SOME CONSIDERATIONS ABOUT THE GEOMETRY OF THE BOUNDARIES BETWEEN UNITS OF THE SOUTH IBERIAN AND FLYSCH TROUGH DOMAINS FROM COMMERCIAL SEISMIC PROFILES AND WELLS

A. Crespo-Blanc[1] y M. Luján[2]

[1] *Departamento de Geodinámica - IACT, Universidad de Granada - CSIC, Fuentenueva s/n,18071 Granada (acrespo@ugr.es).*
[2] *Instituto Andaluz de Ciencias de la Tierra, Consejo Superior de Investigaciones Científicas, Fuentenueva s/n, 18071 Granada (mlujan@ugr.es).*

Abstract: The interpretation of commercial seismic lines coupled with well data, in an area situated north of the Gibraltar Straits, sheds light on the geometry of the boundaries between the Subbetic and Flysch Trough units; that is, respectively, the units derived from the South Iberian paleomargin and the units composed of rocks deposited in a deep trough which separated the South Iberian and the Maghrebian paleomargins. This trough was obliterated from the Early Miocene onwards by the westward movement of the continental metamorphic rocks belonging to the Alboran Domain (Betic-Rif internal zones), which collided with the two paleomargins. In the external zones, two seismic units are differentiated, which according to the available correlation with commercial wells, correspond to the Flysch units laying over the Subbetic units. In the studied area, the depth of this boundary is situated mainly between 1,000m and 1,500m. Surface data together with seismic data show that within the Flysch Trough Domain —in the study area comprising the Aljibe and Algeciras units— Aljibe unit represents the uppermost unit, and that its structure corresponds with an imbricate thrust system.

Key words: Betic-Rif orogen, Gibraltar Arc, Flysch Trough units, Subbetic units, commercial seismic profiles, wells.

Resumen: En un área situada al norte del Arco de Gibraltar, la interpretación de líneas de sísmica comercial junto con datos de sondeos, permiten precisar algunos aspectos de la geometría de los límites entre unidades del Subbético, que derivan del paleomargen Suribérico, y del Surco de los Flyschs, que derivan de una cuenca profunda que separaba los paleomárgenes Suribérico y Magrebí. Este surco ha sido obliterado a partir del Mioceno inferior por la migración hacía el oeste de las rocas metamórficas de origen continental pertenecientes al Dominio de Alborán, las zonas internas del orógeno bético-rifeño, que colisionó con los dos paleomárgenes. En las zonas externas, se han diferenciado dos unidades sísmicas que corresponden, según las correlaciones que se pueden hacer con datos de sondeos, con las unidades de Flysch que reposan sobre las unidades del Subbético. En la región estudiada, la profundidad del límite entre ambos dominios está situada principalmente entre 1,000 y 1,500m. Los datos de superficie junto con los de sísmica muestran que en el Dominio del Surco de los Flyschs —compuesto en el área estudiada por las unidades de Aljibe y Algeciras—, la unidad de Aljibe es la unidad más alta, y que su estructura corresponde con un haz de cabalgamientos imbricados.

Palabras claves: Orógeno bético-rifeño, Arco de Gibraltar, unidades del Surco de los Flysch, unidades subbéticas, perfiles de sísmica comercial, sondeos.

Crespo-Blanc, A. y Luján, M. (2002): Some considerations about the geometry of the boundaries between units of the South Iberian and Flysch Trough Domains from commercial seismic profiles and wells. *Rev. Soc. Geol. España*, 15 (3-4), 193-200.

The Flysch Trough units of the Gibraltar Arc are formed by non-metamorphic rocks derived from detrital sediments deposited in a deep trough, developed on a transform zone of attenuated continental lithosphere, eventually oceanic (Durand-Delga *et al.* 2000), situated between the African and European plates and filled by sediments from Early Cretaceous to Neogene times. This trough was obliterated from the Early Miocene onwards by the westward movement of the Alboran Domain, the internal zone of the Betic-Rif orogen (Fig. 1), which collided with the two paleomargins (Balanyá and García-Dueñas, 1987; 1988). In the northern branch of the Gibraltar Arc, the shortening produced an accretionary prism, mostly west- or northwest-vergent, formed by the Flysch Trough units and by the Subbetic units, the latter deriving from the

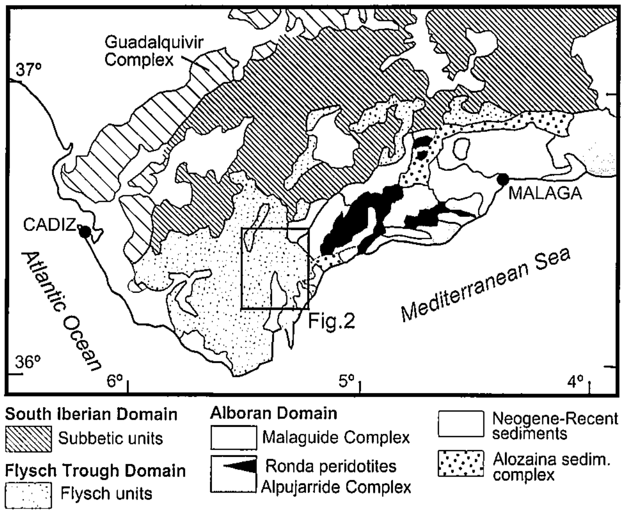

Figure 1.- Main tectonic complexes north of the Gibraltar Straits in the Betic-Rif orogen.

South Iberian paleomargin.

The stratigraphical and sedimentological character of the rocks that form the Flysch Complex have been studied in previous works (e.g. Chauve, 1960; Didon, 1960; 1969), but little data is available about the structure and kinematics of the tectonic units that make up the Flysch Complex (e.g. Luján *et al.*, 1999, 2000). The aim of this paper is to shed light on the geometry of the boundaries between the Subbetic and Flysch Trough units where they can not be observed directly, from the interpretation of commercial seismic lines coupled with well data. The study area is situated west of the Alboran Domain, north of the Gibraltar Straits.

Geological setting

Two main units have been distinguished in the Flysch Trough Domain (Fig. 2): the Aljibe unit (Chauve, 1960; Didon, 1960; Didon and Peyre, 1964) and the Algeciras unit (Didon, 1960, 1969). These units

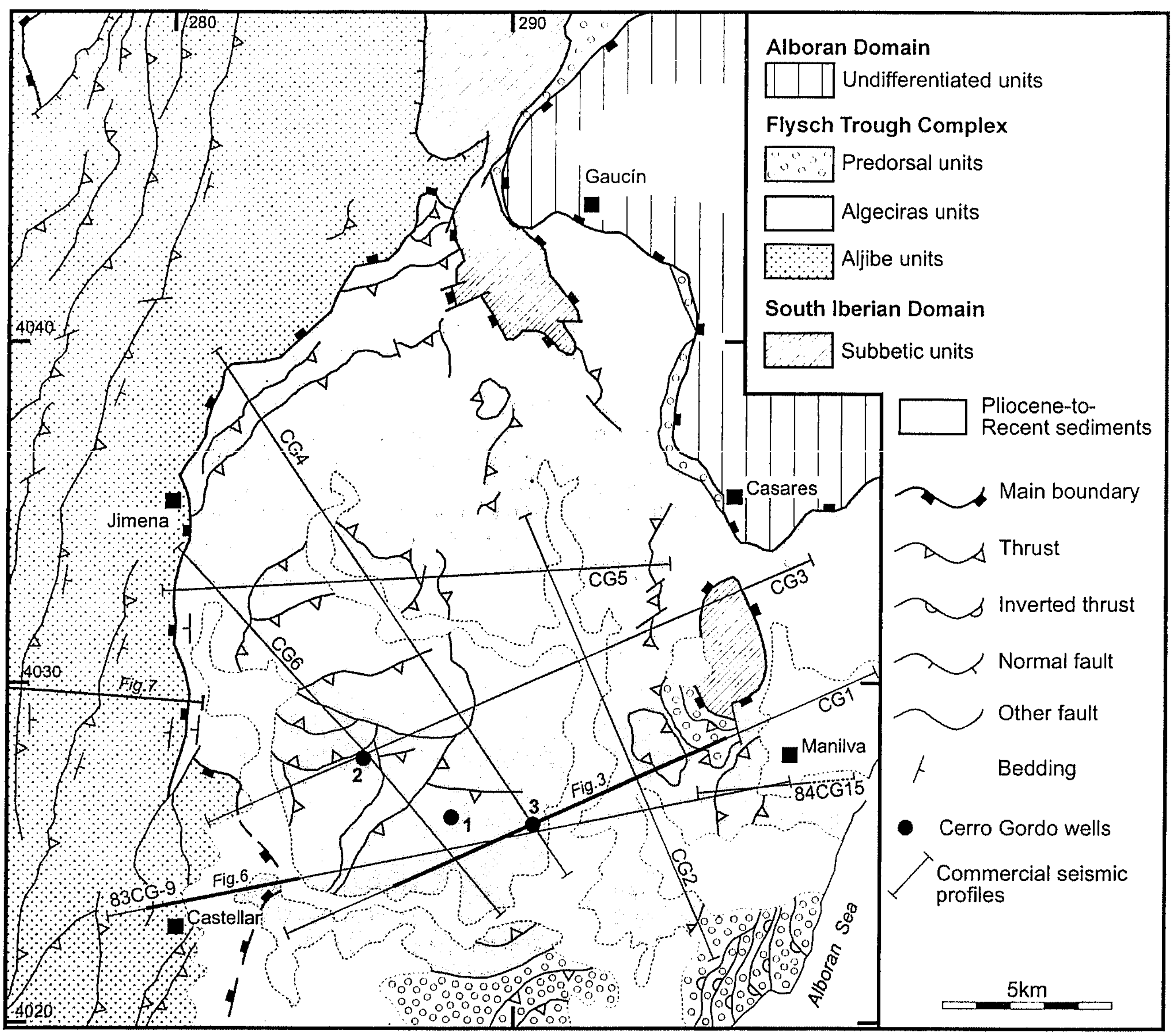

Figure 2.- Tectonic map of the studied area, modified from García de Domingo *et al.* (1994) and Esteras *et al.* (1988). Location on Figure 1. The thick lines on profiles CG1 and 83CG-9 correspond to the segments of the profiles represented in Figures 3 and 6, respectively.

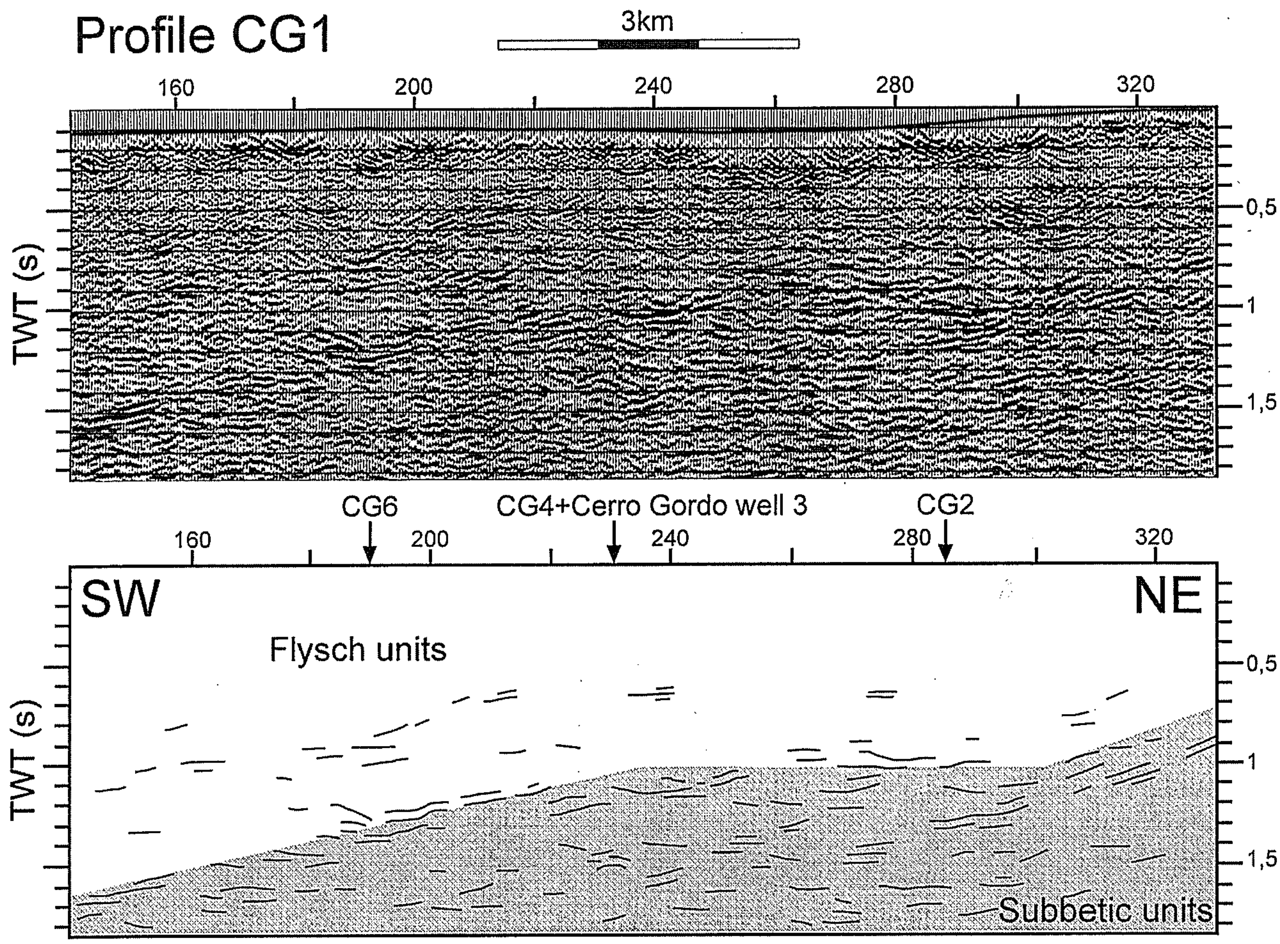

Figure 3.- Segment of Profile CG1 and corresponding line drawing (located on Figure 2). The arrows indicate where other profiles cut line CG1. Observe the two seismic units which correspond with the Flysch unit lithologies and the Subbetic limestones and dolostones (shaded in grey in the line drawing). Reference datum plane situated at 0 m.

comprise two well-differentiated terms. Their lower term, Cretaceous to Oligocene in age, contains mainly siltstones and is similar in both units. The upper term of the Aljibe unit is made up of sandstones and siltsones (Aquitanian to Early Burdigalian in age; Esteras *et al.*, 1995), while the upper term of the Algeciras unit is represented by a "marly-sandy-micaceous" flysch (Oligocene to Aquitanian in age; Didon, 1969). The structure of the Aljibe unit, which underwent WNW-ESE shortening, corresponds with an imbricate thrust system, post-Aquitanian in age (Luján *et al.*, 2000). In the study area, the structure of the Algeciras unit is not well known due to very poor outcrops, whereas a few kilometres south of the study area, NE-SW-trending imbricated thrusts are observed (Esteras *et al.*, 1988).

The Subbetic units lie structurally below the Flysch units, as can be observed in the northern part of the study area (Fig. 2). The lithostratigraphy of the Subbetic units includes: a) a Triassic sequence made up of carbonate rocks (Muschelkalk facies), together with gypsiferous claystones and fine-grained sandstones (Keuper facies); b) a Jurassic sequence formed by dolomite rocks superposed by massive limestones; and c) an alternating of pink pelagic marls and marly limestones, Late Cretaceous to Paleogene in age.

Seismic data and correlations with wells

In the study area, onland exploration activities have yielded around twenty seismic profiles and three commercial wells. These data were acquired between the late fifties and the early eighties by Eniepsa, Shell and Valdebro, among others. From the available profiles, only seven are interpretable. Profiles CG1 to CG6, located in Fig.2, were made in 1982, and the available copies are migrated. Profile 83CG9/84CG15 is a merged final stack, processed in 1984. They can be interpreted down to approximately 1.5 seconds, in points 2.0 seconds (two-way travel time).

The poor quality of the profiles, often with segments which cannot be interpreted, allows only two seismic units to be differentiated. Fig. 3 illustrates a segment of line CG1, representative of these units. The upper unit is marked by transparent zones alternating with parallel reflectors, of low amplitude, high frequency and very short lateral continuity. The lower seismic unit is characterized by chaotic and discontinuous reflectors alternating with scarce strong and more continuous reflectors, with a lower frequency and higher amplitude than those of the upper unit. The boundary between the two units is frequently marked by prominent high-

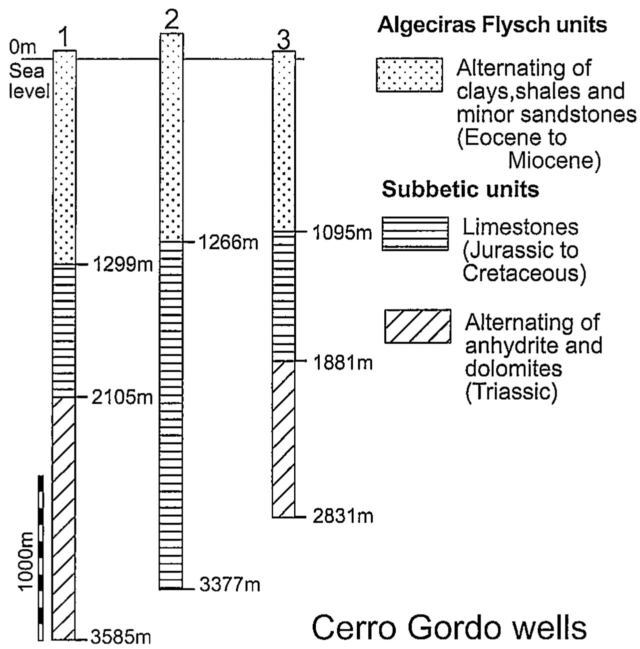

Figure 4.- Main lithologies drilled in Cerro Gordo wells, according to IGME (1987). Location on Figure 2.

amplitude parallel reflectors of variable lateral continuity (Fig. 3). It must be stressed that this reflection band can be observed in any profile; and that when it appears in crosscutting seismic lines, it is situated at the same travel time in both profiles. The line-drawings obtained from the seismic data permit us to draw the boundary between units and to follow some prominent reflectors within each unit, as those illustrated in Fig. 3. Nevertheless, no internal tectonic structures such as thrust or normal fault or sedimentary features can be reliably drawn in any profile.

The wells Cerro Gordo 1 to 3, executed between 1959 and 1961 (IGME, 1987), through which some profiles run (Fig. 2), make possible some correlations between lithologies and seismic character together with rough estimations of seismic velocities. The drilled lithologies are illustrated in Fig. 4. It shows that the first approximately one thousand meters correspond with an alternating of clays, shales and minor sandstones which belong to the Algeciras unit (IGME, 1987). Below, the Jurassic and Cretaceous limestones of the Subbetic units were drilled. In wells 1 and 3, below the carbonate rocks, anhydrite alternating with dolomites represent the Triassic rocks. It is suggested that the variation in the seismic character of the different units observed in the profiles corresponds with the change of lithology: the relatively transparent upper unit would correspond with the Flysch unit, while the lower unit probably represents the carbonate rocks. We should observe this boundary merging with the surface along Lines CG1 and CG3, as these lines cut, or run very near, a tectonic window of Subbetic materials (Fig. 2). Uninterpretable segments of these lines near the Subbetic window hinder direct correlations, although reflectors dipping towards the WSW in the eastern part of both profiles are coherent with the interpretation that the variation in seismic character corresponds with the change of lithology.

If the upper and lower seismic unit correspond with the Algeciras Flysch and Subbetic units, respectively, rough estimations of seismic velocities can be made. For example, in Cerro Gordo well 3, the Flysch sequence attains 1,095m (Fig. 4); whereas in line CG1, the prominent reflector supposedly marking the boundary between lithologies is situated at approximately 1 second (two-way travel time, reference datum plane situated at 0m, Fig. 3). Then, the seismic velocity for the clays, shales and minor sandstones of the Flysch unit should be around 2.2km/s, which is coherent with the velocity range of this type of rocks (e.g. Telford *et al.*, 1976). Similar velocities of Flysch rocks can be estimated by correlations between line CG3 and well Cerro Gordo 2. Based on a velocity of 2.2 km/s for the Flysch units, the depth of the top of the carbonate rocks of the Subbetic units can be estimated along the segments of the profile where the boundary between Subbetic and Flysch units is marked by prominent reflectors. These depths, mostly between 1,000m and 1,500m, are illustrated in Figure 5. The dashed lines represent segments drawn according to the geometry of the reflectors situated below the Flysch-Penibetic unit boundary, assuming that they are parallel.

The boundary between the Algeciras and Aljibe units

In the western part of Line 83CG9/84CG15, a reflection band dipping towards the WSW can be followed up to the surface (Fig. 6). This band merges with the boundary between the Algeciras unit, situated to the east, and the Aljibe unit situated to the west. It clearly shows that along this segment, the Aljibe unit is superposed on the Algeciras unit.

A representative cross-section of the geometry of the Aljibe unit adjacent to the boundary between the Algeciras and Aljibe units is illustrated in Fig. 7. The dip of this boundary has been drawn according to the depth calculated from the seismic profile, by assuming a velocity of 2.2 km/s. A mean dip of 20° is obtained for the 2.5km profile length along which the boundary is observed. The structural map of the Aljibe unit, together with the strata polarity, is coherent with an imbricate thrust system (Luján *et al.*, in press). It is suggested that the individual thrust faults determined by the surface geology curve downward to the sole thrust represented by the Algeciras/Aljibe boundary, underlined in the seismic profile (Fig. 7). It must be stressed that ploughed farmlands generally occupy the area where this boundary should outcrop, and it is not possible to observe kinematic criteria along it nor to test whether the supposed sole thrust surface shows a westward transport direction, similar to that of the individual thrust faults (Luján *et al.*, 1999).

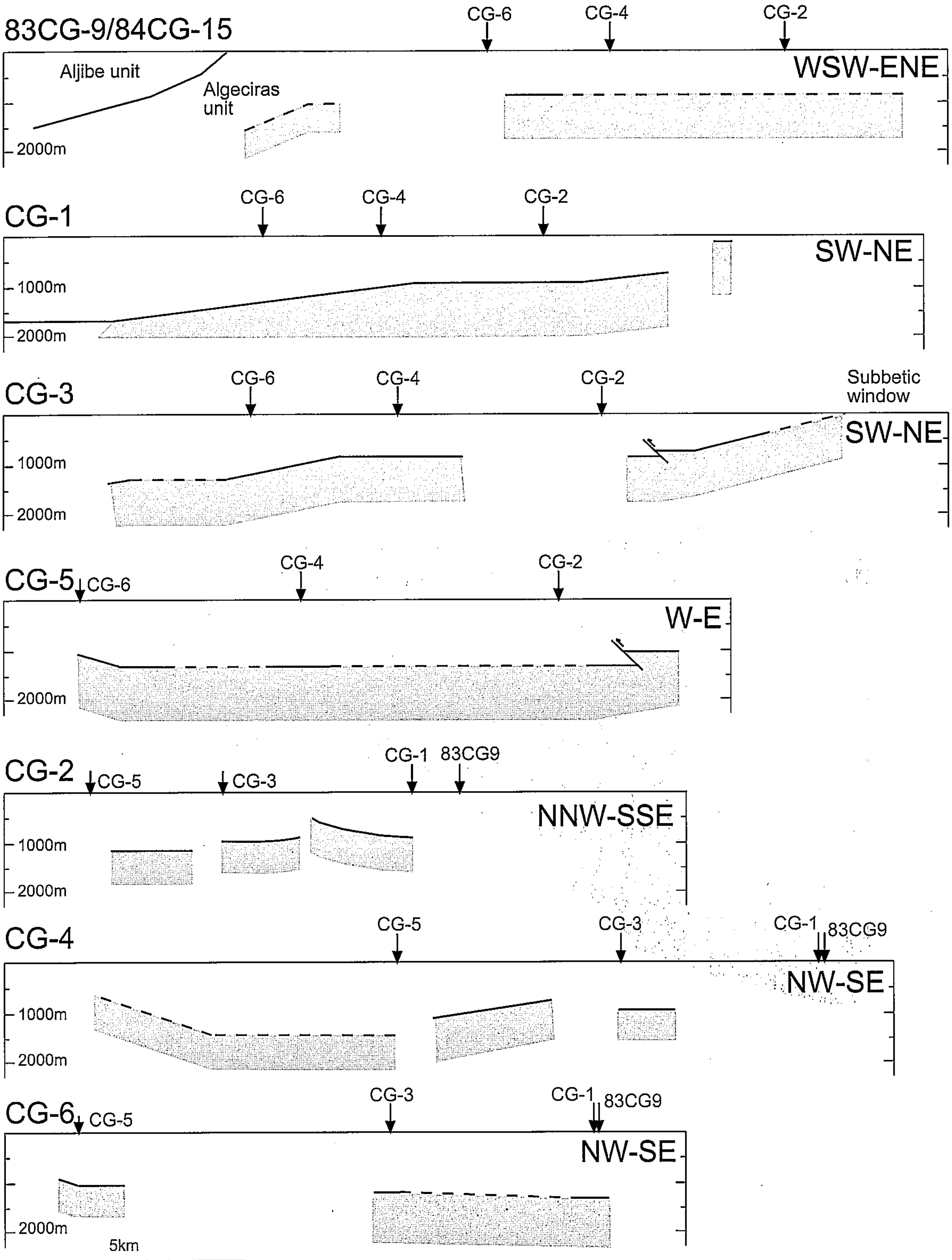

Figure 5.- Approximate depth of the top of the Subbetic limestone units (Subbetic-Flysch units boundary) along the studied seismic profiles. The time-depth conversion is based on a velocity of 2.2 km/s for the Flysch unit.

Discussion and conclusions

The geometry of the boundary between the alternating of clays, shales and minor sandstones which belong to the Algeciras unit and the top of the carbonate rocks of the Subbetic units, as drawn from the seismic profiles, is coherent with the field data. In fact, in the approximately SW-NE-directed profiles (Fig. 5), a deepening of this boundary towards the SW, well constrained in profile CG-1, was expected, as a commercial well situated 25 km southwest of the studied area drilled more than 3,000m of Flysch rocks (well "Tarifa 1", in IGME, 1987). Moreover, the SW-ward dipping of the Flysch-Subbetic boundary in profiles CG-1 and CG-3 (Fig. 5) is in agreement with the tectonic window of Subbetic materials in the eastern

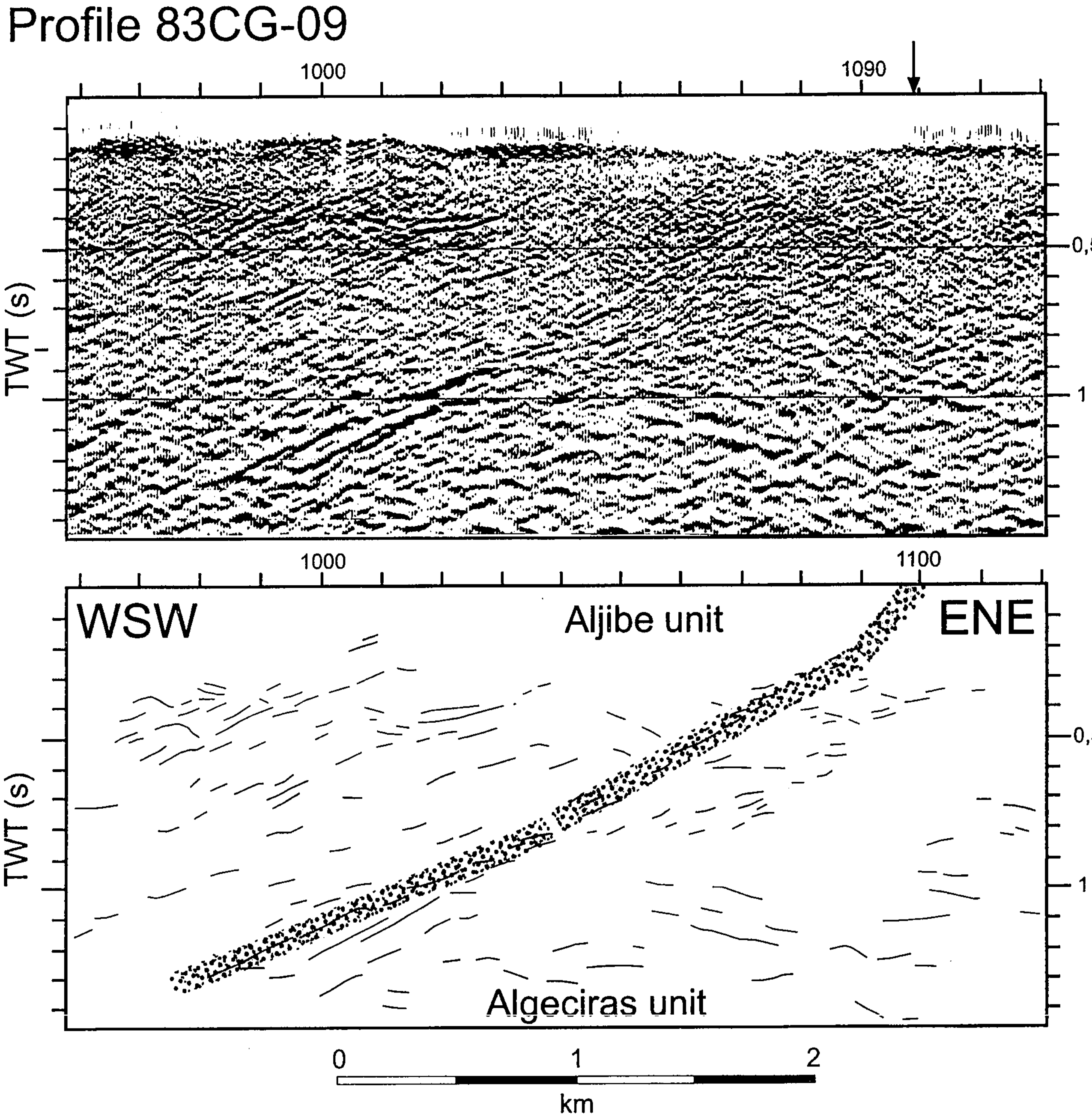

Figure 6.- Segment of Profile 83CG9/84CG15 and corresponding line drawing (located on Figure 2). The reflector band which dips to the WSW (shaded in grey in the line drawing) merges approximately where the boundary between the Algeciras and Aljibe units outcrops (arrow above the seismic line).

part of the study area (Fig. 2). The jump marked by the prominent reflectors which underline the Flysch-Subbetic boundary has been interpreted as a reverse fault in Profiles CG-3 and CG-5 (Fig. 5).

In the study area, the depth of the boundary between Flysch and Subbetic units is interpreted to be situated mainly between 1,000m and 1,500m (Fig. 5). This interpretation is based on an estimation of the mean velocity of the Flysch rocks (2.2 km/s), in turn deduced from the Cerro Gordo well data. If the geometry of the Flysch/Subbetic boundary depicted in Figure 5 is correct, it can be used to make rough estimations of total shortening within the Algeciras unit, even though the internal structure of this unit is unknown. Indeed, if it is assumed that the transport direction during the main shortening event, well constrained towards the W or WNW in the Aljibe unit (Luján *et al.*, 1999, 2000), is similar for both the Aljibe and the Algeciras units, area balancing (Ramsay and Huber, 1987) can be applied along profile CG5, E-W-directed. Providing that no change in area took place during deformation, we may compare the area occupied by an undeformed Algeciras sequence, whose stratigraphic thickness is estimated between 800m (Didon, 1969) and 1,110m (Martín-Algarra, 1987), to the area we have to fill with Flysch material between the Flysch/Subbetic boundary and the topography. As erosion is neglected, the calculated extension is a minimum value. A negative extension between 0.60 and 0.43, respectively, is calculated. It must be stressed that this estimation, though very

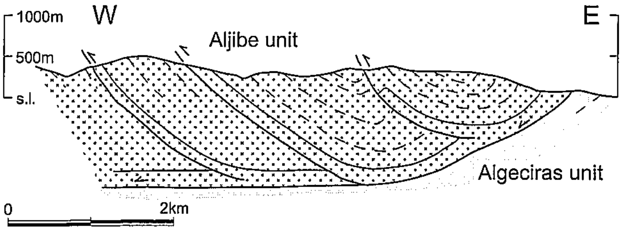

Figure 7: Representative cross-section of the Aljibe unit structure adjacent to the Algeciras/Aljibe unit boundary (located on Figure 2).

rough, is similar to the shortening calculated by line-balancing in the Aljibe unit (0.54, in Luján *et al.*, 1999).

Seismic line 83CG9/84CG15 clearly corroborates that the Aljibe unit represents the uppermost unit of the Flysch Domain, as claimed by Didon (1969), Bourgois (1978) or Martín-Algarra (1987) among others. It has been suggested that the thrust imbrications which form the Aljibe unit are rooted in the Aljibe-Algeciras boundary (Fig. 7), and hence would have developed during the Early to Middle Miocene (Crespo-Blanc and Campos, 2001). In the study area then (from Castellar to 2 km east of Gaucín, Fig. 2), this boundary would have a compressive character. The current position of this supposed sole thrust, dipping to the west, may be due to late, Late Miocene open folding (Crespo-Blanc and Campos, 2001).

Although the proposed solution is geometrically possible, this interpretation should be tested, as the constraints are not sufficient to reject the possibility that this boundary has an extensional character. North of Gaucín, in fact, the current boundary of the Aljibe and the underlying Subbetic units —the Algeciras unit is absent there— is found to be a normal low-to-moderate angle fault, with a SW-ward hangingwall movement, which cuts the imbricate thrust system within the Aljibe unit (Fig. 2, Luján *et al.*, 2000). The cartographic continuation of this normal fault, middle Miocene in age (op. cit.), has not yet been established, and it is not ruled out that it could constitute the lower boundary of the Aljibe unit throughout the study area. In this case, the individual thrust faults of the thrust slices would not be rooted in the Aljibe-Algeciras unit boundary, but would be cut by this low-to-moderate angle normal fault.

Geophysical models of the Gibraltar Arc area, which include the interpretation of gravimetric data (Torné *et al.*, 1992 and references therein), seismic refraction profiles (Barranco *et al.*, 1990 and references therein) and crustal tomography (Dañobeitia *et al.*, 1998) are available. The interpretation of the commercial seismic and well data presented in this paper with respect to the geometry of the boundaries between units of the Flysch Trough and of the Subbetic Domains provides constraints for future geophysical and tectonic models of the Gibraltar Arc, which represents the westernmost segment of the peri-mediterranean orogenic belt.

Acknowledgments

This study was supported by Grant BTE2000-0581. We thank Jean Sanders for reviewing the English version.

References

Balanyá, J.C. y García-Dueñas, V. (1987): Les directions structurales dans le Domaine d'Alboran de part et d'autre du détroit de Gibraltar. *Comptes Rendus de l'Académie des Sciences de Paris*, 304: 929-932.

Balanyá, J.C. y García-Dueñas, V. (1988): El cabalgamiento cortical de Gibraltar y la tectónica de Béticas y Rif. En: *II Congr. Geol. España*, Simposios: 35-44.

Barranco, L.M., Ansorge, J. y Banda, E. (1990): Seismic refraction constraints on the geometry of the Ronda peridotite massif (Betic Cordillera). *Tectonophysics*, 184: 379-392.

Bourgois, J. (1978): La transversale de Ronda (Cordillères bétiques, Espagne). Données géologiques pour un modèle d'évolution de l'Arc de Gibraltar. *Annales Scientifiques, Université de Besançon (France)*, 30: 1-445.

Chauve, P. (1960): Structure géologique de la région centrale de la Province de Cadix. En: *Livre à la mémoire du Professeur Fallot. Mémoire hors-série de la Société géologique de France*, 1: 257-264.

Crespo-Blanc, A. y 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: 1615-1630.

Dañobeitia, J.J, Sallarès, V. y Gallart, J. (1998): Local earthquakes seismic tomography in the Betic Cordillera (southern Spain). *Earth and Planetary Science Letters*, 160: 225-239.

Didon, J. (1960): Le Flysch gaditan au Nord et au Nord-Est d'Algésiras (Prov. de Cadix, Espagne). *Bulletin de la Société Géologique de France*, 7/2: 352-361.

Didon, J. y Peyre, Y. (1964): Sur deux dispositifs tectoniques remarquables dans les Cordillères Bétiques à l'Ouest du Méridien de Malaga (Andalousie). *Comptes Rendus de l'Académie des Sciences de Paris*, 259: 1988-1991.

Didon, J.(1969): *Etude géologique du Campo de Gibraltar.* PhD thesis, Univ. de Paris. 539p.

Durand-Delga, M., Rossi, P., Oliver, P. y Puglisi, D. (2000): Situation structural et nature ophiolitique de roches basiques jurassiques associées aux flyschs maghrébins du Rif (Maroc) et de Sicile (Italie). *Comptes-Rendus de l'Académie des Sciences de Paris, Earth and Planetary Sciences,* 331: 29-38.

Esteras, M., Feinberg, H. y Durand-Delga, M. (1995): Nouveaux éléments sur l'âge des grès numidiens de la nappe de l'Aljibe (Sud-Ouest de l'Andalousie, Espagne). En*: IV Coloquio Internacional sobre el enlace Fijo del Estrecho de Gibraltar, SECEG*, 2: 205-215.

Esteras, M., Muñoz, P. y Sandoval, N. (1988): *Mapa Geológico del Estrecho de Gibraltar.1:100.000*. SECEG, Madrid.

García de Domingo, A., Hernaiz Huerta, P., Balanyá, J.C. y García-Dueñas, V. (1994): *Mapa Geológico de España 1:200.000, hoja nº 87 (Algeciras).* ITGME, Madrid.

IGME (1987): *Contribución de la exploración petrolífera al* *conocimiento de la Geología de España.* IGME, Madrid, 481p.

Luján M., Crespo-Blanc, A. y Balanyá, J.C. (1999): Structure and kinematics of the Aljibe Unit, north of Cádiz Province (Flysch Trough Complex, Betics). *Geogaceta*, 26: 47-50.

Luján M., Balanyá J.C. y Crespo-Blanc A. (2000): Contractional and extensional tectonics in Flysch and Penibetic units (Gibraltar Arc, SW Spain): new constraints on emplacement mechanisms. *Comptes-Rendus de l'Académie des Sciences de Paris, Earth and Planetary Sciences* 330: 631-638.

Luján, M., Storti, F., Balanyá J.C., Crespo-Blanc A. y Rossetti, F. (2002): Role of décollement material with different rheological properties in the structure of the Aljibe thrust imbricate (Flysch Trough, Gibraltar Arc): an analogue modelling approach. *Journal of Structural Geology*, en prensa.

Martín-Algarra, A. (1987): *Evolución geólogica alpina del contacto entre las zonas internas y las zonas externas de la Cordillera Bética.* Tesis Doctoral, Univ. Granada, 1.271p.

Ramsay, J.G. y Huber, M. (1987): *The techniques of Modern Structural Geology. Volume 1: Strain Analysis.* Academic Press, London, 307p.

Telford, W.M., Geldart, L.P., Sheriff, R.E. y Keys, D.A. (1976): *Applied Geophysics.* Cambridge University Press, Cambridge, 860p.

Torné, M., Banda, E., García-Dueñas, V. y Balanyá, J.C. (1992): Mantle-lithosphere bodies in the Alboran crustal domain (Ronda peridoties, Betic-Rif orogenic belt). *Earth and Planetary Science Letters*, 110: 163-171.

Manuscrito recibido el 7 de marzo de 2002
Aceptado el manuscrito revisado el 10 de octubre de 2002