ACTA GEOLÒGICA HISPÀNICA. *Homenatge a Lluís Solé i Sabarís.* t. 14 (1979) pàgs. 129-134

Strain determinations using deformed Radiolaria. Malaguide Complex, Southern Spain

por Rafael GALVEZ and Miguel OROZCO

Departamento de Geotectónica, Universidad de Granada (Spain).

RESUMEN

En este trabajo se exponen los resultados de las primeras medidas de deformación finita realizadas en la Cordillera Bética. Estas medidas se han obtenido a partir de radiolarios deformados que aparecen en una secuencia de rocas silíceas del Complejo Maláguide (Zonas Internas). La secuencia estudiada está formada por estratos delgados, muy bien definidos, de potencia total reducida (5-6 metros) e intensamente plegados.

Las técnicas de análisis de la deformación, suponiendo que el volumen permanece constante, muestran la existencia de dos grupos de radiolarios deformados: El primero de ellos ha sufrido extensiones de hasta el 80 % en la dirección del eje mayor (X) del elipsoide de deformación finita y acortamientos de hasta el 40 % en la dirección del eje Z; en el segundo grupo, perteneciente a otro afloramiento, la extensión llega a ser del 200 % y el acortamiento en la dirección del eje Z de hasta el 60 %, habiendo ocurrido también un acortamiento en la dirección del eje intermedio (Y) de un 20 % aproximadamente. Esta más intensa deformación se interpreta como el resultado de la superposición de pliegues. En la mayoría de los casos el plano *X Y* del elipsoide de deformación es paraleo a las superficies de esquistosidad y el eje mayor (X) paralelo a los ejes de los pliegues. Se sugiere una explicación de este paralelismo y de las que podrían calificarse bajas razones axiales de los elipsoides, a pesar de la fuerte deformación tectónica que revelan los mantos de corrimiento y los pliegues isoclinales con esquistosidad de plano axial existentes en la región.

ABSTRACT

Deformed radiolaria of a chert sequence belonging to the Maláguide Complex (Betic Cordillera) were used to obtain the first finite strain measurements made in this range. The rocks investigated have well-defined bedding surfaces and form a succession of small thickness (5-6 m.) which had been intensively folded.

Assuming constant volume, strain analysis techniques reveal the existence of two groups of deformed radiolaria: the first has suffered extensions of up to 80 % in the direction of the long axis (X) of the finite strain ellipsoid and shortenings of up to 40 % in the direction of the Z axis; the second group, made up of radiolaria from another locality, has undergone extensions of up to 200 % and shortenings in the Z direction of up to 60 %, in this case, there has also been a shortering in the intermediate direction (Y) of about 20 %. The higher strain in the last case is interpreted as being the result of superimposition of folds. In most cases the XY plane of deformation ellipsoids is parallel to the cleavage surfaces and the long axis (X) parallels the neighbouring fold-axes. An explanation is suggested for this parallelism and also for the rather striking fact that the axial ratios of the ellipsoids are not very high in spite of the strong deformation undergone by the zone as manifested by nappe structures and isoclinal folds with associated axial-plane cleavage.

INTRODUCTION

To determine the state of finite strain in rocks a fairly great variety of objects have been used as markers, some more frequently than others. In addition to the most commonly used ooids, fossils and conglomerate pebbles, there are other materials available for these measurements: reduction «spots»; nodules; pisolites; spherulites, amygdules and vesicles in volcanic rocks. Reference to the use of radiolaria as «strain markers» are very seldom found; the paper of Bryan and Jones (1955) concerning the radiolarian jaspers of the Neranleigh-Fernvale Group in Queensland could be quoted in this respect.

In the Betic Cordillera, now relatively well known in its general features of lithology, structure, metamorphism, etc. no finite strain study had been carried out until the present one (see Julivert et al., 1974). The External Zones of the Cordillera seem to be the most suitable for such research, because the proper material (oolite-limestone, fossils,...) can be found there; whereas the Internal Zones seemed less suitable because of the more complicated structure and variable degree of metamorphism. However, the existence of radiolaria in a chert sequence belonging to the Paleozoic of the Malàguide Complex (the uppermost tectonic unit of the Internal Zones) led us to attempt such a study in that part of the Cordillera.

The initial shape of the objects is known and the rocks have a wide distribution in the Internal Zones of the range which, in turn, will allow future studies in many other parts. As these radiolarian cherts occur worldwide in sequences of very different age the possibility of using them in finite strain studies must be emphasized.

MATERIALS

Radiolarian cherts in the area studied make up a sequence which is included in a series of lutites, sandstones and limestones. Although the age of the chert sequence is not well known, it must be between Upper Silurian and Visean.

The rocks investigated are found in a succession of thin (5-10 cm) layered chert, radiolarites and the intermediates, with some clay films between; colours vary and may be black, pink, grey and white. Bedding is regular and well defined, the sequence thickness being small (5-6 m). It is crossed by a dense network of joints, which make it difficult to obtain specimens of a proper size. The outcrops investigated are small: some hundred square meters at most, their locations are shown in fig. 1.

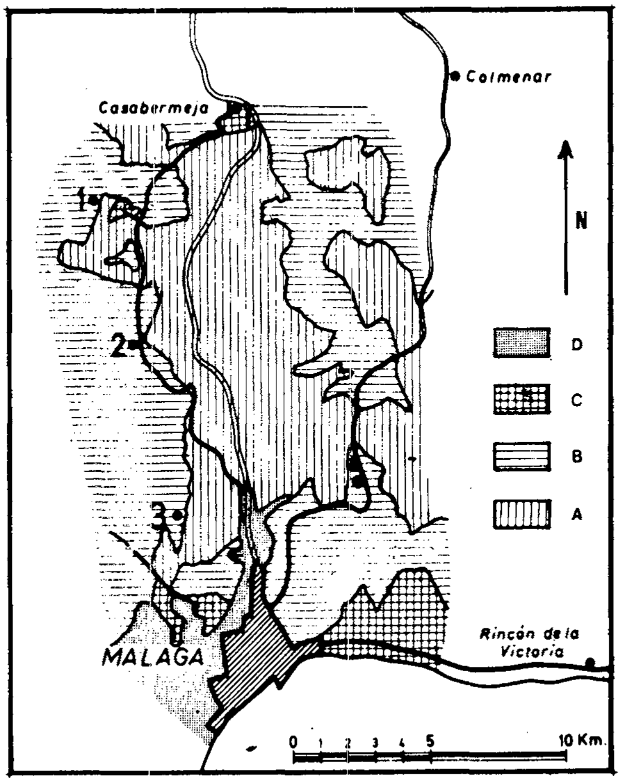


Fig. 1. A schematic geological map of the area showing the outcrops studied: A) lower unit B) intermediate unit C) higher unit D) Pliocene and Quaternary.

Through the microscope the rock appears as a cryptocristalline aggregate of quartz of different colours with some very small mica flakes. Quartz-filled fracture cleavage and veins are present and, in some specimens, concentrations of iron and manganese oxides and cubic ore crystals (pyrite?) occur.

Radiolaria included in the rock show elliptical cross-sections with the large axis shorter than 0.5 mm and generally in the range 0.1-0.2 mm. Usually no special structure can be seen at the border or the inner part of the fossils; however in some cases spines and pores developed on the siliceous shell have been preserved (fig. 2). These features are distinguishable where the rock is impregnated by oxides. If the rock does not have such a staining, the colour contrast between radiolaria and matrix is low and the boundaries are not well defined; it is then advisable to make the sections thicker than normal.

Fig. 2. Pore development in a double radiolarian shell.

Even with a 15 x hand-lens, radiolaria are difficult to distinguish in the field; so no specimen should be rejected on the basis of a negative test. In our case 30 % of the specimens were not suitable because of lack of radiolaria. Near the bedding surface radiolaria are usually more common and better preserved than in the middle of the layer.

Initial shape

Radiolaria both in the fossil and in the present forms can live isolated or be part of a colony, and show a great variety of shapes and structures. Spherical and ellipsoidal forms are rather common; the shell may be double or multiple or absent.

In the thin sections we have studied, whatever the orientation of the cut may be, shapes are always elliptical, with variable axial ratio. Hence it can be inferred that the initial shape of the fossils was either spherical or ellipsoidal. As we have not found (Moore, 1954) references to ellipsoidal radiolaria of Devonian age with a structure and organization similar to the ones described, we conclude that the radiolaria studied must have been originally spherical in shape, and they probabley belong to the superfamily *Liosphaericae,* sub-order *Spumellina.*(1)

METHOD OF STUDY

Specimen selection and orientation was done in the usual way, measuring the different structural features: bedding, fold-axes, axial-planes and cleavages at every locality. Two thin sections from each specimen were made, one parallel to the cleavage (or the fold axial-plane) and another perpendicular to it and the fold-axis; in several cases a third section was made perpendicular to the others.

Two methods were tried in the measurement of the radiolaria: in some instances a binocular microscope with a mechanical stage and a graduated eyepiece was used; in other cases the section was placed on a slide-projector and the shape of the radiolaria obtained by projecting the thin section onto a sheet of paper and drawing the outlines of the fossils; then the orientation of the ellipse axes in relation to a reference line was measured. In several cases both methods were employed in order to compare the results obtained.

Relatively little time was spent measuring the ellipse dimensions and orientations compared with the time needed for other tasks. It was thought advisable to measure, whenever possible, a fairly large number of objects. Axial ratios and orientations from each section were tabulated and the mean and the standard deviation of the mean were calculated.

Orientation of the principal planes of the ellipsoids

At the beginning of the study it was assumed that the XY planes of the deformation ellipsoids were parallel, or nearly so, to the cleavage planes, either the X or Y axis being parallel to the fold axes.

1. A paleontological discussion is beyond the scope of the present paper. For details, see Moore (1954).

TABLE I

Strain data

Sample	Locality	$\overline{X/Y}$	Standard deviation	Standard deviation from the X mean orientation.	$\overline{Z/Y}$	Standard deviation	Standard deviation from the Y mean orientation	Axial ratio X:Y:Z
CB-100	1	3,96	0.95	2,5°	0,60	[illegible]	8,3°	3,96: 1: 0,60
CB-102	1	4,10	0,74	1,46°	0,52	0,07	5,16°	4,10: 1: 0,52
CB-103	1	3,55	0,73	2,47°	0,55	0,07	5,29°	3,55: 1: 0,55
CB-150	2	1,64	0,26	6,41°	0,79	0,09	26,04°	1,64: 1: 0,79
CB-151	2	1,58	0,16	8,14°	0,70	0,09	7,45°	1,58: 1: 0,7
CB-153	2	1,80	0,27	2,91	0,67	0,08	7,5°	1,80: 1: 0,67
CB-154	2	1,52	0,17	6,91°	0,80	0,085	29,3°	1,52: 1: 0,80
CB-155	2	1,66	0,21	8,13°	0,77	0,081	11,95°	1,66: 1: 0,77
CB-156	2	1,48	0,19	6,96°	0,69	0,106	11,84°	1,48: 1: 0,69
CB-157	2	1,71	0,26	5,40°	0,65	0,117	11,24°	1,71: 1: 0,65
MG-329	3	1,54	0,19	8,75°	0,704	0,076	15,78°	1,54: 1: 0,704
MG-331	3	1,57	0,19	6,66°	0,71	0,128	3,27°	1,57: 1: 0,71

Thin sections were taken: one parallel to cleavage; a second one perpendicular to cleavage and to the fold axis and in some cases a third section perpendicular to the other two.

This assumption was seen to be correct when the sections were examined under the microscope: in those parallel to cleavage, the X axes of the ellipses were parallel (or nearly so) to the bedding trace; in the second type of section, the Y axis was parallel to the cleavage trace too.

Ellipsoids were represented graphically by means of a logarithmic deformation plot (fig. 3) in which the ratio of the longer to the intermediate ellipsoid axes (log X/Y) was plotted as ordinate and the ratio of the shorter to intermediate axes (log Z/Y) was plotted as abscissa (Flinn, 1962; Wood, 1973). Ellipsoids with K=1 (plane strain), were plotted along the median line; the area below this line was the field of the flattening-type ellipsoids ($0 \leq k < 1$) and the one above the line is that of constrictional-type ellipsoids ($1 < K$ ∞).

From fig. 3 it is evident that the mean deformation ellipsoids of the different localities are all of the constrictional type, although they fall into two groups. The largest one belongs to specimens from localities 2 and 3, and shows a dimensional shortening parallel to the short axis of the ellipsoid (Z) of between 40 % (Z = 60 % *d*) and 20 % (Z = 80 % *d*) and an extension in the direction of the long axis of between 40 % (X = 140 % *d*) and 80 % (X = 180 % *d*) *d* being the equivalent volume sphere diameter, assuming constant volume during deformation. The other group is composed of specimens from locality 1 and shows more intensive deformation: a shortening in the Z direction of between 50 % (Z = 50 % *d*) and 60 % (Z = 40 % *d*) and an average lengthening in the X direction of 200 % (X = 300 % *d*); in this case there has also been a dimensional shortening in the Y direction of about 20 % (Y = 80 % *d*), so that the mean deformation ellipsoid has a pronounced constrictional character.

Relation of ellipsoids to local structures

The chert sequence, as has already been pointed out, shows many folds, some of which have developed axial-plane cleavage. It has been observed that in most cases the (XY) principal plane of the strain ellipsoids is parallel to the cleavage surfaces. This parallelism is mantained even where cleavage is bent near the layer boundaries showing a sigmoidal section; in these instances measurements were taken only in the middle part of the layer.

It must be emphasized that in the cases we have studied the long axis of the strain ellipsoid is parallel to the axes of the folds where the specimens were taken.

DISCUSSION

The shapes of the strain ellipsoids obtained, do not show a very high deformation, which would seem to contradict the known general structural features of the Internal Zone of the Betic Cordillera, even those of the Malâguide Complex (superposed nappe structures, generalized development of cleavage on slates, and even limestones, of age and location

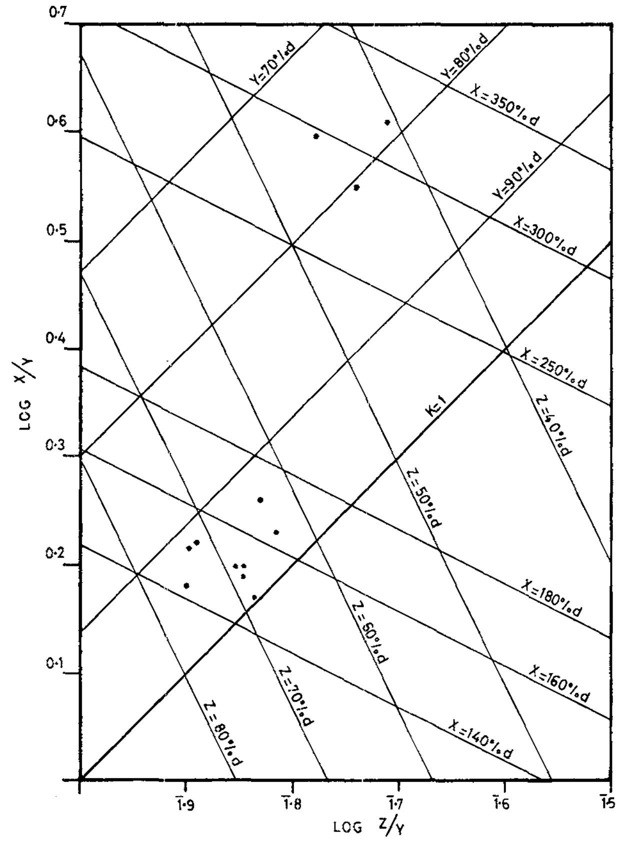
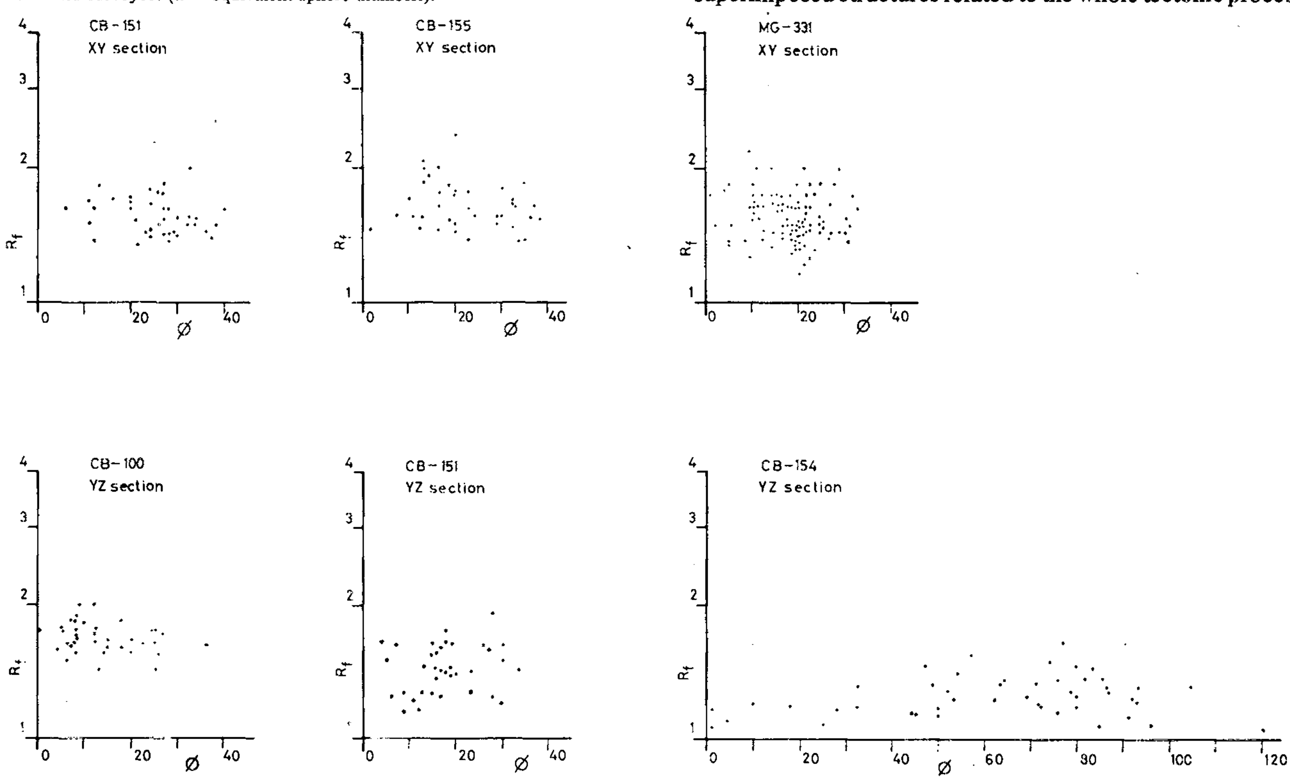


Fig. 3. Logarithmic deformation plot for mean deformation ellipsoids of the localities surveyed. (d = equivalent sphere diameter).

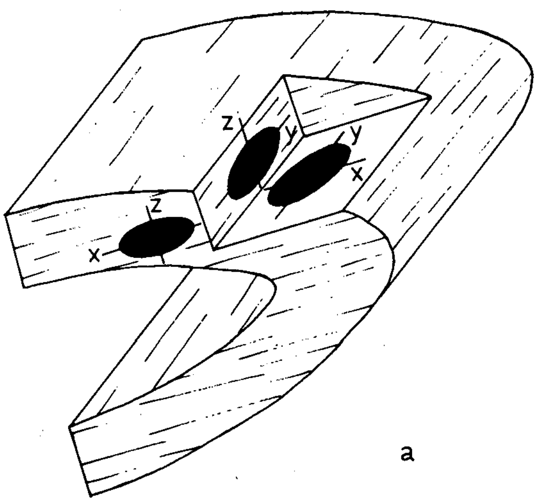
similar to the rocks investigated). However, this fact must be considered bearing in mind that the present shape of radiolaria is the final result of different phases of deformation, some of which could counteract the effects of the others.

The superimposition of structures in the Betic Cordillera was recognized years ago (Egeler and Simon, 1969). In the investigated silexite localities the authors have found (Galvez and Orozco, in press), that at least four phases of folding exist. The existence of this superimposition may be guessed at from plotting the relationship between the axial ratio and the orientation of the ellipses in a particular section on a graph (fig. 4) in the manner described by Dunnet (1969). It is clear from the figure that the distribution of points is fairly asymmetric on the following basis: 1) the different number of points in each of the four quadrants, defined by the mean of the orientations, ∅, and the logarithmic mean of ratios, R_f and 2) the lack of coincidence of the mean of ∅ with the maximum and minimum values of R_f.

The superimposition of deformations is also reflected by other observations; in some sections two oblique cleavages appear, the long axes of the ellipses being parallel to one of them. This is the case of the three samples from locality 1, for which the constrictional shape of the ellipsoid is very evident (Fig. 3) These samples are taken on a fold, which folds a previous lineation, resulting from the intersection of bedding and cleavage. This structure results from a superimposition of folds like that described by Ramsay (1967, p. 520) as «Type 1 interference pattern» —where there is a small angle of approx. 20° between the fold axis. This superimposition could account for the higher deformation of these samples and the strong constrictional character of the ellipsoids. Therefore, to have a better picture of the progress of deformation it is necessary to consider other facts, such as those furnished by the study of folds, cleavages, lineations and the analysis of superimposed structures related to the whole tectonic process



(Orozco and Galvez, 1979; Galvez and Orozco, in press). An interesting out of these papers is that the first structures developed are isoclinal folds, with axial plane cleavage in slates. These isoclinal folds have been modified by further chevron and conjugate type folds, whose axial planes make a high angle with those of the first phase. The radiolaria might be changed in the first folding phase into flattened ellipsoids, with the XY plane parallel to the bedding, or nearly so, except in the hinge zones (fig. 5a). Because of the shortening shown by these folds and the related cleavage it seems a reasonable assumption to consider that the axial ratios X/Z and Y/Z should be high. The superimposition of chevron-type folds would involve a shortening parallel, or nearly so, to the XY plane of the former ellipsoids and a lengthening in the direction of the Z axis. Even assuming no extension along the later fold axes, and as these folds are less tight that the previous ones, the most probable result would be that the longest axes of the resulting ellipsoids were parallel to the chevron folds axes, in agreement with our most common findings (fig. 5b). In the cases where the second deformation was not so high, the orientation of the finite strain ellipsoids would be a relict of the first ones, the long axes of the ellipses remaining parallel to the bedding, and making a high angle to the cleavage related with the latter folds (fig. 6).



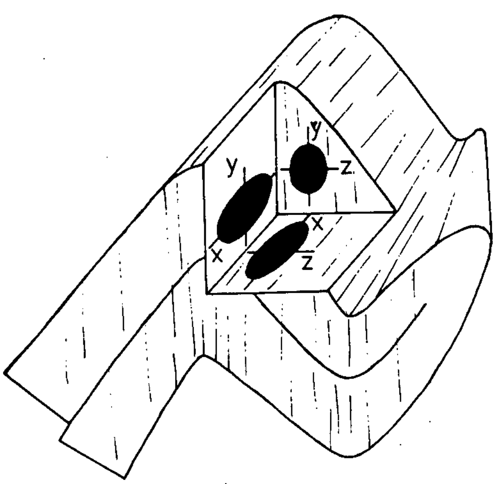


Fig. 5. Possible mechanism to explain the final shape of the strain ellipsoid. See text for explanation.

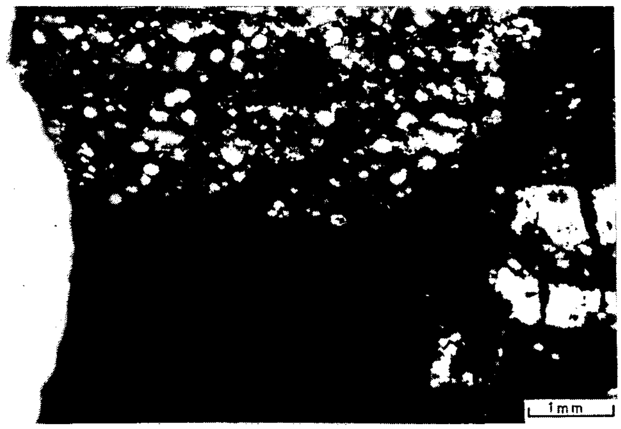


Fig. 6. Section perpendicular to cleavage and fold-axis. Note that the long axes of the ellipses make a high angle with the cleavage, being parallel to bedding traces.

Other aspects of deformation

The deformation has not been strictly homogeneous, as may be inferred from some observations. In some slides (see fig. 7) there are veins or cleavage surfaces filled with quartz which bend slightly around neighbouring radiolaria, showing that there was some difference in competency between fossils and matrix during deformation. The existence of styliolites and other pressure solution structures also demonstrates the occasional lack of homogeneity in deformation.

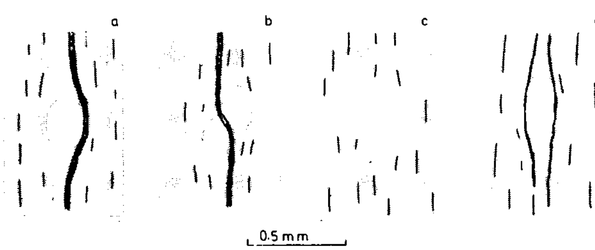


Fig. 7. Sketch to show some features illustrating that deformation was not strictly homogeneous.

Taking into account the siliceous nature of both radiolaria and matrix the difference in competency between them might be explained by the difference in grain size: the average diameter of grains constituting the matrix is about 0.005 mm, whereas the radiolaria, with a longest dimension of about 0.15 to 0.20 mm are composed of recrystallized siliceous material, enclosing small grains which are the same size as those of the matrix.

As a consequence of this lack of homogeneity, the bulk finite strain is not fully reflected in the shapes of the deformed radiolaria. The determination of the difference between the actual finite strain and that deduced from radiolarian shapes is a difficult problem, although some approach to it may be made. Thus, assuming that the viscosity ratio between the radiolaria and the matrix is similar to that quoted by Gay (1968), 1.5 for coarse quarzite-fine quarzite, a dimensional shortening of, say, 30 %, deduced from radiolarian shape would represent 45 % in the surrounding matrix.

A certain variation of the axial ratios in relation to the size of radiolaria has also been observed. The areas of the ellipses against their axial ratios for 25 thin sections have been plotted; two of the plots are represented in fig. 8. They have been separated into two groups according to their axial ratios, both with approximately the same number of points. For the two sections, the average area for the group with lower axial ratios is higher that that for the other group. The difference is not usually great, but significant, as it appears in most of the measured sections: the mean axial ratio is higher in smaller radiolaria.

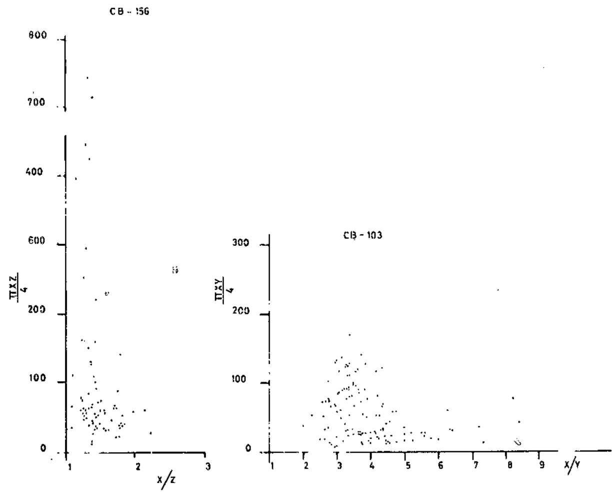


Fig. 8. Plot axial-ratio against ellipse areas for two sections.

As far as we know this relationship has not yet been clearly explained. It might be argued that the viscosity ratio between the radiolaria and matrix is higher for the larger radiolaria because of difference in grain size but this difference does not seem enough to account for it. Another explanation could be a systematic error, committed when measuring the length of ellipse axes; if the radiolaria boundary does not exactly coincide with a division on the scale, the observer might tend to overestimate the length of the long axis and underestimate that of the short one, so that the calculated axial ratio would be greater that the actual one. The relative error so introduced would be greater for the smaller radiolaria.

ACKNOWLEDGEMENTS

We gratefully acknowledge the critical review of the manuscript made by Professor A. Estévez, University of Granada, Spain.

REFERENCES

BRYAN, W. A. and JONES, O. A., (1955): Radiolaria as critical indicators of deformation. *Univ. Queensland Pres, Dept. Geology,* IV: 1-11.

DUNNET, D. (1969): A techniques of finite strain analysis using elliptical particles. *Tectonophysics,* 7. (2): 117-136. Amsterdam.

EGELER, C. G. and SIMON, O. J. (1969): Sur la tectonique de la Zone Betique, (Cordillères Bétiques, Espagne). *Verh. Kon. Ned. Akad. v. Wetensch. Afd. Natuurk.* (eerste reeks), 25-3: 90 pp. Amsterdam.

FLINN, D. (1962): On folding during three-dimensional progressive deformation. *Quart. Jour. Geol. Soc. London,* 118: 385-433.

GALVEZ, R. and OROZCO, M.: Complex folding interference patterns in the Betic. Range. Bol. Geol. y Min. España (in press).

GAY, N. C. (1968): Pure shear and simple shear deformation of inhomogeneous viscous fluids. 2. The determination of the total finite strain in a rock from objects such as deformed pebbles. *Tectonophysics,* 5 (4): 295-302. Amsterdam.

JULIVERT, M., FONTBOTÉ, J. M., RIBEIRO, A. y CONDE, L. (1974): *Memoria del Mapa Tectónico de la Península Ibérica y Baleares.* Inst. Geol. y Min. España. Madrid, 113 pp.

MOORE, R. C. (1954): *Treatise of Invertebrate Paleontology (D) Protista 3.* Geol. Soc. America and Univ. Kansas Press.

OROZCO, M. and GALVEZ, R. (1979): The development of folds in bedded chert and related rocks in the Malaguide complex, Southern Spain. *Tectonophysics,* t. 56; 277-295.

RAMSAY, J. G. (1967): *Folding and Fracturing of Rocks.* McGraw Hill, New York, 568 pp.

WOOD, D. S. (1973): Patterns and magnitudes of natural strain in rocks. *Roy. Soc. London, Philos. Trans.:* A 274, 373-382.

Received, june 1978.