Folding development in the Penibetic Units around the western front of the Alboran Domain (Betics)

Desarrollo de pliegues en las Unidades Penibéticas alrededor del frente occidental del Dominio de Alborán (Béticas)

J.C. Balanyá [1], M. Luján [2], A. Crespo-Blanc [3]

[1] Dpto. de Ciencias Ambientales, Universidad Pablo de Olavide, Cra. de Utrera km 1, 41013 Sevilla. Email: jcbalrou@dex.upo.es
[2] Instituto Andaluz de Ciencias de La Tierra, CSIC-Universidad de Granada, 18071 Granada. Email: mlujan@ugr.es
[3] Dpto. de Geodinámica, Universidad de Granada, Campus Fuentenueva s/n, 18071 Granada. Email: acrespo@ugr.es

ABSTRACT

Miocene shortening within the Penibetic Units (South Iberian Domain) near the western end of the Alboran Domain (Betics hinterland) developed in two phases with different morphologic and structural characteristics. F_1 folds are angular, asymmetrical, NW- to SW-vergent, and early-to-middle Miocene in age; they develop a widely distributed spaced cleavage. F_2 folds, late Miocene in age, result in upright or box shaped, kilometric-scale folds with no associated cleavage. The spatial zonation of the F_1 folding style suggests that the folds were partially generated by shearing during the overthrusting of the Alboran Domain.

RESUMEN

En las Unidades Penibéticas (Dominio Sudibérico) próximas al frente occidental del Dominio de Alborán, el acortamiento ocurrido en el Mioceno desarrolló dos fases de plegamiento de características morfológicas y estructurales diferentes. Los pliegues F1, de edad Mioceno inferior a medio, son angulares y asimétricos, tienen vergencia de componente O y desarrollan un clivaje espaciado. Los pliegues F2, de edad Mioceno superior, son pliegues rectos o en caja, tienen tamaño kilométrico y no desarrollan clivaje. La zonación del estilo de los pliegues F1 sugiere que, al menos en parte, fueron generados por cizallamiento durante el cabalgamiento hacia el ONO del Dominio de Alborán.

***Key words**: Gibraltar Arc, Betics, Penibetic, Miocene folding.*

Geogaceta, 31 (2002), 131-134
ISSN:0213683X

Introduction

The Subbetic units are composed of the detached sedimentary cover of the South Iberian Domain. These rocks, Triassic to Paleogene in age, were deformed during the Miocene as a result of the westward movement of the Alboran Domain (metamorphic internal zone of the Betic-Rif orogen) over the South Iberian and African paleomargins (Fig. 1). During this orogenic event, the Gibraltar Arc formed (Balanyá and García-Dueñas, 1988). In this Arc, rocks derived from a deep trough are preserved, sandwiched between the South Iberian and the Alboran Domains. This trough was situated originally between the two paleomargins, and its detached sedimentary infill now forms the Flysch Complex (Fig. 1).

Previous works carried out on the most internal Subbetic units, the Penibetic units, have provided considerable data concerning the tectonic evolution (folding and faulting phases), kinematic transport directions and structural trend variations during the Neogene deformation of these units (Bourgois, 1978; Martín-Algarra, 1987; Kirker and Platt, 1998; Luján *et al.*, 2000; Crespo-Blanc and Campos, 2001; Crespo-Blanc *et al.*, submitted). In particular, Luján *et al.* (2000) and Crespo-Blanc and Campos (2001) evidenced two phases of folding, separated by an extensional event. The main shortening event, west to northwest-vergent, occurred during the early-to-middle Miocene. Middle Miocene extensional reactivation took place and low-to-moderate-angle normal faults developed, cutting the previous thrusts and folds. Finally, large-scale folds developed during the late Miocene. In this paper, preliminary data about minor structures associated with folds together with the folding mechanism are presented. These data concern folds mainly associated with the most important shortening event in an area contiguous to the western end of the Alboran Domain.

Small-scale structures associated with early-to-middle Miocene F_1 folds

The lithostratigraphic sequence of the Penibetic units is made up of: a) a thick (over 600 m) Triassic to Jurassic sequence, formed mainly by massive carbonate rocks; b) a sequence of marls alternating with marly limestone (300-400 m thick) formed by the "White beds" and "Red beds" formations, respectively early Cretaceous and late Cretaceous to Eocene in age; and c) a Paleogene to early Miocene flysch sequence.

The tectonic map of the Penibetic units around the western end of the Alboran Domain is illustrated in Figure 2. It is divided into structural domains from A to

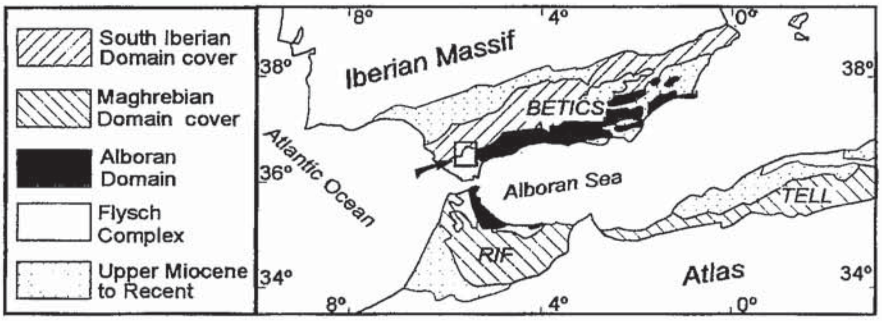

Fig. 1.- Regional setting of the study area.

Fig. 1.- Marco regional del área estudiada

F according to their increasing distance from the Alboran Domain front. This front is considered as the present-day boundary, N30E-directed, approximately between Gaucin and Atajate (Fig. 2).

Due to the main shortening, early-to-middle Miocene in age, thrusts and folds affected the Penibetic rocks (Luján *et al.*, 2000; Crespo-Blanc and Campos, 2001). Structural decoupling took place between the Jurassic competent limestones and the more ductile Cretaceous to Eocene marly sequence. The limestones deformed mostly by thrusts and thrust-related folds, while the marly sequence deformed by chevron-type folds (Fig. 3), hereafter F_1, ubiquitous in the studied area. The axes of F_1 folds, which are northwest- to southwest-vergent, are represented in Figure 2. They trend N-S to NE-SW in the northern part (structural domains A, B, D and F) and N-S to NNW-SSE in the southern part (structural domains C and E). Despite the fold trend variation, the main characteristics of F_1 fold style and associated minor structures are similar throughout the structural domains.

The F_1 folds are metric to hectometric, with straight or slightly curved hinge lines. They are tight-to-open angular, chevron-type folds, with a narrow hinge zone and quite straight limbs (2-4 E to 2-3 F classes of Huddleston, 1973; Fig. 4B). Saddle reefs are frequent in the hinge zones of the folds. The material transfer from the limbs to the saddle reefs is likely accomplished by a solution-precipitation process and/or brittle-ductile flow. Saddle reefs, together with bulbous and collapsed hinges (Fig. 3A), limb thrusts (Fig. 3B), or S-C structures thinning the limb zone suggest that the folds were formed during a process of chevron-type folding (Ramsay, 1974).

Spaced cleavage is commonly associated with F_1 folds. Two main types of pressure-solution surfaces, marked by concentration of insoluble material (clays, oxides) at places together with calcite growths, can develop (Fig. 4A):

a) Stylolites with toothlike-geometry, straight or oblique (slickolites). In marly limestones of domains A, B, C and D, column amplitude is about 1 mm and distance between slickolites is between 1 and 2 cm, while in more competent limestones, column amplitude reaches 1 cm and the pressure-solution surface interval varies between 5 and 15 cm.

b) Pressure solution surfaces showing anastomosed morphologies. It must be stressed that in marly limestones, the spacing between foliation planes is about 1.5 cm in domains A to D and 8 to 10 cm in domains E and F.

In competent layers, cleavage generally shows a convergent fan pattern toward the inner part of the fold. The fan pattern is roughly symmetrical with respect to the axial surfaces, and the angle between the fold axial plane and the cleavage in the limbs can reach 40°, which suggest that little bed-parallel shortening or bed-parallel shearing occurred before the folding of the layers.

Tectonic stylolites that do not show a systematic arrangement respect to F_1 fold axial plane also occur. They are subvertical, generally with hummocky morphologies, and stylolite columns forms high angles to the stylolite envelope (Fig. 4A). Preliminary results do not allow us to establish clear chronologic relations regarding to other types.

It is possible to make some rough estimations of the shortening due to F_1 folding. Total shortening has been estimated at the moment only in domains B

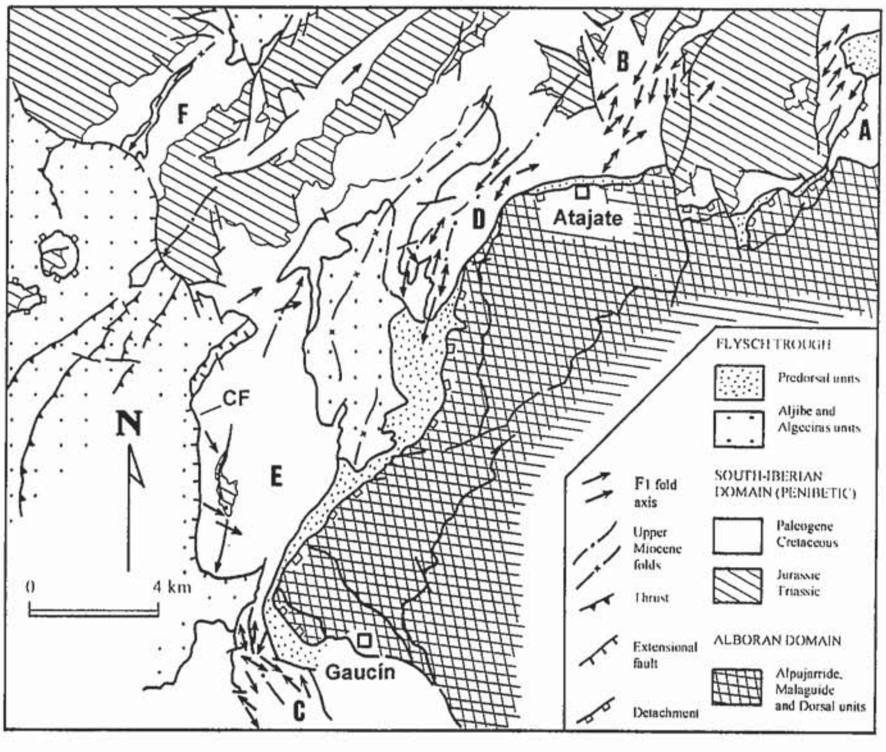

Fig. 2.- Tectonic map of the Penibetic Units near the western front of the Alboran Domain. Each arrow of F_1 fold axis corresponds to a representative value from 5 to 10 measurements. A to F, structural domains, ordered according to their increasing distance from the Alboran Domain front. Contacts inside the Alboran Domain correspond to tectonic boundaries between major unit types.

Fig. 2.- Mapa tectónico de las Unidades Penibéticas junto al frente occidental del Dominio de Alborán. Cada flecha de un pliegue F_1 corresponde a un valor representativo entre 5 y 10 medidas. A a F, dominios estructurales, ordenados de acuerdo con su distancia creciente respecto del frente del Dominio de Alborán. Los contactos dentro del dominio de Alborán corresponden a límites tectónicos entre unidades mayores.

and C. For instance, Figure 4D illustrates a series of folds along almost 100m. By comparing the final and initial length of the beds, the estimated shortening is between 20 and 25 percent.

In domains A to D, a 5 to 10 percent shortening due to pressure-solution has been estimated by taking into account the cleavage spacing and stylolite amplitudes.

It is important to note some differences between their structural features when F_1 folds are compared. Structural domains A to E are arranged along the mean tectonic transport direction (approximately towards the WNW) with respect to the current position of the Alboran Domain front (or its projected position when eroded), and the F_1 mean interlimb angle tends to increase towards more external domains (from A to E; Fig. 4C). Moreover, the cleavage intensity decreases in domain E as compared with domains A to D. Some observations on the cleavage within domain F indicate the same tendency, although interlimb data are too scarce to allow comparison.

Upper Miocene large-scale F_2 folds

Kilometric-scale F_2 folds, late Miocene in age, affected the previous structures (Luján *et al.*, 2000; Crespo-Blanc and Campos, 2001). In the western part of the study area in particular, F_2 antiforms and synforms deform an extensional fault representative of the middle Miocene extensional event (CF, Colmenar fault of Fig. 2), which in turn crosscuts the F_1 folds.

The F_2 fold trend varies from NE-SW in the northern part to N-S and NNW-SSE in the central and southern parts, respectively (Fig. 2). Although these late folds are almost parallel with the trend of the previous ones, which makes it difficult to evidence structural superpositions, it can be observed that in structural domain E, the Jurassic limestones represent the core of an F_2 fold, while the F_1 folds measured in the Cretaceous to Paleogene rocks are clearly oblique. The F_2 folds are large-scale upright or box-shaped folds which do not develop axial plane cleavage. They are not cylindrical, and have frequent double plunging morphology. Their axial trace is sinuous and vanishes rapidly (Fig. 2). As a result, folds of similar morphology, orientation and age that have been found in the Flysch units can not always be followed across the Penibetic-Flysch units boundary.

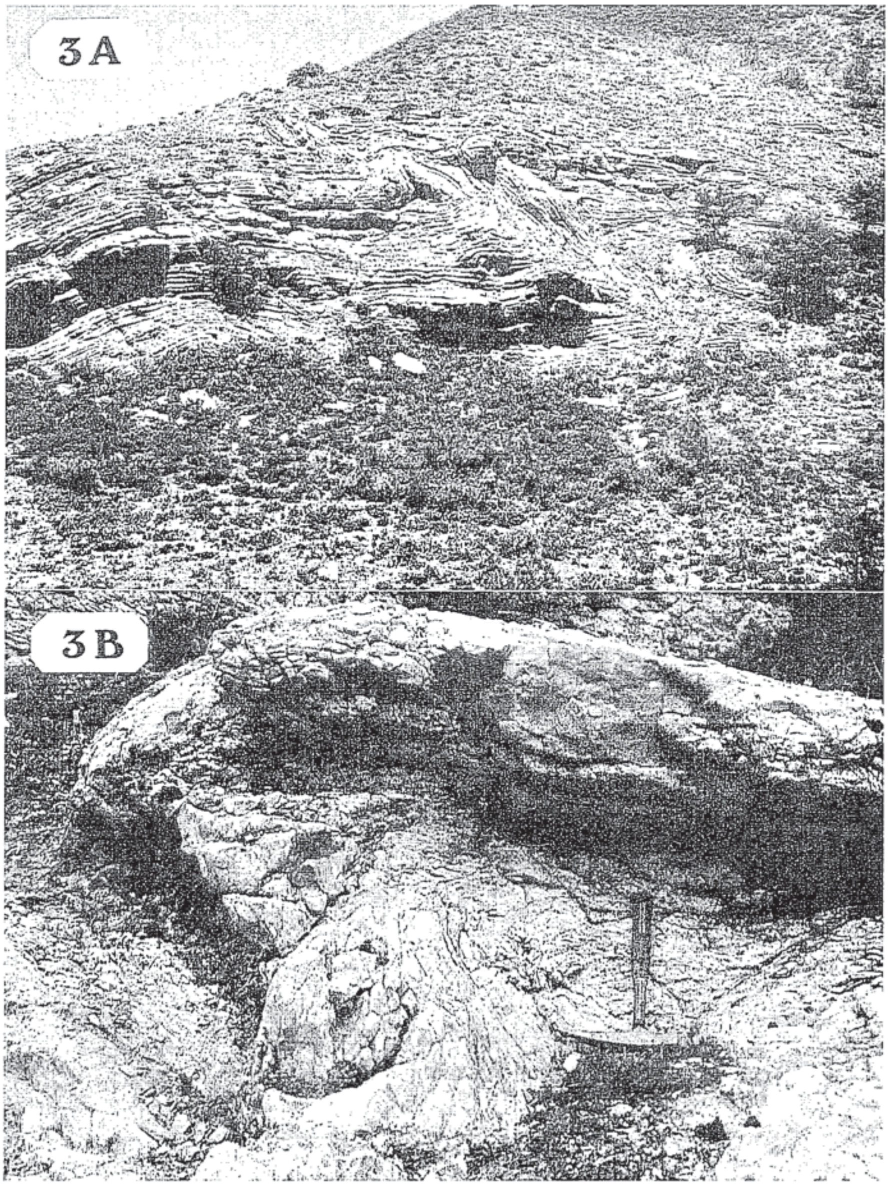

Fig. 3.- A) View close to the profile of an F_1 fold. Observe the chevron-type morphology and the development of bulbous and hinge collapsed zone. Real length is 50 m long. West is to the left. B) Hinge zone of the previous fold, where a limb thrust develops. Anastomosed spaced cleavage can be seen in the upper limb. West is to the left.

Fig. 3.- A)Vista aproximada coincidente con el perfil de un pliegue F_1. Obsérvese la morfología de tipo chevron y el desarrollo de zonas bulbosas y de colapso de charnela. La longitud real es de 50 m. El Oeste queda a la izquierda. B) Zona de charnela del pliegue anterior en la que se desarrolla un "limb thrust". Puede verse un clivaje espaciado anastomosado en el flanco superior. El Oeste queda a la izquierda.

Final remarks

The angular F_1 folds associated with the main shortening event observed in the Penibetic units, early-to-middle Miocene in age, show significant variation of fold axis trend. They swing from NE-SW to NNW-SSE around the western end of the Alboran Domain and show a NW- to WSW-vergence. Nevertheless, despite this variation, the fold style and associated minor structures observed in the Cretaceous to Paleogene marly limestones are similar in variably oriented folds. It shows that F_1 folds were generated during a single folding phase, which produced a minimum shortening of 25 percent. The minor structural features associated with F_1 folds, such as constant asymmetry or curved hinges, together with the relationships between both the interlimb angle and the cleavage intensity with the distance to the Alboran Domain front could indicate significant shearing during the development of the F_1 folds. This shearing could have been

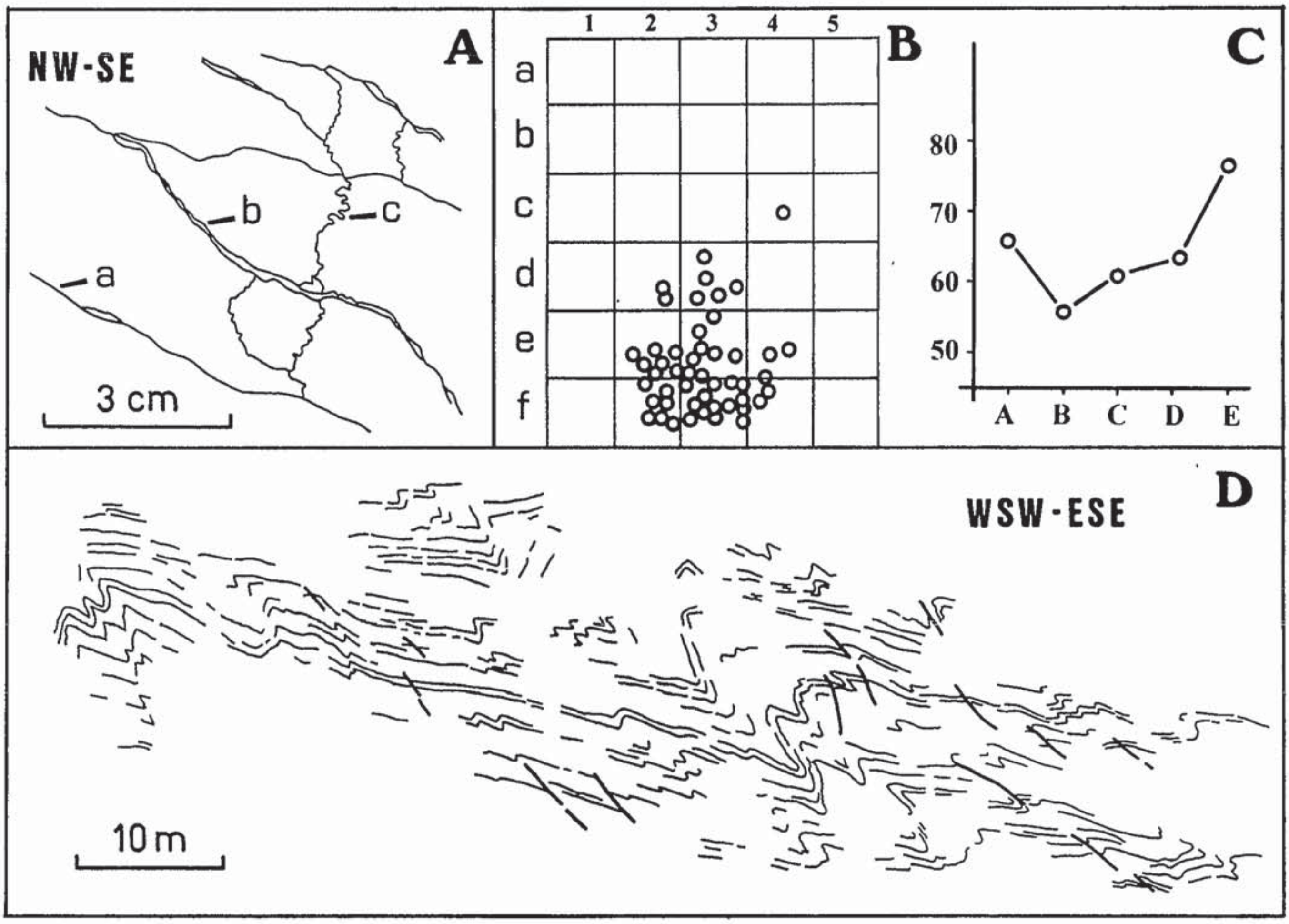

Fig. 4.- Selected examples of morphological and structural characteristics of F_1 folds. A) geometry of smooth pressure-solution surfaces unfilled (a) or filled (b) by calcite growths, and vertical stylolites (c); bedding is parallel to the scale bar. B) Representative example of fold shape *vs.* amplitude of F_1 folds belonging to B domain according to Huddleston's classification (1973). C) Mean interlimb angle of F_1 folds measured in the different structural domains (A to E) ordered according to their position with respect to the Alboran Domain front. D) series of F_1 folds, drawn from slides (C domain); the estimated shortening of a single layer is between 20 and 25 percent.

Fig. 4.- Ejemplos seleccionados de las características morfológicas y estructurales de los pliegues F_1. A) Geometría de las superficies presión- disolución de contorno suavizado, sin (a) o con (b) crecimientos de calcita, y estilolitos verticales (c); la estratificación es paralela a la barra de escala. B) Ejemplo representativo de la forma respecto a la amplitud de los pliegues F_1 pertenecientes al dominio B, de acuerdo con la calsificación de Huddleston (1973) . C) Valores medios del ángulo entre flancos medidos en diferentes dominios estructurales (A a E) ordenados de acuerdo con su posición respecto al frente del Dominio de Alborán. D) Tren de pliegues F_1, dibujado a partir de fotografías (dominio C); el acortamiento estimado de una capa simple está entre el 20 y 25 %.

induced by the thrusting of the Alboran Domain over the South Iberian paleomargin. The reason why a variation of trend is observed may now become a matter of debate, though the irregular shape of this Domain may partly explain the variation (see e.g. Kirker and Platt, 1998).

Acnowledgements

This study was supported by grant BTE2000-0581. We wish to thank Jean Sanders for reviewing the English version and an anonymons reviewer for helpful suggestions.

References

Balanyá, J.C., García-Dueñas, V., (1988): In: Sociedad Geológica de España, Segundo Congreso Geológico de España (vol. Simposios), Granada, pp.35-44.

Bourgois, J. (Ed.), (1978): *Annales Scientifiques de l'Université de Besançon (France)*, 30, 1-445.

Crespo-Blanc, A., Campos, J., (2001): *"Structure and kinematics of the South Iberian paleomargin and its relationship with the Flysch Trough units: Extensional tectonics within the Gibraltar Arc fold-and-thrust belt (Western Betics)" Journal of Structural Geology* 23 (10): 1615-1630.

Kirker, A., Platt, J.P., (1998): *J. Geol. Soc. London* 155, 193-207.

Huddleston, P. J.,(1973): *Tectonophysics* 16, 1-46.

Luján M., Balanyá J.C., Crespo-Blanc A., (2000): *C .R. Ac. Sci. Paris, Sciences de la Terre et des planètes* 330, 631-638.

Martin-Algarra, A., (1987): Tesis Univ. Granada, Dpto. estratigrafía y paleontología (ed), 1- 1271

Ramsay, J.G., (1974): *Geol. Soc. Am. Bull.* 85, 1741-1754.