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Constriction in a transpressive regime: an example in the Iberian branch of the Ibero-Armorican arc

R. DIAS and A. RIBEIRO

Department Geologia, Faculdade Ciências, Universidade Lisboa, Edifício C2-5° piso, Campo, Grande, 1700 Lisboa, Portugal

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Abstract—Detailed strain analyses in the Armorican quartzites have been performed in various places within the Centro-Iberian Zone of western Europe. The observed strain pattern shows that in the inner Ibero-Armorican arc, as well as near the hinge zone, sinistral transpression produces constrictive ellipsoids. In the outer arc, away from the hinge zone, the deformation regime produces plane strain to oblate strain ellipsoids. Some of these data clearly contradict existent kinematical models, which associate constriction with transtension, and consider transpression zones to generate oblate strain ellipsoids. However, newly developed models show that it is possible to obtain a wide range of finite strain ellipsoids in transpression zones if one takes account of lateral escape, axial depression and volume change.

The geodynamic implications of the strain analyses suggest generation of constriction in a transpressive regime, caused by lateral expulsion in front of the Cantabrian indenter that produced the Ibero-Armorican Arc. This mechanism was responsible for the Variscan wrench component in western Europe, which was mainly sinistral in Iberia and dextral in Britanny. In Iberia, the displacement by lateral escape was easily accommodated by subduction of the South Portuguese Terrane under the Ossa-Morena Zone of the Iberian Terrane.

INTRODUCTION

THE recognition that lithospheric plates, whatever their geometry, moving over the surface of the Earth, must suffer oblique collision, led Harland (1971) to propose that transpression should be a widespread mechanism in collisional belts. Since then, transcurrent fault systems, at least partially coeval with contractional deformation, have been described in virtually all deformation belts (Hudleston *et al.* 1988, Oldow *et al.* 1990). Due to the complexity of such regimes (Harland 1971), the related structures cannot be explained by simple deformation mechanisms. This situation led to a series of models which consider the finite strain deformation as a combination of simple shear and pure shear, with or without volume change (Davies 1984, Sanderson & Marchini 1984, Fossen & Tikoff 1993). All these models provide methods of testing the validity of the strain regimes proposed for natural deformed rocks (Davies 1984). In most cases, they do not provide unique interpretations of the natural structures: "the strengths and weakness of the models must be judged against further data and observations" (Sanderson *et al.* 1980, p. 300).

The most detailed analysis of transpression is given by Sanderson & Marchini (1984). Their work, which describes the geometrical rules governing transpression and transtension, has become popular and widely applied. One of the most important conclusions of their study, later corroborated by Fossen & Tikoff (1993), was the statement that transpression zones generate oblate strain ellipsoids, while prolate strains are restricted to transtension. However, it is not unusual to find in the literature descriptions of constrictional strain associated with transpression zones (e.g. Hudleston *et al.* 1988, Corsini *et al.* 1991). In the former case, the authors attributed this to local instabilities (Hudleston *et al.* 1988). Recent strain analysis in the Centro-Iberian autochthon contradicts such an interpretation. Indeed, over the whole the northern part of this region, which has been affected by transpression during Variscan times (Ribeiro *et al.* 1990), prolate ellipsoids clearly predominate.

This paper discusses the strain patterns in a transpression region during Variscan times, and suggest some alternative models for strain in transpression zones.

TECTONIC SETTING

The continuity between the Variscan structures of Iberia and Armorica in western Europe has been recognized since Argand (1924). Although the correlation of the structures between these two regions is still questionable (e.g. Lefort 1989), most recent studies accept the existence of this major feature in the Paleozoic (e.g. Brun & Burg 1982, Matte 1986, Burg *et al.* 1987, Ribeiro *et al.* 1990). The marked arcuate shape of the Variscan Fold Belt in western Europe is known as the Ibero-Armorican Arc. The arc was thought to have been produced by indentation of the Cantabrian Block, producing a sinistral sense of shear in Iberia and a dextral sense in Armorica (Fig. 1) (Matte & Ribeiro 1975). According to Harland (1971), any orogenic belt with a curvature greater than a great circle and forming between two plates, must involve some degree of transpression; this is the case of the Ibero-Armorican Arc. In Armorica dextral wrenching was proposed as the main regime for the early Variscan deformation phase, coeval

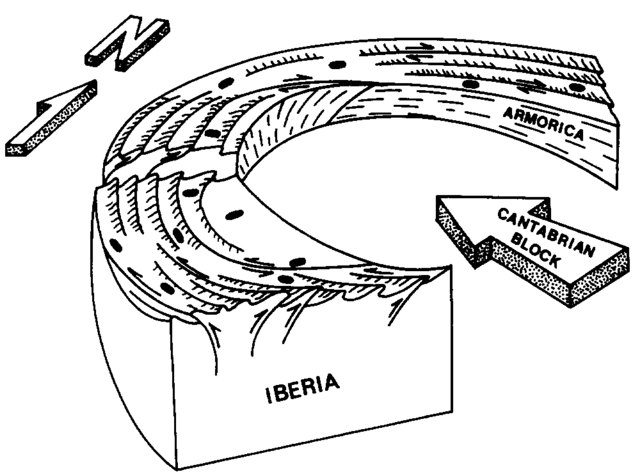

Fig. 1. Schematic block diagram illustrating the genesis of the Ibero-Armorican Arc in western Europe, by the indentation of the Cantabrian block, according to Matte & Ribeiro (1975).

with sinistral wrenching in Iberia and generating the Ibero-Armorican Arc (Matte & Ribeiro 1975). This model was initially criticized (Audren *et al.* 1976), but dextral wrenching in Armorica was confirmed by Gapais & Le Corre (1980) and modelled mathematically (Percevault & Cobbold 1983). For the same region, dextral transpression was also proposed (e.g. Sanderson 1984), because the strain pattern is more consistent with simultaneous simple shear combined with shortening across the whole zone. In what concerns the Iberian branch, the sinistral transpression predominates in its northern part (Ribeiro *et al.* 1979, 1990, Silva *et al.* 1990, Dias & Ribeiro 1991). We will describe briefly some of the main features commonly found in the northern part of the Centro-Iberian autochthon, which indicate the coeval development of compressional and left lateral wrench structures during middle to upper Devonian. More details can be obtained in the papers cited above, and references therein.

Transpressional regime in northern Portugal

The structure of the autochthon in northern Portugal is essentially due to the first and main Variscan deformation event (D_1). The related folds, well developed in the Ordovician–Armorican quartzites, have a general NW–SE trend which, however, can vary widely along the strike, underlining the south branch of the Ibero-Armorican Arc (Fig. 2a). The folds are mainly upright to steeply inclined and clearly develop a fan-like structure, which is explained by a flake model (Fig. 2b) (Ribeiro *et al.* 1990). The fold axes plunge gently northwest when approaching the hinge zone of the Arc; however, in the southeast and east they present a series of culminations and depressions along the major folds, that can be explained by differential flattening across the axial plane (Fig. 3a) (Ribeiro 1974). The contemporaneous stretching lineation usually has a very low plunge, and is subparallel to fold axes, typical for this part of the Variscan autochthon. This indicates significant extension parallel to the orogen, and the formation of folds parallel to the maximum stretch (Watkinson 1975). This orogen-parallel extension is also manifest by frequent boudinage of bedding planes, with long axes subperpendicular to the stretching lineation (Fig. 3b). Similar structures are found in southwest Ireland in relation to transpression (Sanderson 1984). The orientations of these strain fields suggests oblique collision (Ellis 1986).

The S_1 cleavage is generally subparallel to fold axial planes, but locally, it is possible to find transected folds (Dias 1986). Sometimes these folds are spacially associated with minor ones which present an axial plane cleavage (Fig. 3c), which suggests left-lateral progressive deformation. Other structures commonly found in D_1 folds, also denoting sinistral wrench movement coeval with the formation of the folds, are the deflection of *Skolithos* worm burrows (Fig. 3d) (Dias & Ribeiro 1991) and oblique striae on kinematically active bedding planes (Fig. 3e) (Coke *et al.* 1993).

Transpression during the D_1 event is responsible for major faults (Fig. 2a) subparallel to the coeval main folds. This is a feature very similar to what happens with the 'tectonic slides' widely mentioned in the British literature, and is a common situation found in transpression regions (Harland 1971, Borradaile *et al.* 1988). Related to some of the major faults are en échelon folds at a low angle to the fault trend (Fig. 3f), as predicted in transpressive regimes (Sanderson & Marchini 1984). Another manifestation of transcurrent strike-slip movement is the frequent development of ductile shear zones in the quartzitic horizons (Dias 1986), which contain en échelon quartz veins at a high angle to the movement plane (Fig. 3g).

Finite strain analysis in the Centro–Iberian autochthon

To estimate the finite strain in the Centro-Iberian autochthon we have chosen the Armorican quartzites of Ordovician age. These rocks have a widespread distribution throughout the arc and are usually only deformed by the D_1 Variscan event. Moreover, they have also been used in finite strain studies in Brittany, France (Bouchez 1977, Law 1986).

In order to estimate the strain ellipsoids, we used two strain markers: *Skolithos* (worm burrows) and quartz grains. For the *Skolithos* data, we have applied the method proposed by Dias & Ribeiro (1991). For the quartz grains we studied three orthogonal thin sections, using the normalized Fry method (Erslev 1988). This method proved to be better than the R_f/ϕ technique for the estimation of strain in such rocks (Garcia *et al.* 1993). The Armorican quartzites of the Centro-Iberian Zone are an homogeneous material with quartz grains in a very pure quartzitic matrix, in which the undulose extinction is frequent but the subgranulation and the recrystallization phenomena have only a localized development; so the Fry methodologies seem to be an appropriate way of estimating the strain. The data for the three sections have been combined using the methodology proposed by De Paor (1990).

We have chosen nine areas (Fig. 2a) for this study. All

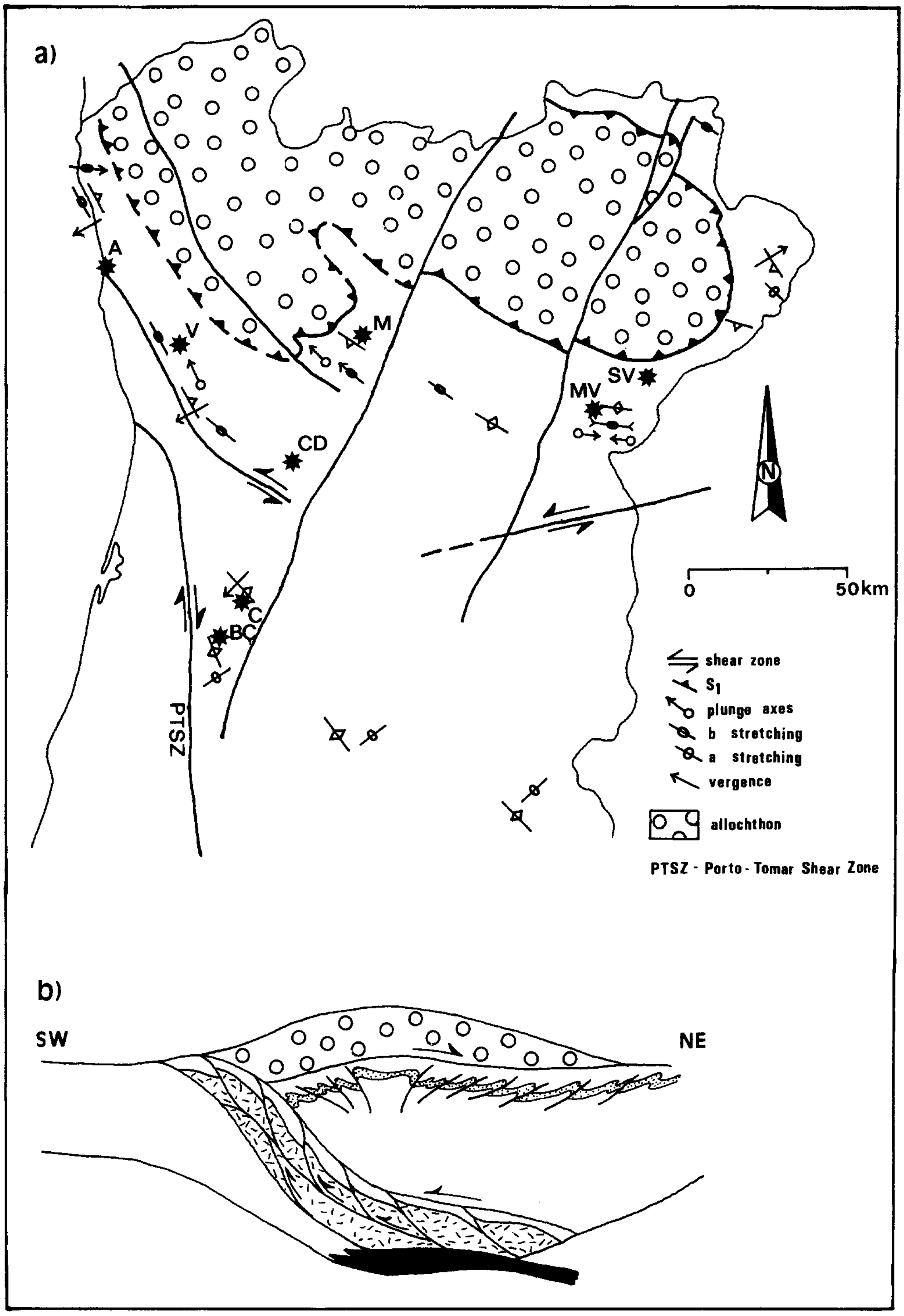

Fig. 2. (a) Major D_1 Variscan structures in the Centro-Iberian autochthon. The black stars show sample localities and their abbreviations (see Table 2). (b) Simplified cross-section along the Centro-Iberian Zone showing the fan-like structure of the D_1 folds developed in the autochthon (simplified from Ribeiro *et al.* 1990).

of them present good exposures of Ordovician quartzites. However, only in two regions (Torre de Moncorvo and Marão) was it possible to estimate the strain ellipsoids using the *Skolithos* method (Dias & Ribeiro 1991); indeed, the worm tubes have an extremely heterogeneous distribution, being very rare in most areas. The strain features for Marão (Dias, Coke and Ribeiro, unpublished data) and Torre de Moncorvo (Dias & Ribeiro 1991 and unpublished data) can be easily visualized in a Ramsay logarithmic plot (Fig. 4) (Ramsay & Huber 1983). There we can see that most of the strain ellipsoids plot in the constriction field. Table 1 presents the data for the mean strain ellipsoids for both regions, which have been estimated using the weighted mean centre (Ebdon 1977).

The strain values obtained using the quartz grains as strain markers and applying Erslev's normalized Fry method (1988), are presented in Table 2 as mean ellipsoids for all the sampled regions. Figure 5 is the Ramsay logarithmic plot for these data.

Figure 6 compares the strain values from the two different strain markers, in two regions. For each

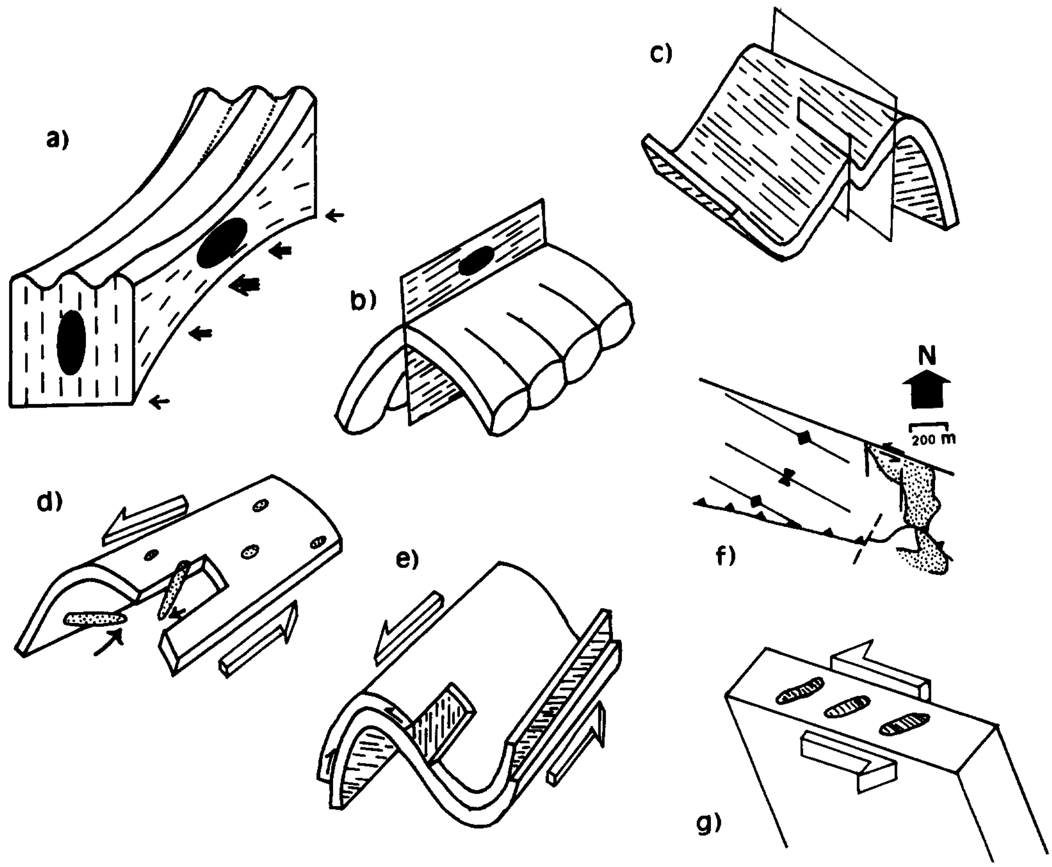

Fig. 3. Main structures developed in the Centro-Iberian autochthon during the transpressive D_1 event (see text for more details). (a) Fold axis—parallel stretching; (b) boudins; (c) transected folds; (d) deflection of *Skolithos*; (e) oblique striae on bedding planes; (f) en échelon folds; (g) en échelon quartz veins.

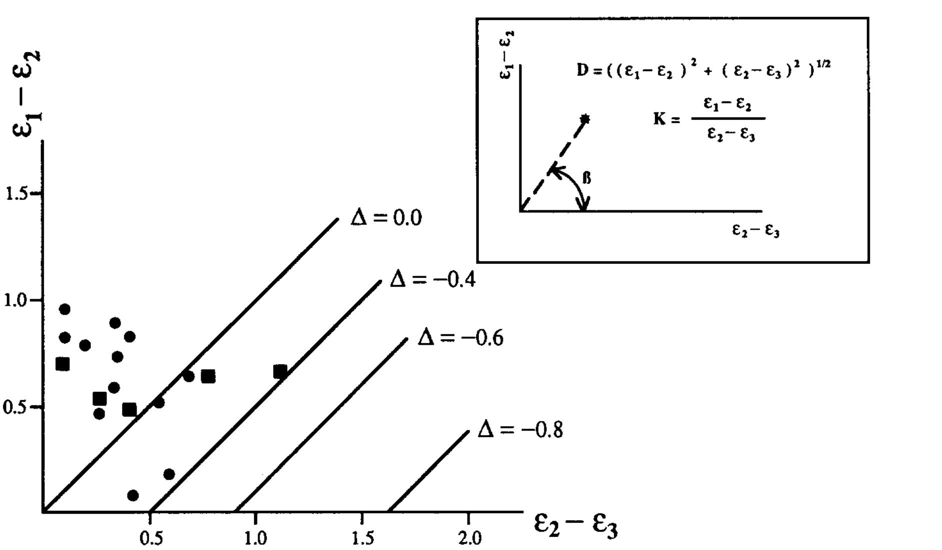

Fig. 4 Ramsay logarithmic plot for *Skolithos* of Torre de Moncorvo (squares) and Marão (circles) regions. The inset shows the strain parameters used in this work following Ramsay & Huber (1983, pp. 201–202). Tan β = K. Data from Dias & Ribeiro (1991). Δ are lines of apparent volume loss.

region, both mean ellipsoids were in the constriction field, with similar values for the K and β parameters. However, the intensity of the strain seems to be very different when we use the two strain markers. Looking at the D parameter, which can be considered as a measure of the strain intensities if the ellipsoids have similar K values (Ramsay & Huber 1983), we get significantly higher values with *Skolithos* than with quartz grains. Detailed strain analysis in these rocks shows that this difference could be related to the grain boundary sliding mechanisms (Dias & Ribeiro, work in progress); while the *Skolithos* method is sensitive to the grain boundary sliding mechanism the Normalized Fry is not. However, although different deformation mechanisms

Table 1. Weighted mean strain ellipsoids using *Skolithos* data

Region	K*	β*	D*	N†
Marão	1.78	61°	0.72	11
Moncorvo	1.13	49°	0.77	6

*K, β and D as in Ramsay & Huber 1983, and defined in Fig. 4.
†N is the number of samples.

Table 2. Weighted mean strain ellipsoids using quartz grain data

Region	K*	β*	D*	N*
Apúlia (A)	1.18	50°	0.17	2
Valongo (V)	1.30	52°	0.23	15
Castro Daire (CD)	1.16	49°	0.17	5
Marão (M)	1.55	57°	0.16	17
Moncorvo (MV)	1.33	53°	0.16	7
Souto da Velha (SV)	2.11	65°	0.25	4
Caramulo (C)	0.64	33°	0.15	5
Buçacol (BÇ1)	0.93	43°	0.25	2
Buçaco2 (BÇ2)	2.74	70°	0.27	2
Vila Velha Ródão (B)	0.82	39°	0.14	2

*K, β, D and N as in Table 1 and Fig. 4.

give rise to different measured strain intensities, the shape of the estimated strain ellipsoids is similar, as already described by Lacassin & Van Den Driessche (1983).

Concerning the spatial variations of strain it seems that the northern samples have a different behaviour from the southern ones (Figs. 5 and 7). Here we only use the quartz grains data, due to the scarcity of the *Skolithos*; nevertheless, this is not a problem because the shape of the strain ellipsoids obtained when using the two methods is very similar (Fig. 6). In the northern region, constrictional forms predominate, while in the south, plane strain and oblate forms are more important. Using the weighted mean (Ebdon 1977) of strain ellipsoids for each region (Table 2), this could be emphasized by drawing a map with lines for equal values of the β (or K) parameter (Fig. 8). We find that the contours are subparallel to the Variscan structures, as might be expected. Our results show the association of prolate strains with regions where transpression predominates (Moncorvo/Souto da Velha, Marão, Apúlia/Valongo/Castro Daire) and the prolate forms. Apparent flattening and plane strain are important only when the wrench component vanishes. The constrictional anomaly in the Buçaco syncline is clearly linked with the N–S Porto-Tomar dextral shear zone (Fig. 2a). Indeed, only in the vicinity of the fault (BÇ1) do we get prolate ellipsoids while in the rest of the structure (BÇ2) plane strain seems to dominate (Dias & Ribeiro 1993). A relation between the movement along the fault and the prolate strains seems to be confirmed because, when approaching this discontinuity, the β contours tend to be subparallel to the Porto-Tomar shear zone (Fig. 8) becoming oblique to the NW–SE Buçaco Variscan syncline.

In a previous study (Dias & Ribeiro 1991), the data on *Skolithos* in Moncorvo region show a large dispersion (Fig. 4) with constriction in the long limb and apparent flattening in the short limb of the mesoscopic Variscan fold. Hence, local folding could introduce a lot of 'noise' in the data. This is also shown by the *Skolithos* data of Marão (Fig. 4 and work in progress), where it is also possible to find some oblate forms. However, the *Skolithos* strain data for the two regions show a slightly different behaviour. In Marão the tectonic situation corresponds to the long limb of a first-order anticlinorium (Fig. 9a); the tendency to less constriction in local second-order short limbs is not enough to modify the strain ellipsoids into the apparent flattening field. In

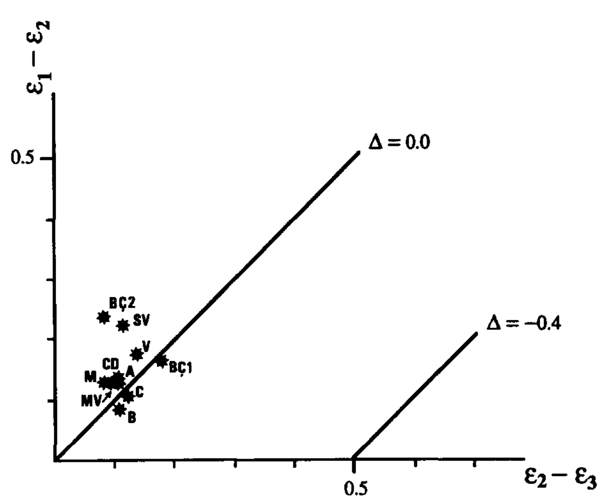

Fig. 5. Projection in a Ramsay logarithmic plot of the weighted mean strain ellipsoids of the sampled areas (see Table 2 for more details). Compare with Fig. 4.

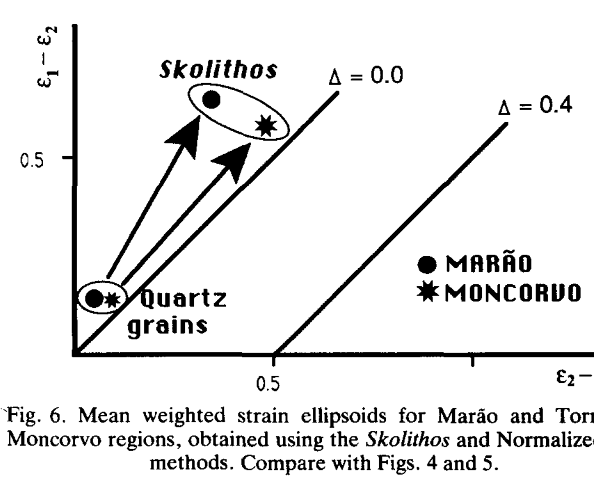

Fig. 6. Mean weighted strain ellipsoids for Marão and Torre de Moncorvo regions, obtained using the *Skolithos* and Normalized Fry methods. Compare with Figs. 4 and 5.

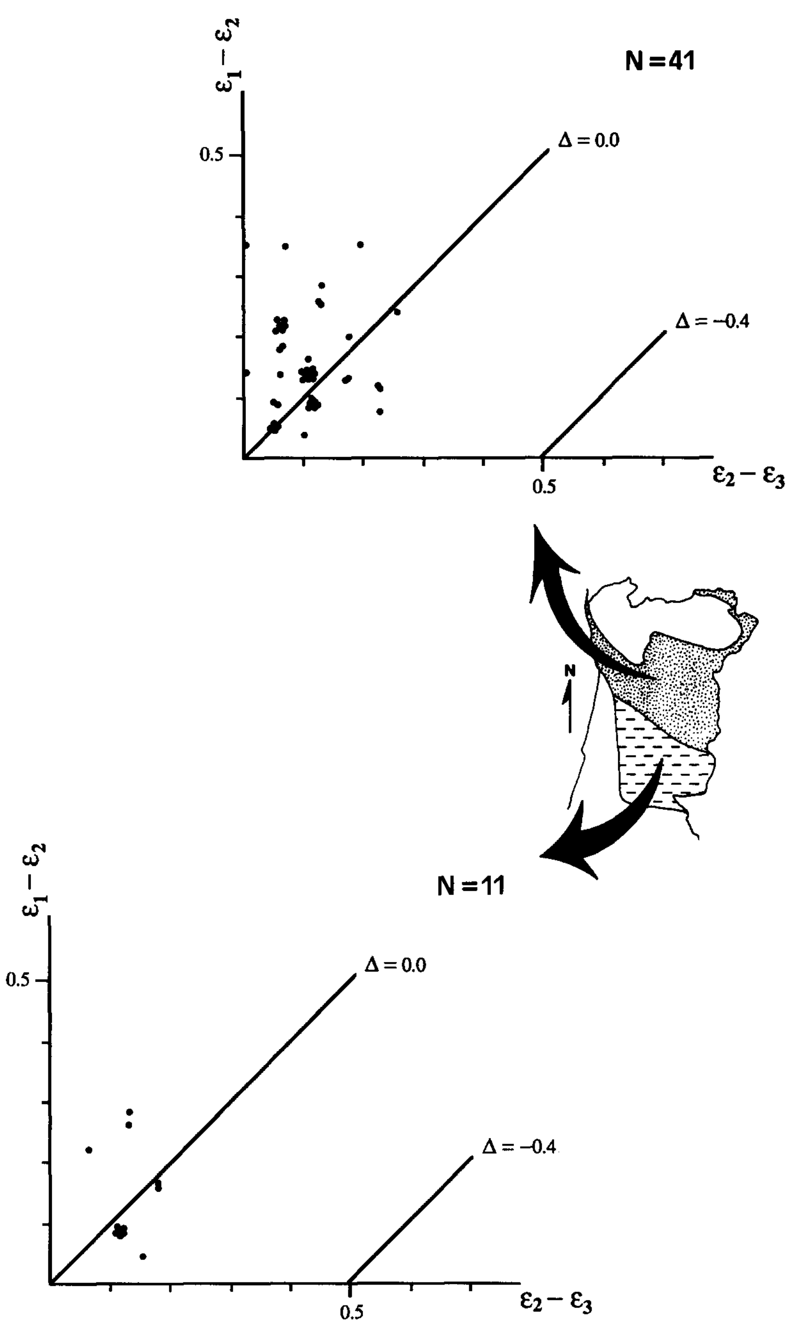

Fig. 7. General Ramsay logarithmic plots for all the strain ellipsoids measured in the northern and southern Centro–Iberian autochthon (as indicated on sketch map). All the ellipsoids have been estimated using quartz grains as strain markers.

Moncorvo the tectonic situation corresponds to the hinge zone of a first-order synclinorium (Fig. 9b); the tendency to less constriction in local second-order short limbs is usually enough to move the ellipsoids from the constriction to apparent flattening field. Nevertheless, what must be emphasized is the gravity centre of the data which, for both regions, falls in the constriction field (Table 1). The same is found with the strain ellipsoids obtained using quartz grains as strain markers; Table 2 data are weighted mean strains for each area, where the 'noise' introduced by disturbances related to local structures is reduced.

As already discussed, the spatial relation between prolate strain ellipsoids and transpression regimes found in Centro-Iberian Zone is completely unexpected using the available kinematical models for such regimes (Sanderson & Marchini 1984, Fossen & Tikoff 1993). The Centro-Iberian autochthon has an obvious northern continuation in the Centro-Armorican Zone (Robardet 1976, Young 1990), where steep Variscan folds subparallel to main strike-slip faults, with a subhorizontal stretching lineation are also observed, and considered indicative of dextral transpression (Sanderson 1984). In this paleogeographic domain constrictional strain ellipsoids have also been described (e.g. Bouchez 1977, Le Théoff 1977). This poses the same problem as for the Centro-Iberian data: how do we achieve constriction in transpression?

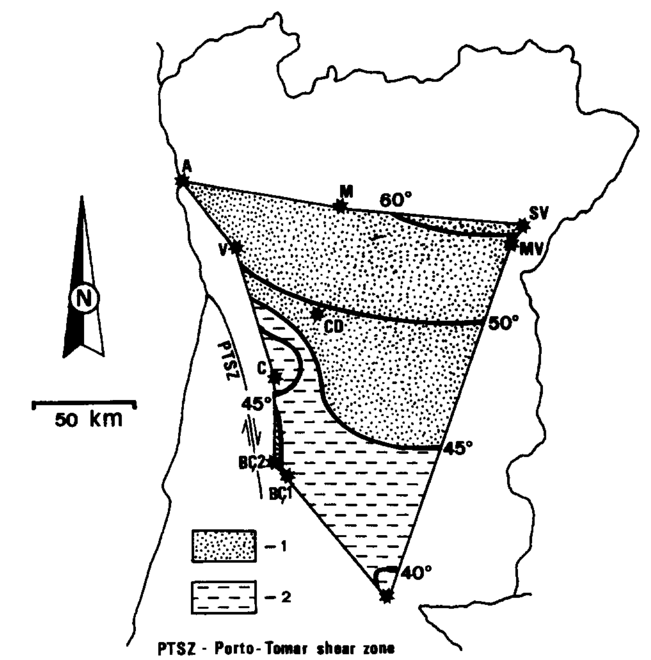

Fig. 8. Contours of equal shapes of the strain ellipsoids in the Centro-Iberian autochthon (see text for more details). 1—Stippled shading: prolate forms (K > 1; β > 45°); 2—dashed shading: oblate forms (K < 1; β < 45°).

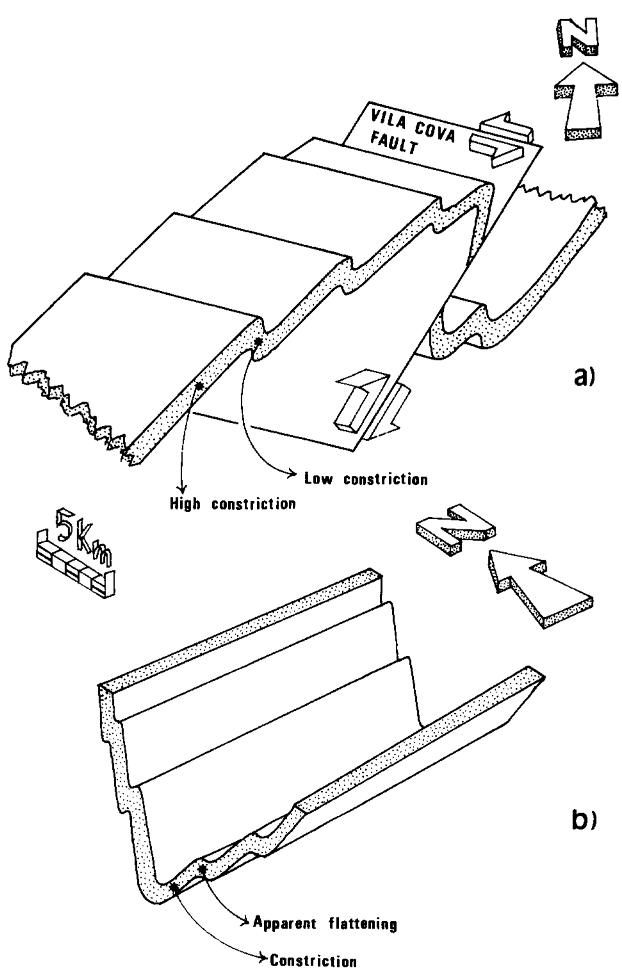

Fig. 9. Strain variation along second-order folds in: (a) Marão region; (b) Moncorvo region.

KINEMATICAL MODELLING OF TRANSPRESSIVE REGIMES

The available kinematical models for transpression zones (Sanderson & Marchini 1984, Fossen & Tikoff 1993), are unable successfully to explain the constrictional strain in the Ibero-Armorican Arc, a Variscan macrostructure where the transpression has nevertheless been widely recognized in recent studies. The models may not therefore be appropriate for all transpression zones, although they are probably good approximations for many cases. We need an alternative model which can explain our data. Computer-modelling can be used to judge by the close agreement between the natural and model generated strain pattern (Davies 1984).

However, these models should be used carefully, as model interpretations are not unique, and other models may be found that give equally satisfactory results (Sanderson *et al.* 1980). In this section we discuss some possibilities, which seem reasonable for the Ibero-Armorican Arc. Another problem, concerns the advantages of a purely kinematic approach. Some authors (e.g. Schwerdtner 1989), think that such a treatment may be insufficient, because the degree of heterogeneity must be evaluated under appropriate dynamic conditions. Nevertheless, as we are mainly concerned with the relation between a given deformation regime and the shape of the strain ellipsoid, without intending to investigate the development of structures in a transpression zone, the approach seems reasonable.

In order to establish a computer simulation model for transpression, we need to choose the suitable types of elemental deformation. Following Ramsay (1967) and Ramberg (1975) irrotational pure shear and rotational simple shear may be considered as two suitable classes of deformation. Most strain simulations use a combination of these, sometimes with volume change, in order to produce realistic deformations. This will also be our approach to the problem, and we closely follow Sanderson & Marchini (1984) in methodology. The main advantage of their chosen strain factorization was to yield parameters which were representative of the finite shortening normal to, and shear strain parallel to, the zone boundary.

Sanderson & Marchini model

These authors considered a vertical transpression zone which is laterally confined in such a way that there is no stretching along the zone leading to extrusion of materials at its ends. Then, the shortening across the zone results in an area change, which must be compensated by vertical thickening, in order to conserve volume. The compatibility problems normally involved in such deformations (Ramsay & Graham 1970), are reduced by letting the upper surface be represented by the surface of the Earth (Fossen & Tikoff 1993). Using the parameters shown in Fig. 10(a), the deformation was

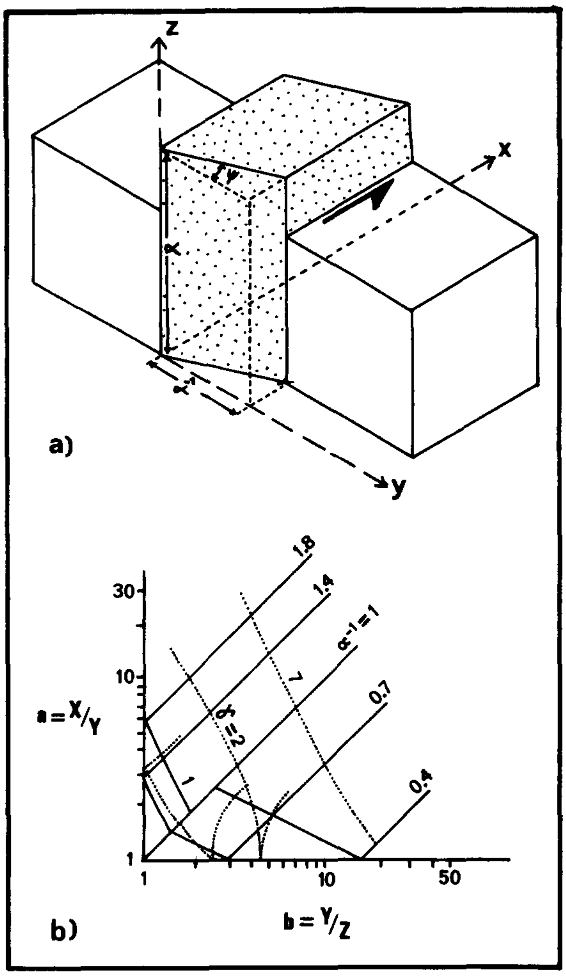

Fig. 10. Classic model for transpression with vertical escape (adapted from Sanderson & Marchini 1984). (a) Model. (b) Finite strain pattern.

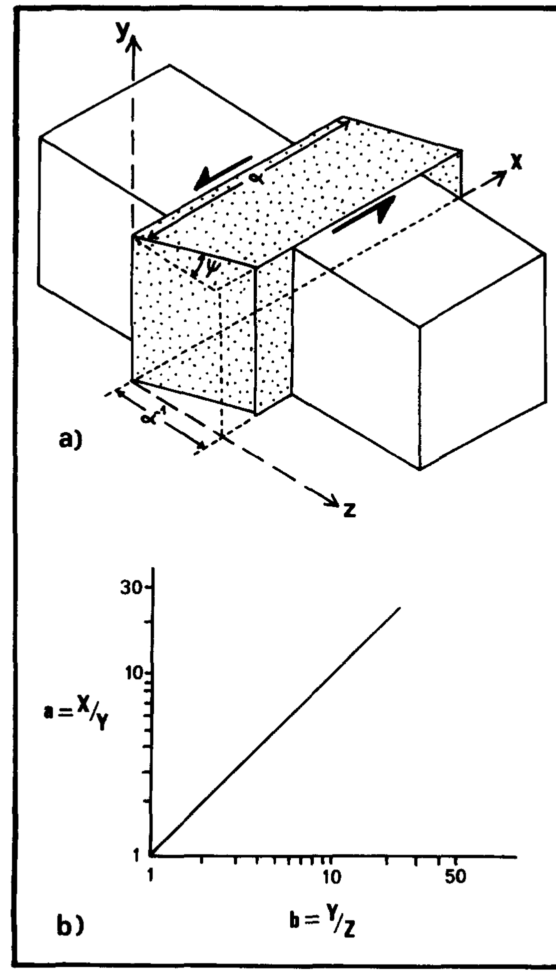

Fig. 11. Transpression with lateral escape. (a) Model. (b) Finite strain pattern.

factorized into pure shear (α) and simple shear (γ) components (Sanderson & Marchini 1984) as follows:

$$D = \begin{pmatrix} 1 & \gamma & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \alpha^{-1} & 0 \\ 0 & 0 & \alpha \end{pmatrix}.$$

Doing the calculations suggested by the authors, it is easy to evaluate the finite strain for different values of parameters γ and α. The results in Fig. 10(b) are a simplification from Sanderson & Marchini. As postulated in their work, for transpression ($\alpha^{-1} < 1$) oblate strain ellipsoids are produced, while transtension ($\alpha^{-1} > 1$) produces prolate strain. As already stated, this is not consistent with data from the Ibero-Armorican Arc. The orientation of the major axes of strain ellipsoids may be either horizontal or vertical (Sanderson & Marchini 1984).

Alternative models

We present some alternative models for transpression zones and how these may affect the final strain state. However, combinations of shear strains and longitudinal strains can result in a wide range of deformation geometries (Coward & Kim 1981, Coward & Potts 1983). So the following models are only a few possibilities for the Ibero-Armorican Arc. Other models might give similar results.

In these models we use coordinate axes that are different from those of Sanderson & Marchini (1984), with the y axis vertical, and z and x both horizontal; z is perpendicular to the shear zone, while the x axis is parallel to the transpressive margin. This nomenclature only affects the formulation of the matrices and not the final results.

(*a*) *Lateral escape*. The application of the Sanderson & Marchini model for collisional orogens leads to strong crustal thickening. This agrees with the models proposed by some authors (e.g. Houseman & England 1986) for fold belts, like the Himalayas. However some authors suggest that the same orogens could be developed with substantial lateral escape, coeval with the shortening (e.g. Molnar & Tapponier 1977, Cobbold & Davy 1988), or developed mainly in the latest phases of orogeny (Dewey *et al.* 1986). In what concerns the Ibero-Armorican Arc, the data are consistent with lateral expulsion as the main deformation regime during early Variscan times. Thus, a new model should be developed, where the shortening across the transpression zone is compensated by horizontal stretching

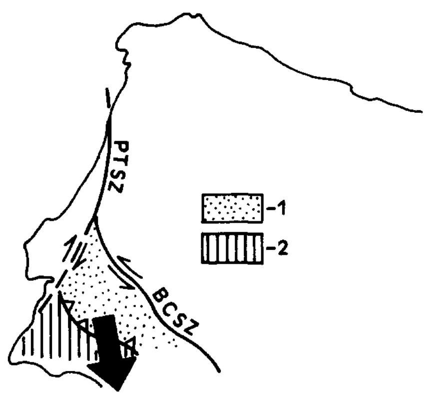

Fig. 12. Early Variscan lateral escape (major arrow) in the south branch of the Iberian–Armorican Arc. 1—Ossa–Morena Zone; 2—South Portuguese Zone; BCSZ—Badajoz–Córdova shear zone; PTSZ—Porto–Tomar shear zone.

(Fig. 11a). The compatibility problems for such a deformation, mainly the accommodation of the material expulsed, could be obtained in Iberia by subduction of the South Portuguese Terrane under the Ossa-Morena zone of the Iberian Terrane (Fig. 12).

This model can be factorized using the following matrices:

$$D = \begin{pmatrix} 1 & 0 & \gamma_{xz} \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \alpha & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \alpha^{-1} \end{pmatrix} = \begin{pmatrix} \alpha & 0 & \alpha^{-1}\gamma_{xz} \\ 0 & 1 & 0 \\ 0 & 0 & \alpha^{-1} \end{pmatrix}.$$

The finite strain for different values of the parameters is given in Fig. 11(b). Plane strain ellipsoids are characteristic of this kind of deformation, as would be expected due to superposition of two plane strains in the xz plane.

(*b*) *Lateral escape and axial depression* As previously mentioned, the Variscan fold axes in the Centro-Iberian autochthon usually plunge towards the hinge zone of the Arc (Ribeiro *et al.* 1990). However, locally they show a more sinuous pattern with major culminations and depressions, although always presenting low plunges. This geometry can be explained by differential flattening across the axial planes (Fig. 3a) (Ribeiro 1974). The compatibility problems for such a heterogeneous deformation poses serious obstacles in purely kinematical modelling. To overcome this difficulty, we have superposed an extra shear component on the previous model, perpendicular to the structures, which can be responsible for the axial plunge (Fig. 13a). In the Sanderson and Marchini model, with vertical escape, the domains which suffered increasing shortening produce axial culminations, while in the lateral escape model they produce axial depressions (Ribeiro 1974).

To simulate such deformation we can use the following matrices:

$$D = \begin{pmatrix} 1 & 0 & 0 \\ \gamma_{yx} & 0 & 0 \\ 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & \gamma_{xz} \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \alpha & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \alpha^{-1} \end{pmatrix}$$

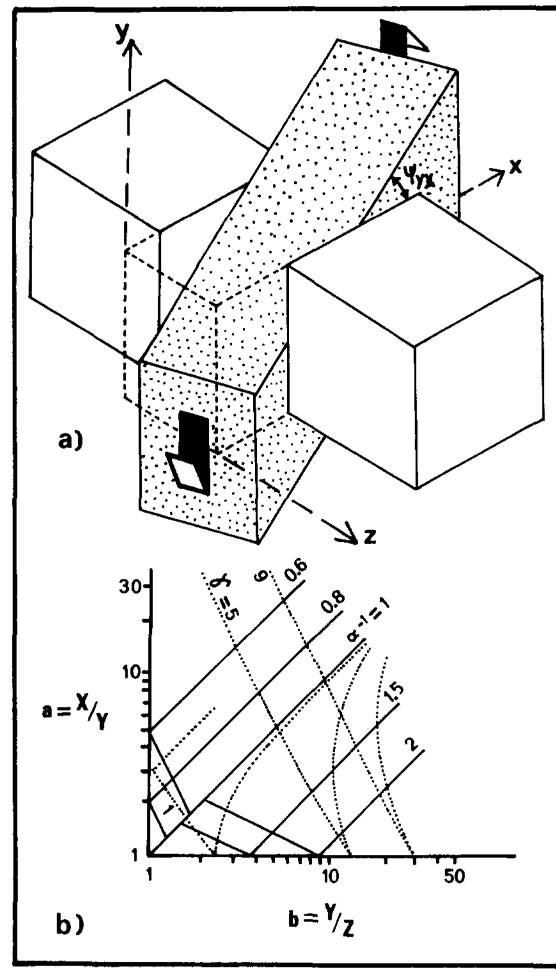

Fig. 13. Transpression by lateral escape (Fig. 11a) with an extra shear component, which could be responsible for axial depressions. (a) Model. (b) Finite strain pattern.

$$= \begin{pmatrix} \alpha & 0 & \alpha^{-1}\gamma_{xz} \\ \gamma_{yx}\alpha & 1 & \alpha^{-1}\gamma_{xz}\gamma_{yx} \\ 0 & 0 & \alpha^{-1} \end{pmatrix}.$$

Figure 13(b) gives the finite strain for a γ_{yx} value of 0.5, which corresponds to a shear angle of 27°. The constriction regime is clearly predominant for such a deformation. Although this is not a simple example of transpression, it seems a plausible one, for the southern branch of the Ibero-Armorican Arc. In this model, neither the fold axes nor the stretching lineation are horizontal; however they still present low plunges which are compatible with those usually found in the Centro-Iberian autochthon.

(*c*) *Lateral escape and volume change*. The models discussed above all considered the transpression zone to behave as a closed system; i.e. deformation without volume change. This is probably not a very plausible situation for natural deformations. As we are dealing with finite strain ellipsoids, we must consider that material might be lost, either during diagenic compaction or during tectonic deformation of the rocks. In order to simulate the diagenic compaction we have considered, in our model with lateral escape, a previous

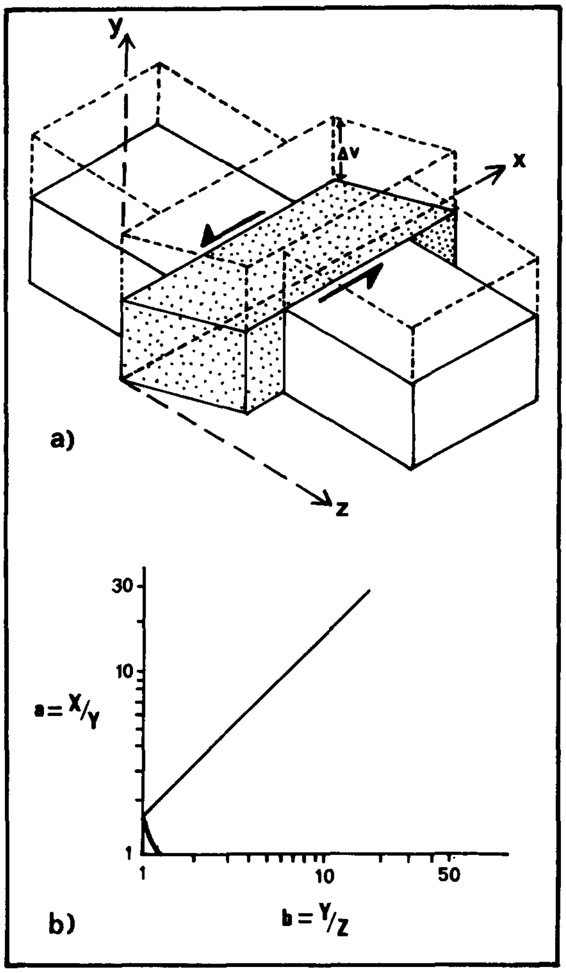

Fig. 14. Transpression with lateral escape, affecting a material which has been previously deformed by diagenic compaction. (a) Model. (b) Finite strain pattern.

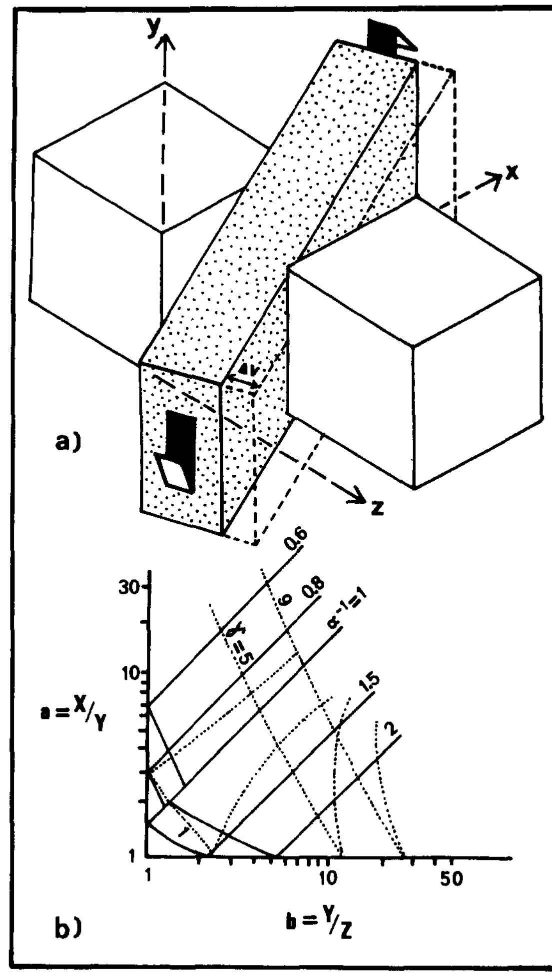

Fig. 15. Transpression as in Fig. 13(a), but with tectonic volume loss. (a) Model. (b) Finite strain pattern.

deformation by vertical shortening (Fig. 14a); this was achieved using the following matrices:

$$D=\begin{pmatrix}1 & 0 & \gamma_{xz}\\ 0 & 1 & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\alpha & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & \alpha^{-1}\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & 1+\Delta v & 0\\ 0 & 0 & 1\end{pmatrix}$$

$$=\begin{pmatrix}\alpha & 0 & \alpha^{-1}\gamma_{xz}\\ 0 & 1+\Delta v & 0\\ 0 & 0 & \alpha^{-1}\end{pmatrix}.$$

Figure 14(b) shows the strain ellipsoids associated with such deformation, for 20% of volume loss. All the strains are constrictive. Ramsay & Huber (1983, p. 186) also predict constriction, by the superposition of a diagenic process and a weak tectonic deformation. However, in their case, they used a situation of late vertical stretching and as the deformation increases, the ellipsoids become oblate. In our case we always get a constrictional finite strain associated with a tectonic regime of subhorizontal stretching. This could be one possibility for producing prolate finite strain ellipsoids in the Ibero-Armorican Arc. Nevertheless, if this can easily explain the features of the strain ellipsoids obtained using the quartz grains as strain markers, it cannot be applied to the *Skolithos*, as these record no diagenic compaction (Dias & Ribeiro 1991).

Consider, now, a different type of volume loss: a *tectonic volume loss* (Fig. 15a). The chosen matrices are as follows:

$$D=\begin{pmatrix}1 & 0 & 0\\ \gamma_{yx} & 1 & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\alpha & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & \alpha^{-1}(1+\Delta v)\end{pmatrix}.$$

Using 20% as a figure for volume loss, we always produce constriction in transpression zones (Fig. 15b) and, even for small transtensions, we produce the same kind of finite strain. So, this is also a possible mechanism which might explain constriction within zones where transpression predominates.

CONCLUSIONS

The new models may allow a more complete understanding of fault-bounded zones of deformation. We conclude that it is not possible to find one general model for transpression zones. This type of deformation may arise by several combinations of deformations type. So, even with the knowledge of finite strain in such zones, it will be impossible to try any factorization of the deformation mechanisms. The same finite strain ellipsoid could be obtained by a wide range of superposition of simple deformations, a fact already emphasized by some workers (e.g. Coward & Kim 1981, Coward & Potts 1983). Strain ellipsoids considered typical for transpression or transtension (Sanderson & Marchini 1984) may not occur. According to the way transpression is achieved, it may be possible to obtain constriction, flattening or plane strains. Only when it was possible to establish the detailed succession of deformation events in a region, can models of the kinematic history be tested; even then, several models might explain an observed strain pattern.

Our models for the Ibero-Armorican Arc data, are consistent with lateral escape as an important way of accommodating the early Variscan deformation in western Europe. This mechanism, already proposed for the late Variscan deformation of the Arc (Matte 1986) explains lateral expulsion as due to the indentation of a Cantabrian Block. In the Iberian case, it was facilitated by the subduction of the South Portuguese Terrane under the Ossa-Morena Zone of the Iberian Terrane (Fig. 12). Similar tectonic settings have also been proposed for younger collisional orogens, such as the Himalayas (Molnar & Tapponier 1977, Cobbold & Davy 1988), Eastern Alps (Ratschbacher *et al.* 1991) and Arabian Shield (Davies 1984).

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