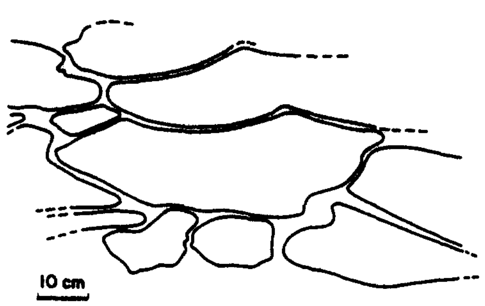


Fig. 14. Field sketch of deformed pillow lava from the Archaean Wabigoon Belt of the Superior Province. The pillows are stratigraphically inverted and the large pillow in the centre shows multiple cusps.

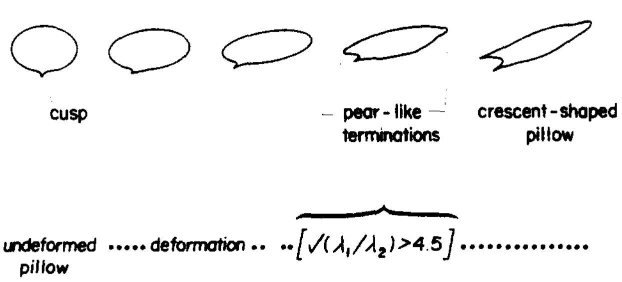


Fig. 18. Schematic sequence of progressively deformed pillows inferred from field observations. When the finite strain ellipse ratio reaches about 4.5 the pillows develop pear-like terminations (cf. Fig. 15), as a result of heterogeneous strain, and subsequently the ends of the pillow become so pointed that it is difficult to identify the cusp (cf. Fig. 17).

shaped like a molar tooth (Fig. 17). There the strain is too heterogeneous to allow its geometrical effects to be removed graphically and no simple comparison is possible with the models of pillows generated by homogeneous strain whether it is coaxial (Fig. 3) or non-coaxial (Fig. 9). Furthermore, it becomes impossible to decide which of the termini of the pillow was formerly the cusp. In cases such as that shown in Fig. 17 no attempt can be made to determine way-up or bedding from the pillows. The general sequence of geometries which seem to occur with advancing strain is summarised in Fig. 18.

CONCLUSIONS

It can be readily ascertained whether or not natural pillows are tectonically strained from the variation in the thickness of their selvages (Borradaile & Poulsen 1981). Where even moderate homogeneous strains have been imposed it may be impossible to directly infer the bedding and way-up directions from the outlines of the pillows. Similarly primary flow directions cannot be inferred from asymmetric cusps nor from sheared pipe amygdales if the pillows have been tectonically strained.

Pillows strained homogeneously in a coaxial history and fortuitously parallel or perpendicular to the principal shortening direction can be used to indicate bedding and way-up. Pillows of other original orientations can have their outlines restored to give the true bedding and way-up directions. Occasionally, multiple-cusp or flat-based pillows facilitate bedding and way-up determinations by inspection in the deformed state.

Apart from these special cases and techniques, homogeneously strained pillows generally do not yield a true indication of bedding or way-up. These problems are exacerbated where the strain is heterogeneous or where it accumulated non-coaxially.

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