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The analysis of deformed belemnites

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Abstract—Deformed belemnites are important strain markers because they allow calculation of actual length changes in deformed rocks. They have been studied in the deformed Lower Lias sequence of part of the French Alps by measuring the orientation of about 100 belemnites at each locality, recording the amount of extension of as many as possible, and locating the sector of arc on the bedding plane occupied by extended belemnites. For comparison, studies on a similar but undeformed Lower Lias sequence in southern England show that dispersed belemnites have no strong initial preferred orientation, and that a proportion of undeformed belemnites show cross-fractures that would allow extension of the rostra from the onset of deformation.

Graphs of frequency *vs* orientation for belemnites at locations deformed by irrotational strain lead directly to an estimate of two-dimensional strain ratio and orientation. Non-random initial distributions and rotational strain produce more complex graphs, which are treated only qualitatively. Extension–orientation graphs show that many deformed belemnites lie within the sector of extension of the strain ellipse. These graphs provide estimates of $1 + e_1$ and $1 + e_2$, which can be cross-checked using the orientation of the lines of no finite longitudinal strain derived from measuring the maximum sector of arc occupied by extended belemnites.

Examples from the French Alps show how the rotational and irrotational strain of initially random samples may be distinguished, and how the more complex case of deformation of non-random samples differs from these. The direction of rotation of the strain ellipse can be derived from the geometry of the graphs of frequency and elongation.

INTRODUCTION

OF ALL THE commonly occurring strain markers in deformed rocks, extended belemnites are perhaps the most significant because they permit calculation of actual changes in length during deformation to be made, and hence absolute values of the principal strains may be calculated. With other types of strain marker, only the ratio of the principal strains is calculated normally. The importance of belemnites as strain markers is emphasised by their relative abundance in parts of the deformed Mesozoic sequence in the French and Swiss Alps, where measurement of the principal strains in the plane of the bedding provides useful information on the change in shape of thrust slices during their emplacement. This paper is based on studies carried out in deformed sedimentary rocks of Lower Liassic age within the Ultradauphinois thrust belt along the northern margin of the Pelvoux Massif, French Alps (Ramsay 1963, Debelmas & Lemoine 1970). Figure 1 shows the major tectonic structures in the area and the locations at which deformed belemnites have been studied.

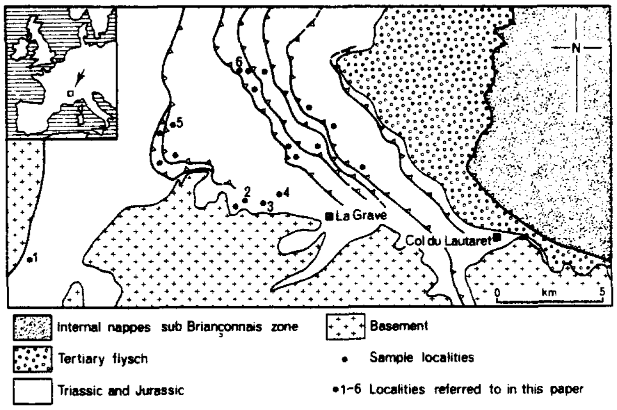

Fig. 1. The southern part of the Ultradauphinois thrust nappe (consisting of Mesozoic and Tertiary sedimentary rocks) around La Grave, Hautes Alpes, France, showing the main thrust faults affecting the external Jurassic cover sequences in relation to the basement of Pelvoux. Localities at which deformed belemnites have been studied are shown by a dot, those that are referred to in the text being numbered as follows: (1) Mont de Lans, (2) Chalet Galan, (3) Chalet Gonon, (4) Le Chazelet, (5) Chalet Josserand, (6) La Buffe.

STATEMENT OF THE PROBLEM

Ramsay (1967) presents a simple technique for calculating strains from extended belemnites, using a Mohr circle solution of the two-dimensional strain equations for either (a) two differently orientated and extended belemnites where the direction of the principal extension within the plane of measurement is known, or (b) for three differently orientated and extended belemnites where the direction of maximum elongation is not known.

An appreciation of the way in which the belemnites deformed is crucial to an understanding of the results obtained. Generally, belemnites being more competent objects in a less competent matrix deform heterogeneously by extension across cross-fractures related to the radial calcite structure of their skeleton. When subjected to shortening strain along their length belemnites may not deform, remaining as objects that are much more competent than their matrix, or they may undergo a small amount of internal ductile strain, or they may become folded. Examination of belemnites lying at a high angle to cleavage in deformed rocks shows a very strong flattening of the slaty cleavage around the belemnite and very little evidence of internal strain within the belemnite, either by the formation of stylolites and sutured grain boundaries or by ductile deformation of calcite shown by curving deformation lamellae.

The use of only two or three extended belemnites to calculate values of the principal strains assumes that any belemnites having the same orientation in an area of homogeneous strain record the same amount of deformation, that is, each extended belemnite records the maximum possible strain. The possibility that one belemnite is less extended than another of the same orientation because of a different competence relative to its matrix, or because one belemnite developed cross-fractures at a different time from another, is ignored. The present work has shown this assumption to be invalid, and therefore puts into doubt strain values obtained from small numbers of belemnites. The results discussed here were obtained from measurements on large groups of belemnites; usually 100 measurements at each outcrop were made within one or several bedding planes covering an area of up to 100 m^2, depending on the abundance of belemnites. The bedding plane is not a plane of principal strain as the cleavage is always more steeply inclined than the gently (east) dipping bedding planes. The angle between bedding and cleavage varies from a few degrees in the west to about 40°in the east of the area shown in Fig. 1. First, however, some observations on belemnites in undeformed rocks are presented.

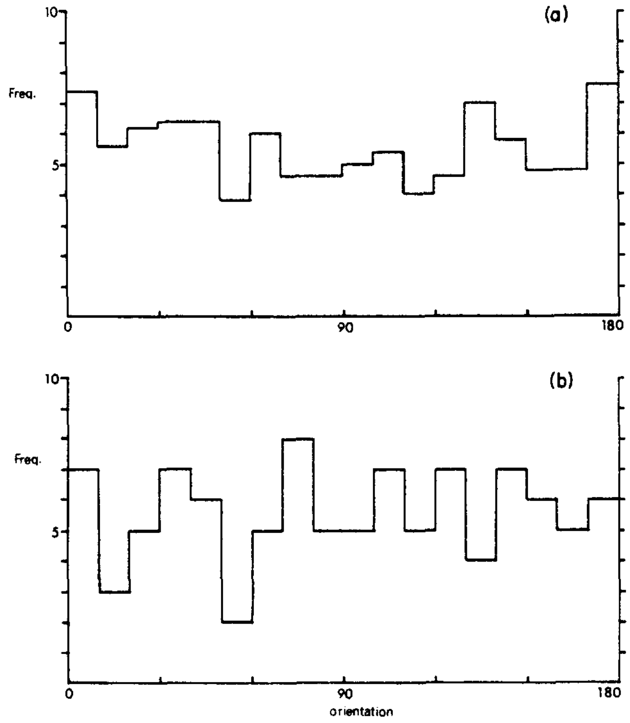

Fig. 2. (a) Percentage frequency *vs* orientation (relative to north) for a sample of 500 belemnites (in bedding planes) from the undeformed Lower Lias near Charmouth, Dorset. (b) Percentage frequency *vs* orientation for 100 consecutive measurements from the sample in (a).

BELEMNITES IN UNDEFORMED ROCKS

The rocks studied in the Ultradauphinois zone of the French Alps are a sequence of alternating limestones and shales of Early Liassic age, individual beds of both rock types usually being between 10 and 30 cm thick (cf. Ramsay 1963). The rocks are everywhere seen to be deformed. The closest approach to these rocks seen in the undeformed state is found in the Lower Lias near Charmouth, Dorset in southern England. Belemnites generally lie within the plane of the bedding and are fairly evenly dispersed on such surfaces. The rocks at Charmouth are strongly bioturbated and disturbed; belemnites preserved at an angle to bedding are common. The occurrence of clear evidence for bioturbation and the incidence of belemnites at an angle to bedding is less frequent in the deformed rocks studied. Some results of a preliminary study of the orientation of large numbers of belemnites in Dorset are shown in Fig. 2. No obvious preferred orientation is revealed. Further statistical work on these samples is being carried out.

Examples of clusters of belemnites occur quite frequently in the Alpine rocks studied, but less so in the Dorset rocks. They generally occupy scour-hollows and winnowed surfaces, and show a clear preferred orientation in some undeformed rocks (Morris, pers. comm., cf. Ager 1963, plate 3 and fig. 5.1). Such closely spaced belemnites have not been measured in the deformed rocks because (a) their initial preferred orientation is unknown, (b) individual belemnites could not rotate freely during deformation and (c) amounts of extension of belemnites may be determined by local heterogeneous strain within the cluster.

Further observations on undeformed belemnites show that many have cross-fractured rostra. In some examples these fractures are continuous with irregular joints in the rock and are clearly late stage. In others (possibly up to 30% of the population), the fracture is confined to the belemnite and may have originated during burial and compaction of the sediments (e.g. sediment filled fractures reported by Bolton, pers. comm.). An example is shown in Fig. 3(a).

In conclusion, the study of belemnites in undeformed rocks suggests that some belemnites may be fractured at an early stage and therefore will record increments of extension from the beginning of deformation. Others may develop fractures during deformation, whilst some may remain unfractured and hence record no extension. This study also suggests that dispersed belemnites in the limestone–shale facies of the Lower Lias show very little primary preferred orientation that would affect orientation distributions in the deformed state. This statement clearly cannot be generalised to other types of sediment or environments of deposition, and all data must be treated carefully. This will become clear in the next section where measurements of deformed belemnites are discussed.

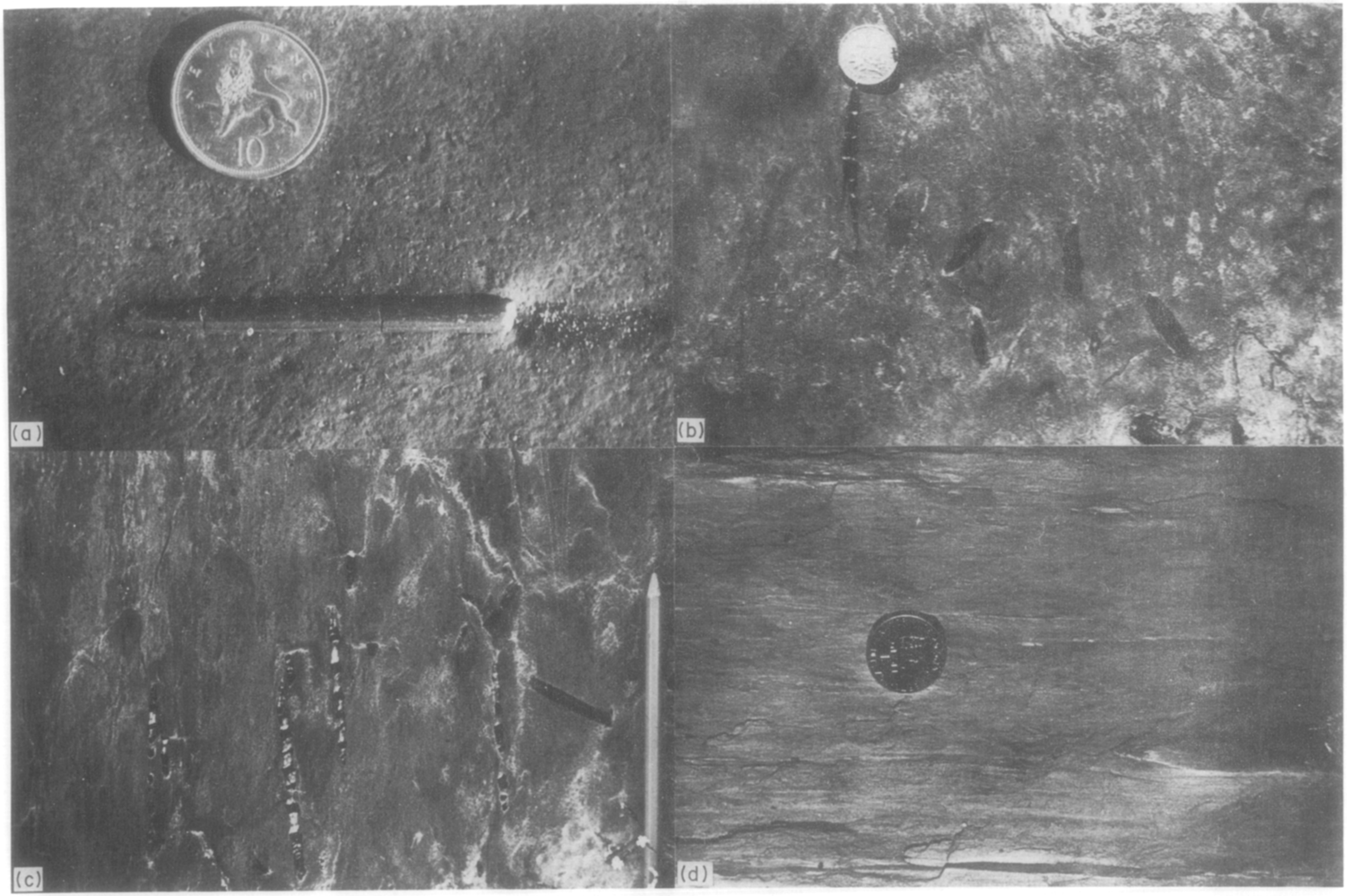

Fig. 3. (a) Undeformed belemnite in the Lower Lias of Charmouth Dorset, southern England, showing how the rostrum is cross-fractured. (b) Belemnites showing a very small amount of extension, Lower Lias, Chalet Galan, near La Grave, Hautes Alpes, France. (c) Belemnites showing a moderate amount of extension, Lower Lias, Chalet Josserand, near La Grave. The gaps between the pulled-apart pieces of belemnite (black) are sometimes filled with calcite and quartz (white) and sometimes with the surrounding matrix of marly limestone (grey). The pencil lies approximately parallel to a strong stretching lineation on this slab where bedding and cleavage are parallel and indistinguishable in the field. At least one belemnite shown, at a high angle to this lineation, remains unextended. (d) A belemnite showing no extension lying parallel to a very strong stretching lineation in a Lower Lias Limestone from Mont de Lans, Isère, France.

BELEMNITES IN DEFORMED ROCKS

A more comprehensive approach to the analysis of belemnites in deformed rocks than that suggested by Ramsay (1967) is made here by recording the extension and orientation of belemnites in samples of about 100 at each outcrop. Three independent approaches to measuring the strain can be made using these data:

(a) Plotting a frequency distribution of orientations;

(b) Plotting an extension *vs* orientation graph;

(c) Locating the sector of arc of extended belemnites and thus defining lines of no finite longitudinal strain.

If an originally randomly distributed sample of belemnites in the plane of the bedding is deformed homogeneously by an irrotational strain with $\lambda_1 > \lambda_2$, then the orientations of belemnites in the deformed state will cluster around the maximum extension direction with a frequency distribution related directly to the strain ratio. Such distributions can then be compared with numerically derived distributions, using the Wettstein relation (Ramsay 1967, 1976), to arrive at a value for this strain ratio. Sanderson (1977) discusses this problem, and shows how the strain modified, uniform distribution approximates closely to the circular Von Mises distribution and how the magnitude and direction of the mean circular vector provide a good estimate of the strain ratio and the orientation of the direction of maximum elongation, respectively. Figure 4 shows a frequency–orientation graph for a sample of belemnites recording the lowest finite strain found in the study of deformed belemnites (Fig. 3b). There is no indication in this graph of the existence of a non-random initial distribution of the belemnites. Figure 5(a) shows the more normal type of frequency distribution encountered in moderately deformed samples of belemnites (these are illustrated in Fig. 3c); the distribution is symmetric and the mode and median coincide.

During deformation in which the strain in the bedding plane involves extension, those belemnites lying in the sector of incremental extension of the strain may undergo elongation. Careful sampling is needed if the amounts of extension recorded by belemnites are to be correctly interpreted, since they depend on the stage of deformation at which cross-fracturing of the belemnites occurred (cf. Ramsay 1967, fig. 5.73). Within a sample of up to 100 belemnites at a locality, between 40 and 80 may show a measurable extension, the remainder being either undeformed or sufficiently poorly preserved that a measure of elongation cannot be made. Plotting a graph of elongation against orientation, an envelope can be drawn round the field of points (e.g. Fig. 5b). This envelope is then used to define the variation in actual extension with orientation, and recognises that belemnites of many orientations record an elongation less than this. The assumption that the sample is representative is clearly implicit, and this is most critical in assuming that at least one belemnite recording the maximum elongation in the rock is included in the sample (Fig. 5b). The occurrence of unextended belemnites throughout the sector of extension of the strain is clearly illustrated in Fig. 8(b). An example of an unextended belemnite lying parallel to a strong stretching lineation is illustrated in Fig. 3(d). For an irrotational and homogeneous strain, the envelope should be symmetric around the orientation of the maximum extension, as seen in Fig. 5(b).

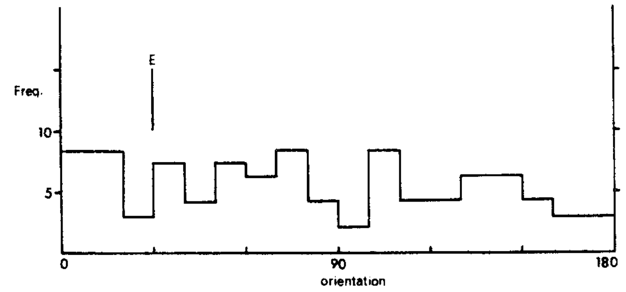

Fig. 4. Percentage frequency *vs* orientation for a sample of 95 belemnites in the deformed Lower Lias, Chalet Gonon, La Grave, Hautes Alpes. *E* indicates the direction of maximum elongation recorded by the belemnites; $1 + e_1 = 1.25$, $1 + e_2 = 0.84$.

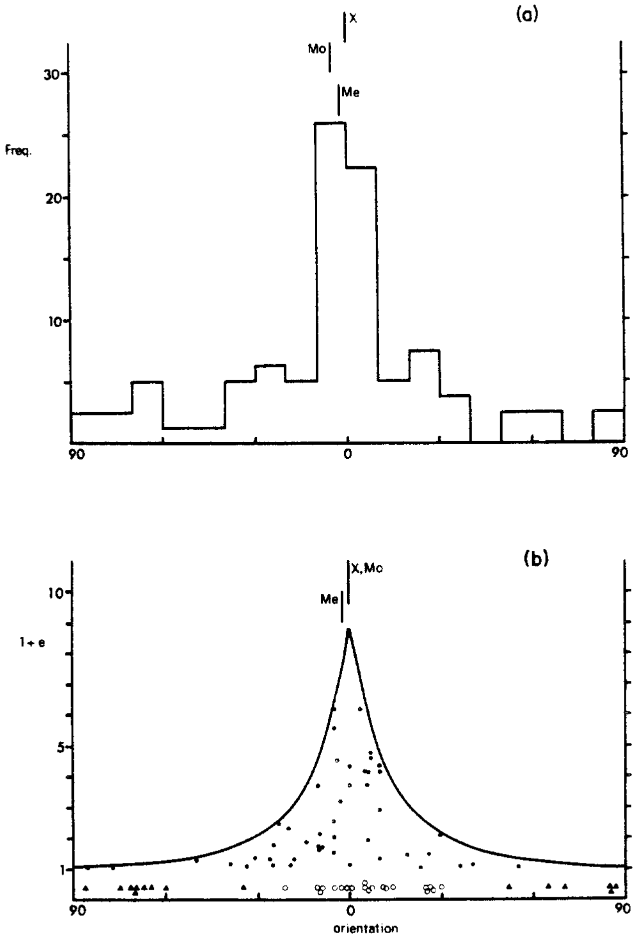

Fig. 5. (a) Percentage frequency *vs* orientation for a sample of 80 belemnites from the deformed Lower Lias, La Buffe, La Grave. *X* — direction of maximum extension of belemnites and stretching lineation. Mo — orientation of modal value. Me — orientation of median value. (b) Elongation *vs* orientation for the belemnites in (a). Solid circles represent extended belemnites; open circles represent the orientation of extended belemnites where it was not possible to measure this elongation; solid triangles represent the orientation of belemnites showing no extension.

A natural consequence of plotting graphs like Fig. 5(b) is that the lines of no finite strain are clearly defined for strains where $\lambda_1 > 1 > \lambda_2$ by the maximum sector of arc occupied by extended belemnites. The distribution of unextended belemnites obviously cannot be used.

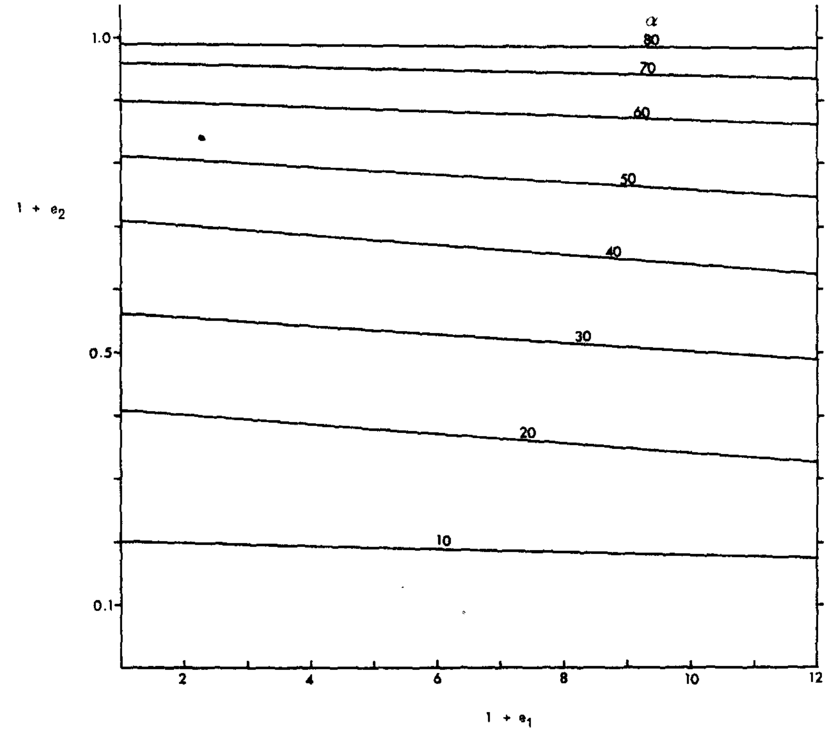

Fig. 6. The orientation of the lines of no finite strain, relative to the direction of maximum elongation within the strain ellipse $\lambda_2 > 1 > \lambda_1$, for a range of values of the principal strains plotted as $1 + e_1$ *vs* $1 + e_2$.

Again, for an irrotational and homogeneous strain, the lines of no finite strain should be symmetric about the direction of maximum extension. Ramsay (1976), extending the work of Talbot (1970), has solved this problem for strains involving a volume change and shows that when the volume change is zero a unique solution to the values of the principal strains may be obtained from the orientation of the lines of no finite strain, but that when the volume change is not zero two solutions are obtained, and additional information is needed to choose between the two. The extended belemnite samples under discussion yield only two-dimensional data and it is therefore not possible to calculate the volume change during deformation without strain data for the third dimension. The solution to the two-dimensional equation giving the orientation of the lines of no finite strain, relative to the direction of maximum elongation, in terms of the magnitudes of the principal strains for no volume change (Ramsay 1967, eq. 3.33) is given in Fig. 6. Using the already measured magnitude of the maximum elongation, a value of the minimum elongation can be interpolated from Fig. 6 and checked against the value obtained from the two-dimensional strain solution to the envelopes drawn on diagrams such as Fig. 5(b). The strain ratio obtained can then be checked against the value derived from the frequency distribution data.

When the position of the plane of measurement within the three-dimensional strain ellipsoid is considered, the position of the lines of no finite longitudinal strain may assume a further significance. Although three-dimensional strain measurements may be difficult to obtain, the orientation of the lines of no finite strain within the plane of measurement (bedding) clearly depends on the orientation of the plane within the strain ellipsoid and on the type of strain ellipsoid. The cleavage and linear fabrics are often sufficient to define accurately the orientation of *XY* and *X*, respectively, relative to the plane of measurement, and from this a prediction of the overall shape of the strain ellipsoid can be made.

If the plane of measurement of the deformed belemnites is the *XY* plane, or lies very close to it, then the orientation of the lines of no finite strain will be related directly to the k — value of the strain ellipsoid, as well as to the two dimensional principal strains as shown in Fig. 6. For this situation, an exact measure of the k — value is obtained for all prolate ellipsoids, assuming no volume change, and a Flinn plot contoured for values of the orientation of the lines of no finite strain in *XY* can be drawn (cf. Ramsay 1967, pp. 154–162). Although the amount of volume change during deformation is rarely known, such a contoured Flinn plot would be modified by volume change.

NON-RANDOM INITIAL ORIENTATIONS AND ROTATIONAL STRAIN

The presence of an originally non-random distribution of belemnites in the undeformed bedding plane, or an element of rotational strain during deformation, will complicate the results derived so far. It is worthwhile considering in a qualitative way the effect that these two factors will have on the geometry of the frequency and extension graphs and on the orientation of the lines of no finite strain.

Consider first a non-random distribution deformed by an irrotational strain. The principal type of non-random distribution in belemnites will be a more or less symmetric type induced by current activity during deposition, often a period of winnowing, though bi-directional distributions may also occur (Ager 1963, Hallam 1967, Morris, pers. comm.). Problems of superimposed strain will generally also involve deformation of non-random distributions produced by the first deformation. Unless the direction of maximum elongation of the strain ellipse coincides with the orientation of the mode of the initial distribution, the strain modified distribution will show a skewed frequency-orientation graph with the mode offset from the direction of maximum elongation (cf. Sanderson 1973). However, since the strain is still irrotational, the envelope on a graph of elongation against orientation will be symmetric around the principal elongation. There will simply be more data points to one side of this direction than to the other, and statistically the envelope and the lines of no finite strain may be more difficult to define.

Among the deformed belemnites measured, only one sample clearly illustrates this type of distribution (Fig. 7). The frequency distribution (Fig. 7a) is skewed and, while the mode is ill-defined, the median is clearly offset from the direction of maximum extension (Figs. 7a & b). Part of the envelope in Fig. 7(b) is ill-defined because of the absence of points over 40° of arc and their low incidence over 95° of arc in the distribution shown in Fig. 7(a).

Next consider the effect of a rotational strain on a sample of initially randomly distributed belemnites. Two types of rotational strain may be distinguished (Flinn 1978) in terms of the resultant strain modified distributions produced. Type one involves addition of strain increments at a constant orientation, increments of body rotation resulting in a rotational finite strain; simple shear is a special example of this. Type two involves addition of strain increments with a progressively changing orientation and obliquely to the orientation of the finite strain ellipse at any stage. The resulting rotational finite strain merges with the case of superposed strain, the division between the two being somewhat arbitrary.

A type one rotational strain will produce a frequency distribution skewed towards the direction to which the maximum extension direction is rotating, and in which the mode and median lie close together but do not coincide, the maximum extension direction lying slightly 'ahead' of both these lines. In practice, at moderate to large strains these lines will lie sufficiently close together to be indistinguishable within the errors of measurement, and the frequency diagram is effectively asymmetric with the median and the mode coinciding and giving the orientation of maximum extension. This type of distribution is illustrated in Fig. 8(a). In contrast, a type two rotational strain involves modification by later increments of non-random distribution induced by earlier increments. As the rotation and amount of strain increase, a distinctly skewed frequency distribution develops in which the median and mode do not coincide with each other or with the direction of maximum extension.

Elongation–orientation graphs should clearly give lines of no finite strain symmetrically related to the maximum extension direction because the finite strain is homogeneous, producing a symmetric strain ellipse. The fact that the lines of no finite strain are asymmetrically distributed (Fig. 8b) brings out an important aspect of belemnite deformation. Since belemnites record increments of extension but not of shortening, as they pass from one sector to the other in the rotating strain ellipse,

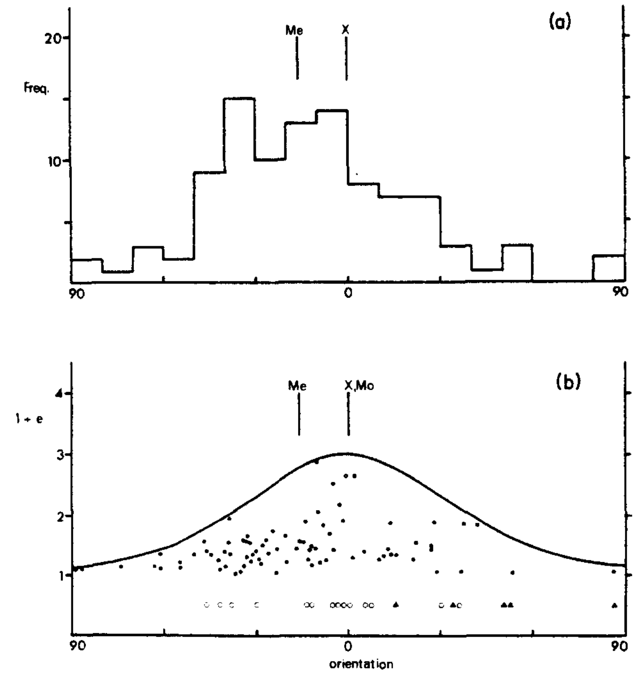

Fig. 7. (a) Percentage frequency *vs* orientation for a sample of 100 belemnites from the deformed Lower Lias, La Buffe, La Grave. The mode of this graph is ill-defined. (b) Elongation *vs* orientation for the belemnites in (a). Symbols and lettering as in Fig. 5.

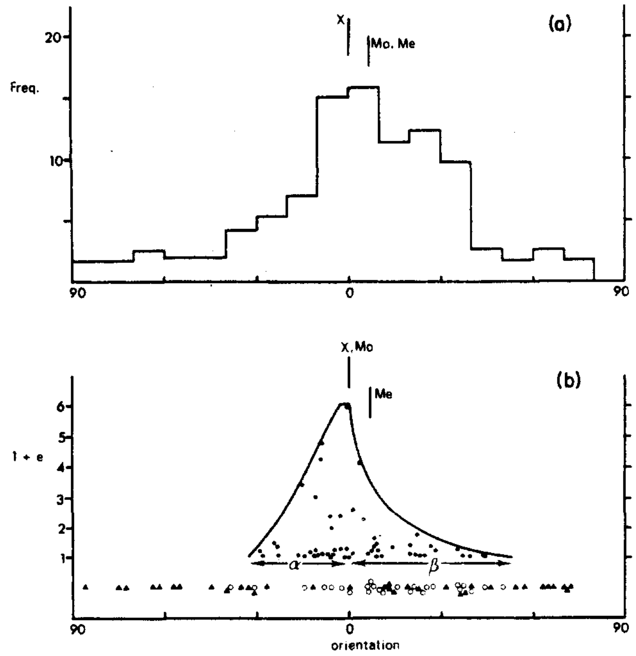

Fig. 8. (a) Percentage frequency *vs* orientation for a sample of 115 belemnites from the deformed Lower Lias, Le Chazelet, La Grave. (b) Elongation *vs* orientation for the belemnites in (a). Symbols and lettering as in Fig. 5. α and β show the angles from X to the lines of no finite strain.

the envelope to a field of points on an elongation–orientation plot will represent apparent extensions for each direction, and will not be an exact record of the extensions of the finite strain ellipse. These envelopes will be asymmetric with the line of no finite strain towards which the maximum extension direction is rotating lying closer to this direction (α in Fig. 8b) than the one 'behind' it (β in Fig. 8b). This asymmetry is therefore extremely valuable in allowing directions of rotation to be deduced from geometric considerations alone. Whether the mode of these graphs can be identified as the direction of maximum extension is debatable. Because belemnites record only increments of extension, certain types of rotational strain may give rise to belemnites showing a greater apparent elongation than that of the maximum extension of the finite strain ellipse. This last statement serves more as a warning than as a means of identifying rotational strains. The ambiguity may be resolved by using strain measurements from other markers such as deformed spots or ammonites.

Finally, rotational deformation of initially non-random distributions will result in a combination of the features described above. The frequency graph will be skewed, the median and mode neither coinciding nor giving the direction of maximum extension. The elongation–orientation graph will show an asymmetric envelope of apparent extension with asymmetrically disposed apparent lines of no finite strain. It is not clear whether any of the measured samples of deformed belemnites resulted from rotational strain (type two) of random or non-random initial distributions, since there is no clear distinction between the two. Whilst asymmetric elongation–orientation graphs are commonly encountered, the frequency graphs usually show that the mode and median and maximum elongation lie close to each other (within 5°, which will arise simply through sampling error), suggesting a type one rotational strain of initially random belemnites. This conclusion is reinforced by the absence of data showing apparent maximum elongations at an angle to the principal strain direction (as recorded for example by a stretching lineation in the field) not attributable to sampling error.

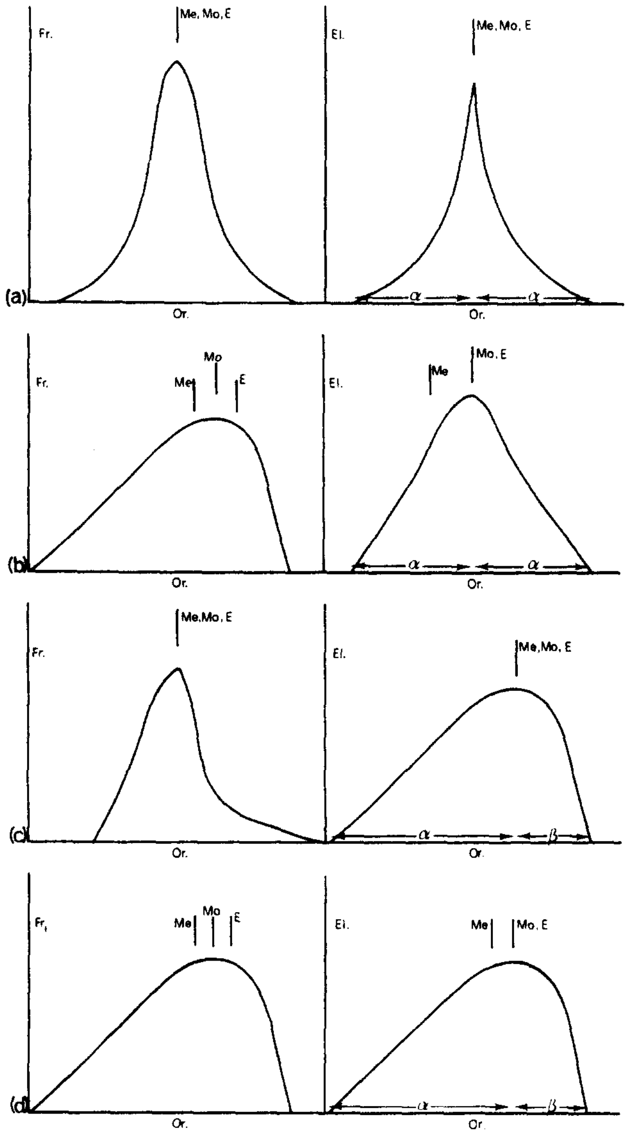

Fig. 9. Schematic representation of frequency (Fr.) *vs* orientation (Or.) graphs (left hand column) and elongation (El.) *vs* orientation (Or.) graphs (right hand column) for the five combinations of strain and original orientation discussed in the text. Mo — modal value, Me — median value, E — maximum elongation of belemnites. (a) Irrotational strain, random initial distribution. (b) Irrotational strain, non-random initial distribution. (c) Rotational strain type one, random initial distribution. (d) Rotational strain type two, random initial distribution; and rotational strain, non-random initial distribution.

CONCLUSIONS

In conclusion, it has been found that most of the distributions in samples of deformed belemnites studied are qualitatively attributable to deformation of initially random belemnites by irrotational or type one rotational strain. The very obvious expression of an initially non-random distribution in a deformed sample is uncommon, and distributions where the directions of the median, mode and observed maximum elongation are distinctly different and also different from the orientation of the principal strain of the finite strain ellipse have not been encountered. Fig. 9 summarises schematically the types of distributions that might be found for each of the five combinations of strain and initial orientation discussed. Figure 9(a) could be extended to show how the shape of the elongation–orientation graph changes as a direct function of the k–value of the strain ellipsoid for the special case only where the plane of measurement coincides, or lies very close to, the principal XY plane, as discussed earlier.

A study of deformed belemnite samples is thus found to have two uses — to provide strain data on the actual changes in lengths of lines, as well as strain ratios, and to provide information on the rotational nature of the strain history. The latter information does not usually arise from a study of most strain markers (e.g. Ramsay 1967). It still remains to be seen what strain data can be derived from deformed belemnites. For irrotational deformation of initially random distributions, the frequency distributions can be used to derive a value for the strain ratio, following Sanderson (1977). For initially non-random distributions, a more complex adaptation of the work of Sanderson (1973) would be needed. However, for both types of initial distribution the Mohr circle solution of Ramsay (1967) can be applied to the envelope drawn to the field of points on an elongation–orientation graph to derive actual magnitudes of principal strains. These figures can be confirmed using the orientation of the lines of no finite strain, if such lines are present in the deformed sample. For deformations involving rotational strain, determination of accurate strain ratios must await completion of the numerical work needed to define the nature of the frequency distributions to be expected, that is the work of Sanderson (1977) needs to be extended. However, for all practical purposes where restoration of deformed strata is required, the approximate magnitudes of principal strains that can be obtained from the type of elongation–orientation graph presented here (e.g. Fig 8(b)) are probably sufficient. Unusual distributions produced by rotational or superposed strains may give no clear indication of the finite strain ratio. Finally, it is clear that measurement of small numbers of deformed belemnites will not distinguish between the different types of strain and initial distribution, and will not allow accurate construction of the elongation–orientation envelope needed to derive the proper magnitudes of the principal strains.

Insofar as a frequency graph is sufficient to distinguish between the irrotational and rotational deformation of an initially random distribution and the deformation (irrotational and rotational indistinguishable) of a non-random initial distribution, samples of some other common linear bedding plane marks, such as certain trace fossils, which provide no information on amounts of extension, may give useful information if their geometry in the undeformed state is known.

FURTHER WORK

The general statements made in this paper are the result of extensive strain studies being undertaken in the deformed thrust sheets of the Ultradauphinois zone of the French Alps (see Ramsay 1963). A full analysis of deformed belemnite samples along the lines discussed is being carried out at present. The work is clearly complex, and while the work of Sanderson (1977) forms a useful basis for the analysis, Sanderson himself points out the need for more numerical work on strain modified non-random distributions. In the present context, a full statistical analysis of belemnite orientation data from undeformed rocks is being carried out by the author, these data being put through various numerically simulated deformations, the results then being compared with both numerically deformed uniform distributions and with naturally deformed samples from the French Alps.

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