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Variscan and Alpine structure of the hills of Barcelona: geology in an urban area

Estructura herciniana y alpina de las colinas de Barcelona: geología en una zona urbana

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Abstract

Line 9 of the underground railway is currently being constructed in Barcelona. This undertaking necessitates tunnelling through a number of hills that are mainly made up of Paleozoic rocks, which exhibit a complex structure due to the superposition of Variscan, Mesozoic, Paleogene, and Neogene structures. We present a geological map of the hills of Barcelona originally compiled at 1:5000 scale. Unpublished field notes from surveys carried out in the 1940s and in the early 1970s were crucial for drawing up this detailed map, which together with subsurface data from public works and our study of the few remaining outcrops, enabled us to provide fresh insights into the structure of this area. We also discuss the age of the structures on the basis of cross-cutting relationships and regional considerations. Our conclusions highlight the ongoing need for a geological survey of cities given that our understanding of their geology depends on impermanent outcrops and on the recovery of lost subsurface data. These considerations call for a suitable management of the geological information in urban areas with a complex geology for planning and developing safe infrastructures.

Keywords: Urban geology, Paleozoic, Barcelona, Variscan Orogeny, Alpine Orogeny

Resumen

Actualmente en Barcelona se está construyendo la Línea 9 del metro. Para ello es necesario perforar las colinas de Barcelona que presentan una compleja estructura, resultado de la superposición de estructuras hercinianas, mesozoicas, paleógenas y neógenas. En este trabajo presentamos un mapa geológico de las colinas de Barcelona originalmente elaborado a escala 1:5000. Para su realización ha sido muy importante disponer de datos de campo recolectados en los años 1940 y 1970, que junto con el estudio de datos de subsuelo y de los pocos afloramientos disponibles, nos han permitido aportar nuevas ideas sobre la estructura de esta zona. Se discute también la edad de las estructuras descritas a partir de sus relaciones cronológicas relativas y de consideraciones regionales. Nuestras conclusiones refuerzan la necesidad de un continuo reconocimiento geológico de las zonas urbanas, ya que el conocimiento geológico depende de afloramientos de carácter efímero y de la recuperación de datos de subsuelo a menudo extraviados. Estas consideraciones reclaman una adecuada gestión de la información geológica de las zonas urbanas con una estructura compleja para llevar a cabo la planificación y el desarrollo de infraestructuras de un modo seguro.

Palabras clave: Geología urbana, Paleozoico, Barcelona, Orogenia Varisca, Orogenia Alpina

1. Introduction

City expansion generates a huge demand for infrastructures in an increasingly reduced space. Cities are therefore forced to grow downwards, which demands underground constructions, mainly transport networks. A precise geological knowledge of the subsurface is crucial for planning constructions and for ensuring safety. However, geological features are increasingly difficult to observe owing to growing urbanization. A sound grasp of the regional geology necessitates the construction of geological maps at large scales (1:5000 or more). This is the case of the city of Barcelona, which in the second half of the 20th century underwent rapid expansion over the hills that form the backdrop to the city. At that time, only 1:50000 scale geological maps were available and the geological features of the newly constructed areas were not recorded by the authorities. A number of outcrops in the hills have been progressively transformed into green spaces or covered by concrete. Very few outcrops remain today with the result that it is difficult to interpret the geology of the subsurface of the city.

The hills of Barcelona are located between the Quaternary littoral plain, where the old part of the city was settled, and the Collserola range (Fig. 1). In the hills, a succession of Paleozoic rocks affected by a number of tectonic episodes is preserved. Apart from the episodes related to the Variscan orogeny, Paleozoic rocks have been deformed by Mesozoic extension, Paleogene compression and Neogene extension. The small size of the mappable units and the scarcity of post-Variscan deposits make it difficult to understand and to date most of the structures.

This paper provides new insights into the structure of the hills of Barcelona. Given the dearth of published reports and outcrops and given the difficulty of obtaining geological data from engineering companies, it was necessary to resort to unpublished field notes (notebooks and field maps) from surveys conducted in the 1940s and in the early 1970s in order to draw up a 1:5000 scale map. This map together with the subsurface data obtained from public works and our study of the few remaining outcrops enabled us to better understand the subsurface structure of this area. The data obtained revealed a complex structural evolution and offered further insights into the way in which the study area helped to complete the regional puzzle.

2. Geological setting

The city of Barcelona, which is located in the northeastern part of the Iberian Peninsula, is built on the Littoral Plain of the Catalan Coastal Ranges between the Besòs and Llobregat rivers and extends up the lower parts of the Littoral Range (Fig. 1). The NE-SW trending ranges and depressions that constitute the Catalan Coastal Ranges are controlled by extensional faults that have formed since the latest Oligocene, mainly during the Miocene, some of which continue to be active at present (Roca and Guimerà, 1992; Perea *et al.*, 2006). The Catalan Coastal Ranges are the onshore margin of the València Trough, which is a complex extensional basin that extends over 250 km along the eastern margin of the Iberian Peninsula (Banda and Santanach, 1992; Sàbat *et al.*, 1997). Most of the blocks forming the western margin of the trough are tilted to the NW and separated by major extensional faults dipping to the SE. The general structure of the blocks consists of a step-like system of half-grabens that descend from the Ebro Basin in the mainland down to the València Trough offshore. Extensional faulting, which is related to the València Trough rifting, controlled both the subsidence of the half-grabens and the uplift of the Catalan Coastal Ranges, the highest elevations of which exceed 1000 m. At the Barcelona transverse, these extensional faults define the following morphostructural units from NW to SE as follows: the Prelittoral Chain, the Vallès-Penedès half-graben, the Littoral Chain and the Littoral Plain (Fig.1). NW-SE trending faults, perpendicular to the major extensional faults, divide these morphostructural units and limit the Catalan Coastal Ranges to the Northeast.

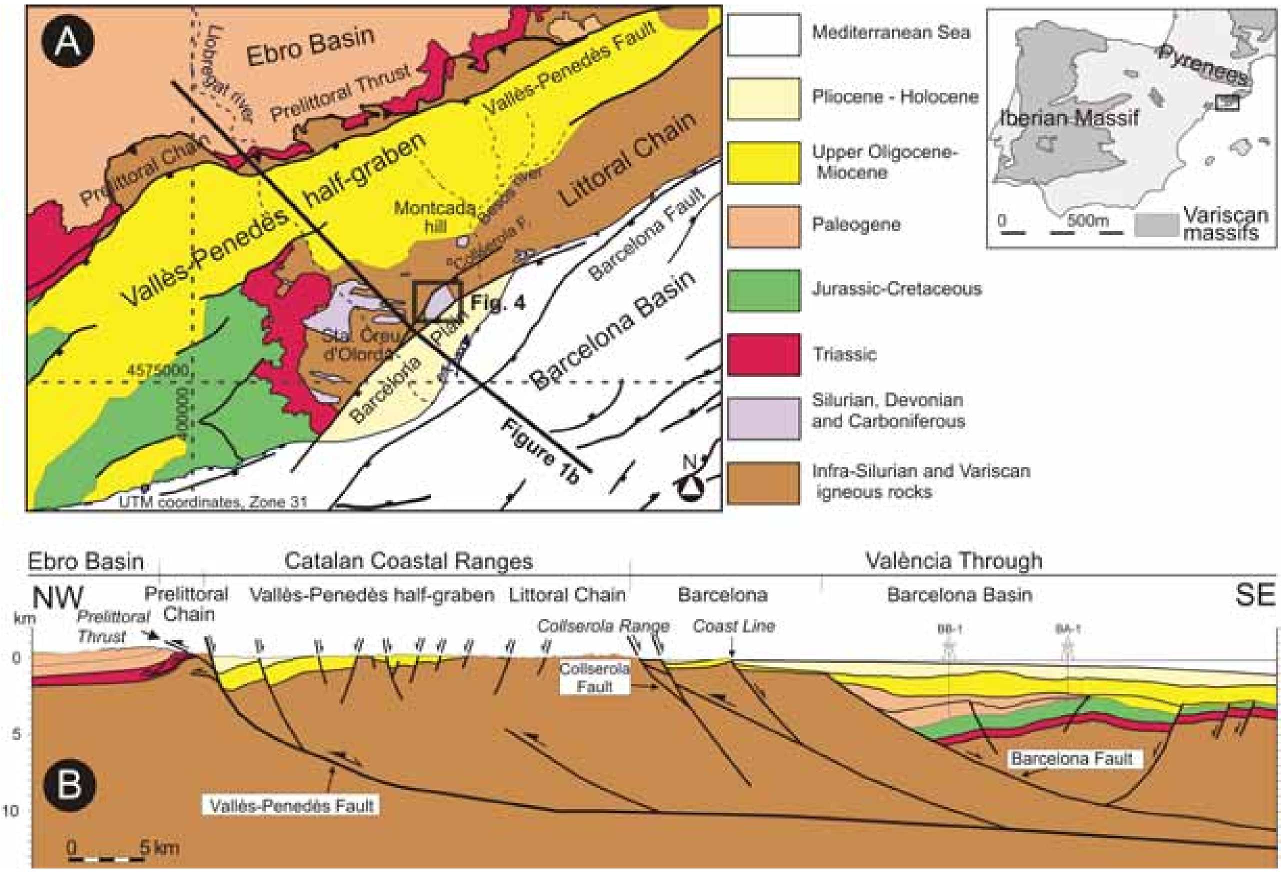


Fig. 1.- a) Simplified geological map of the Catalan Coastal Ranges between the Besòs and Llobregat rivers and adjacent areas; b) Cross section of the Catalan Coastal Ranges and the western margin of the València Trough, after Gaspar-Escribano *et al.* (2004) modified.

Fig. 1.- a) Esquema geológico de las Cadenas Costeras Catalanas entre los ríos Besòs y Llobregat y áreas adyacentes; b) Corte geológico de las Cadenas Costeras Catalanas y del margen oeste del Golfo de Valencia, a partir de Gaspar-Escribano *et al.* (2004) modificado.

Some of the major extensional faults are the result of the negative inversion of earlier contractional faults (Fontboté, 1954). These contractional faults constitute a thrust system that developed during the Paleogene in the context of intraplate compressional tectonics related to the Pyrenean orogeny. This thrust system uplifted the Catalan Coastal Ranges and part of the València Trough. In its turn, Paleogene thrusts inverted major Mesozoic extensional faults at the western edge of the Tethys (Roca, 1994). They are well represented in the Prelittoral Chain, where the Variscan basement overthrusts the Paleogene synorogenic deposits of the Ebro Basin (Fig. 1). It was in this region that the negative inversion of these thrusts was first described (Fontboté, 1954).

The Paleogene uplift of the Catalan Coastal Ranges led to the erosion of the Mesozoic cover and part of the Variscan basement, the resulting debris being deposited in the Ebro Basin. This erosion continued during the Neogene as a result of the footwall uplift of the main extensional faults (Gaspar-Escribano *et al.*, 2004). As a consequence, pre-Variscan Paleozoic rocks and Carboniferous/Permian intrusives (Solé *et al.*, 1998, 2002) crop out in the Littoral and Prelittoral Chains. The horst that forms the Littoral Chain plunges towards the SW in such a way that the Mesozoic cover (Triassic to Cretaceous) is extensively represented southwest of the river Llobregat.

Upper Paleozoic rocks are well preserved in small outcrops at Santa Creu d'Olorda, Montcada hill (Julivert and Durán, 1990a, 1990b) and in the hills of Barcelona. These last hills, the subject of this paper, constitute a small block located in the hangingwall of the Collserola fault, which bounds the Littoral Chain to the SE (Fig. 1). They are separated from the Littoral Plain, here termed Barcelona Plain, by another fault. The hills of Barcelona are mainly made up of an Upper Ordovician to Carboniferous succession. Small outcrops of Lower Triassic rocks (Buntsandstein) constitute the only remnants of the Mesozoic cover in these hills.

The Barcelona Plain is mainly covered by Pleistocene alluvial fans and Holocene near-shore and shore deposits

(Riba and Colombo, 2009). The lower Quaternary deposits overlie the Pliocene series, which is formed by a regressive sequence composed of marine blue marls followed by sands and marls associated with gravel lenses that pass progressively to the lower Quaternary sediments. The only elevations in the plain (Montjuïc hill and Cathedral hill) are constituted by Upper Miocene deltaic units (Gómez-Gras *et al.*, 2001), which are separated from the Pliocene blue marls by the Messinian unconformity. The Barcelona fault bounds the Barcelona Plain to the SE and separates it from the Barcelona Basin (Fig. 1). This basin is an off-shore half-graben filled with a roughly continuous sequence of Lower Oligocene to Present sediments overlying Mesozoic deposits (Roca *et al.*, 1999).

3. Earlier work and methodology

3.1. Earlier work

As stated above, few geological data about Barcelona are available. Almera (1891-1900) published the first geological map (1:40000) and the stratigraphic column of the city. Vaquer (1972) mapped part of the Collserola Range (Littoral Range at the Barcelona transverse), Gil Ibarguchi and Julivert (1988) studied the metamorphic aureole of Barcelona granodiorite west of Barcelona in the Collserola Range, and García-López *et al.*, (1990) described the stratigraphy of the Silurian and Devonian at Santa Creu d'Olorda. The stratigraphy and main structural features of the Variscan rocks of the Catalan Coastal Ranges were reported by Julivert and Durán (1990a, b). Detailed studies of some areas in the city, such as the La Muntanya Pelada and La Rovira hills, were carried out by Vidal Font (1974) and Batlle (1975) at the time of the construction of the tunnel through the La Rovira hill. Given the presence of Triassic rocks involved in thrusts affecting the upper Paleozoic rocks, Cabrera and Santanach (1979) pointed out their Alpine age. Ventayol *et al.*, (2000) compiled the available information and edited a synthetic map of Barcelona (1:25000).

3.2. Data acquisition

The data used to construct the geological map presented here mainly come from unpublished geological information compiled over fifty years. Riba (1949) obtained his degree dissertation on the study of the geology of the hills of Barcelona after exhaustive field work between 1948 and 1949. Although this dissertation is unavailable, Riba provided us with all the notes and maps made during field work, and with a draft of his thesis containing hand-written notes. The comparison of Riba's field descriptions with those of the remaining outcrops enabled us to determine diagnostic criteria for stratigraphic units and to construct the maps of areas that are covered by buildings today. Cabrera and Santanach also furnished field data obtained from 1970 to 1980. Most data from these unpublished field notes are unique given that most of the outcrops have disappeared.

In order to complement the data collected for this study, we conducted fieldwork in the hills and on selected outcrops along the trace of the future Line 9 of the underground railway. We also examined two circular outcrops (22 m in diameter, 15 and 50 m depth) located at the future underground stations, and analysed a series of 60 boreholes along the future tunnel of this underground line.

3.3. Methodology

All the available surface and subsurface data were georeferenced in order to accurately project the data onto cross-sectional planes and construct 3D geological models of selected areas, mainly near the trace of the new underground line (Fernández *et al.*, 2004, 2009). A 3D methodological approach is fundamental when dealing with well data acquired along linear constructions in urban areas since the trace of Line 9 of the Barcelona underground is sinuous, not unlike those of other underground lines. Moreover, the recognition wells were not placed exactly along the trace of the tunnel given that they were drilled at available sites such as crossroads. Such a distribution of wells avoids the use of a simple projection (with a vector that is horizontal and perpendicular to the tunnel trace) of the well data onto a vertical plane following the trace tunnel. This procedure has been the source of grave errors in the geological interpretation of well data in Barcelona, especially in the areas where wells have been aligned subparallel to the main structures. Structural analysis of surface data was performed with the aim of defining projection vectors and the appropriate integration of surface and subsurface data. The huge cylindrical outcrops of the stations and the nearby surface outcrops enabled us to define the 3D attitude of major structural elements, such as the Neogene extensional faults affecting the Variscan rocks. The 3D methodological approach followed was not only the basis for the integration of the surface and subsurface data but was also the basis for the construction of the subcrop geological map below the Quaternary sediments at the southern edge of the hills. This approach was also used to construct precise geological cross-sections.

4. Materials

The materials of the Barcelona hills can be divided into four groups: 1) pre-Variscan series constituted by Upper Ordovician to synorogenic Carboniferous materials; 2) Variscan granodiorites and associated igneous rocks; 3) post-Variscan rocks corresponding to Triassic red beds, and 4) Quaternary alluvial sediments lying on top (Fig. 2).

4.1. The pre-Variscan sequence

The oldest recognized rocks form a heterogeneous sequence of alternating decimetric to metric thick layers of brown shales, quartzites and greywackes. Graphite rich shales abound in the upper part of the succession (Fig. 2). Although its thickness is difficult to determine, a minimum value around 200 m can be proposed. The sequence exhibits marked lateral variations (Fig. 3). In the easternmost area, quartzites and greywackes predominate interbedded with brown or black shales, and some volcanic bodies can be found in the lowermost part of the sequence. In contrast, in the central area, shales predominate in the lower part of the sequence whereas limestones, volcanic rocks and quartzites are abundant in its upper part. In the westernmost area the sequence is mainly made up of brown shales with discontinuous grey layers of graphite rich shales especially abundant towards the upper part of the succession. Brachiopod fauna has been reported (Barrois, 1893; Almera, 1898; Faura i Sans 1913 and Riba,

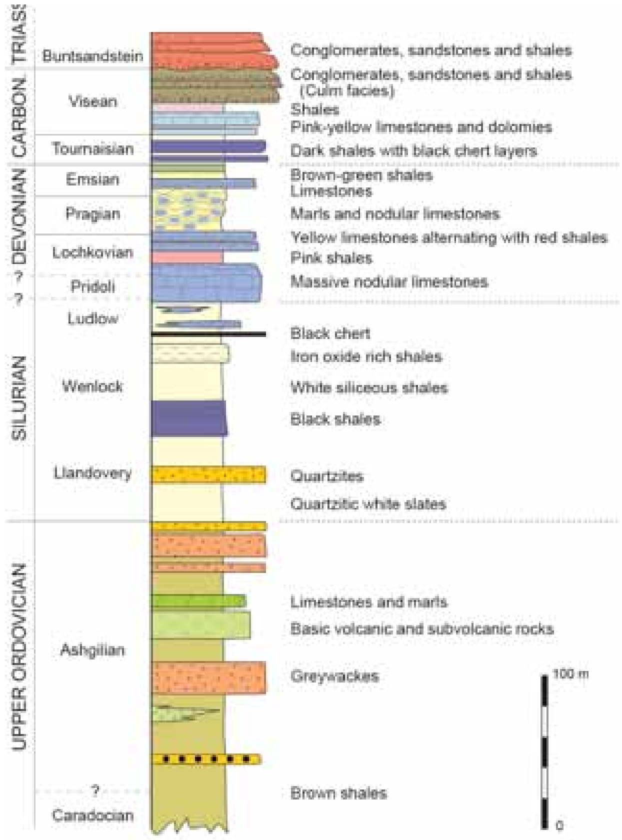


Fig. 2.- Synoptic stratigraphic column of the Paleozoic and Mesozoic rocks of the hills of Barcelona. After Riba (1949), Julivert *et al.*, (1985), García-López *et al.*, (1990) and our own data.

Fig. 2.- Columna estratigráfica sintética de los materiales paleozoicos y mesozoicos de las colinas de Barcelona. A partir de Riba (1949), Julivert *et al.*, (1985), García-López *et al.*, (1990) y datos propios.

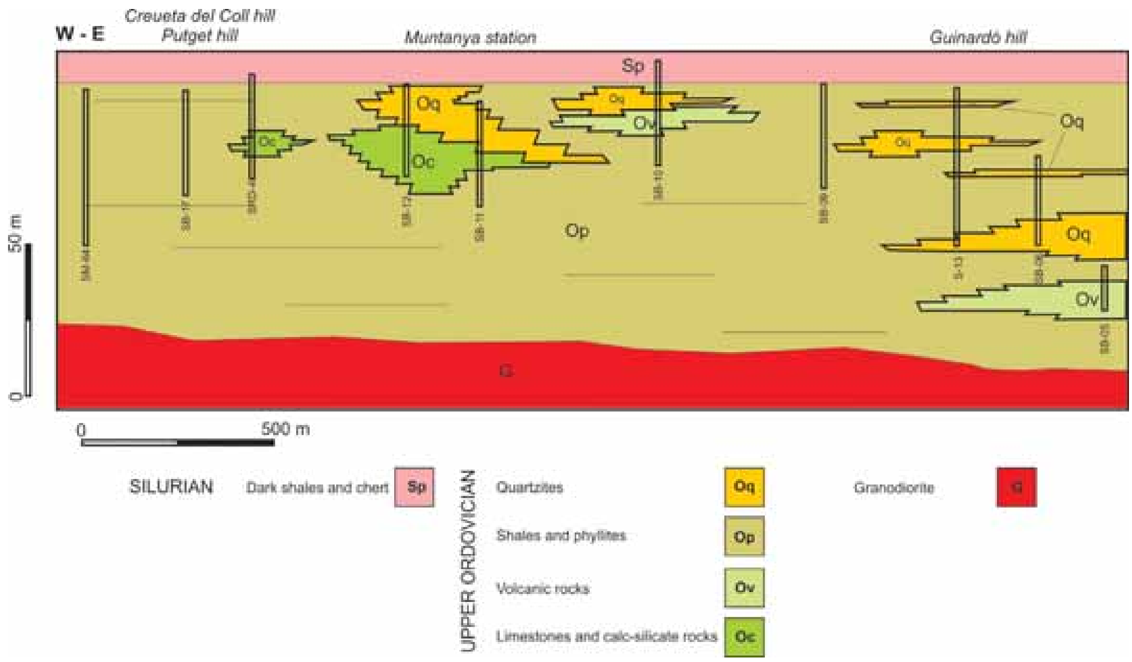


Fig. 3.- Sketch showing the lateral variations of the pre-Silurian succession in the hills of Barcelona and the location of some of the analysed boreholes.

Fig.3.- Esquema que muestra las variaciones laterales de la sucesión pre-silúrica de las colinas de Barcelona con la localización de algunos de los sondeos utilizados.

1949) at different localities in Barcelona (Gràcia, Turó de la Rovira, Muntanya Pelada, Parc Güell), which allows us to assign this series to the Caradoc. However, more recent works have attributed it to the Ashgill, e.g. Meléndez and Chauvel (1979), who studied the cystoids in the hills of Barcelona and Gil Ibarguchi and Julivert (1988), who correlated the series of the Collserola Range with others of the Catalan Coastal Ranges. Durán *et al.*, (1984) attributed an Ashgillian or younger age to this series because of the absence of acidic volcanic rocks interbedded in the series.

These different sequences are overlain by black shales in the study area (Fig. 3). These black shales are interbedded with thin (1-5 cm) and discontinuous layers of black chert. A number of graptolite genuses were found by Almera (1891), Schriel (1929), and Riba (1949), who attributed the black series to the Silurian (Llandovery, Wenlock and Ludlow). The black shales are sulphur-rich (mainly pyrite) and, when weathered, they turn white owing to secondary calcium, magnesium and aluminum sulphates with multi-coloured streaks (red, brown and yellow) produced by the iron sulphates and hydroxides. Near the top of the black series, limestone layers alternate with the shales and become thicker and more abundant upwards, forming a massive nodular grey to bluish stylolitized limestone (Fig. 2). This massive limestone (La Creu Fomation, García López *et al.*, 1990) is present throughout the Catalan Coastal Ranges and has yielded a Pridolian to Lower Devonian (Lochkovian) age according to the characteristic fossils encountered in the neighbouring area of Santa Creu d'Olorda (Almera, 1891; Walliser, 1964, in García-López *et al.*, 1990). Locally at the Creueta del Coll, Parc Güell, Putget and Turó de la Rovira hills, the limestones are nodular with red shale partings and beds giving a *griotte* aspect to the rock. They may be partially dolomitized, rubbing out the previous bedding. The dolomites are rich in pyrite, chalcopyrite, siderite and iron oxide and they present distinctive karst dissolution features. On top of these massive limestones lies a varied lithological unit known as the Olorda Formation (García-López *et al.*, 1990). This consists of a pink shale layer followed by alternating yellow limestones and red shales in layers between 5 and 10 cm thick. A series of marls and nodular yellow limestones with discontinuous shale layers crop out over this alternance. The marls contain orthoceras (Riba, 1949) and have been attributed to the Pragian (García-López *et al.*, 1990). The top of the Olorda Formation is made up of a thin layer of well stratified limestones followed by brown-green shales containing brachiopoda. The limestones and shales have been assigned to the Emsian (see age discussion in García-López *et al.*, 1990). Between the Devonian and the Carboniferous is a gap in the series due to the absence of Mid to Late Devonian fauna (Julivert *et al.*, 1985; Julivert and Durán, 1990a).

Brown-green shales are overlain by dark shales alternating with 15 to 20 cm thick layers of radiolarian black chert. This alternance marks the bottom of the pre-Variscan Carboniferous and constitutes a reference level attributed to the Tournaisian (Julivert and Durán, 1990a; Anadón *et al.*, 1985). It is followed by a red shale layer intercalated with pink-yellow carbonate layers. These limestones have yielded Visean fauna in the neighbouring Papiol area (Anadón *et al.*, 1985; Julivert and Durán, 1990a). A terrigenous succession made up of shales and sandstones with microconglomerate layers form the synorogenic Carboniferous succession (Culm facies), which is recognized in the entire European Variscan realm. In the absence of detailed biostratigraphical data, a Visean age has been assigned to the Culm sequence in most of the Catalan Coastal Range (Julivert and Durán, 1990a).

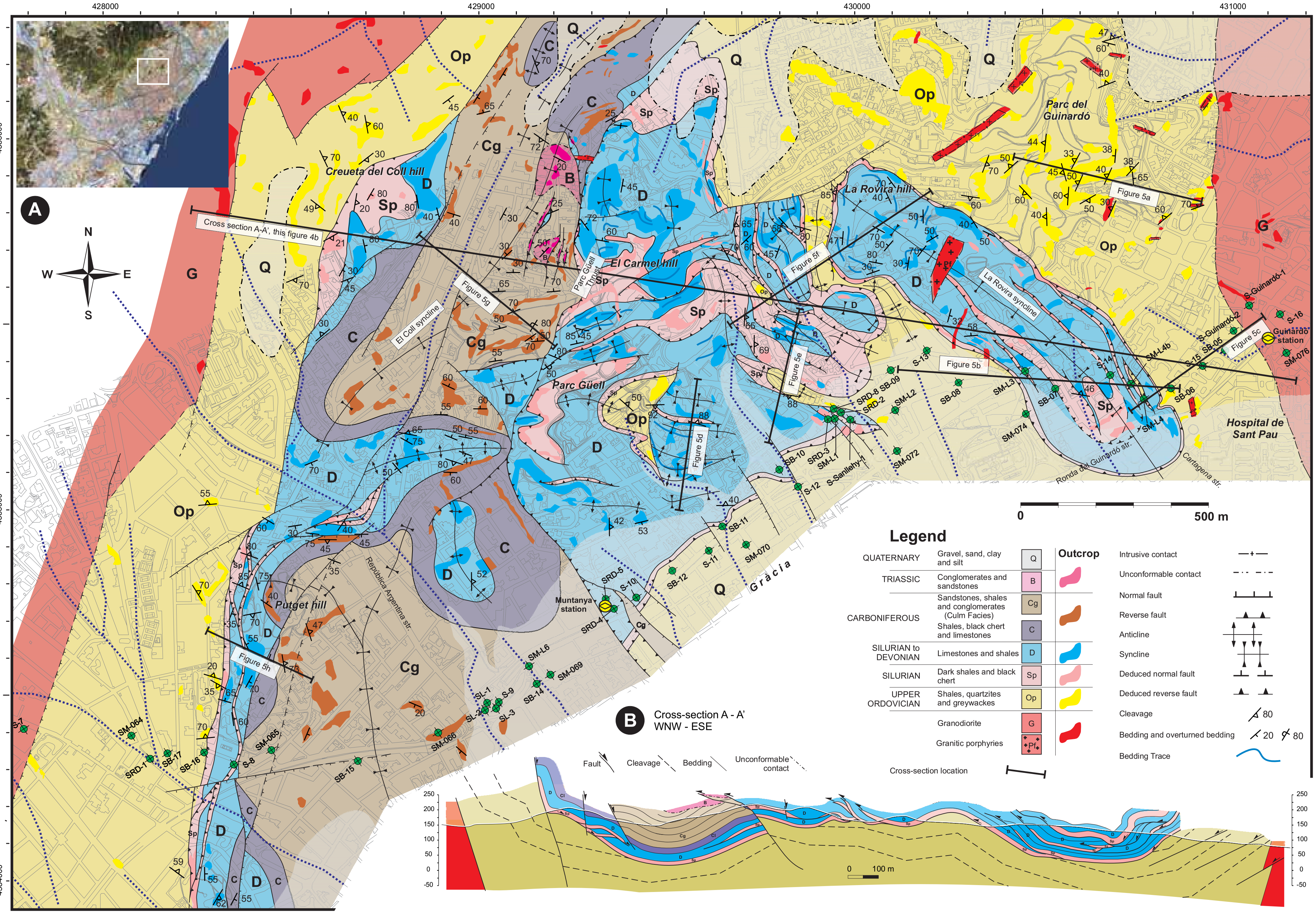
4.2. Metamorphic and igneous rocks

Pre-Variscan rocks are affected by regional metamorphism. Metamorphic grade increases towards the lower stratigraphic levels and ranges from very low-grade in the Carboniferous, Devonian and Silurian rocks to low-grade (greenschist facies) in Upper Ordovician rocks (Sebastián *et al.*, 1990). Upper Ordovician and Silurian rocks show a slaty cleavage defined by the parallel arrangement of muscovite and chlorite. This cleavage was formed synchronously with the main Variscan deformation phase (Julivert and Durán, 1990b).

The main Variscan intrusive rock is the Barcelona granodiorite (Fig. 4a). This belongs to a discontinuous 200 km long batholith that crops out along the Catalan Coastal Range (Enrique, 1990). It is composed of plagioclase,

Fig. 4.- (opposite page).- a) Geological map of the Barcelona hills showing cross section and borehole locations. After unpublished field notes of Riba and Cabrera, and field work conducted by the authors. b) Cross-section of the studied area. Note the variation in the transport direction of the thrust along the section. This variation is due to the fact that the section is perpendicular to the axis of the synclinorium and oblique to the transport direction of the thrusts which are folded by the synclinorium.

Fig. 4.- (página opuesta).- Mapa geológico de las colinas de Barcelona con la localización de los cortes geológicos y sondeos. A partir de datos inéditos de Riba y Cabrera y de datos recolectados por los autores. b) Corte geológico de la zona estudiada. Obsérvese la variación de la dirección de transporte de los cabalgamientos a lo largo del corte. Esta variación es debida a que el corte es perpendicular al eje del sinclinorio y oblicuo a la dirección de transporte de los cabalgamientos plegados por éste.


A
B
Cross-section A - A'
WNW - ESE
Legend
QUATERNARY
Gravel, sand, clay and silt
TRIASSIC
Conglomerates and sandstones
CARBONIFEROUS
Sandstones, shales and conglomerates (Culm Facies)
Shales, black chert and limestones
SILURIAN to DEVONIAN
Limestones and shales
SILURIAN
Dark shales and black chert
UPPER ORDOVICIAN
Shales, quartzites and greywackes
Granodiorite
Granitic porphyries
Outcrop
Intrusive contact
Unconformable contact
Normal fault
Reverse fault
Anticline
Syncline
Deduced normal fault
Deduced reverse fault
Cleavage
Bedding and overturned bedding
Bedding Trace
Cross-section location
Fault
Cleavage
Bedding
Unconformable contact
0
500 m
100 m
Cross section A-A', this figure 4b
Creueta del Coll hill
El Carmel hill
La Rovira hill
Parc del Guinardó
Parc Güell
Parc Güell Thrust
El Coll syncline
La Rovira syncline
Putget hill
Hospital de Sant Pau
Muntanya station
Guinardó station
República Argentina str.
Ronda del Guinardó str.
Cartagena str.
Gràcia
Figure 5a
Figure 5b
Figure 5c
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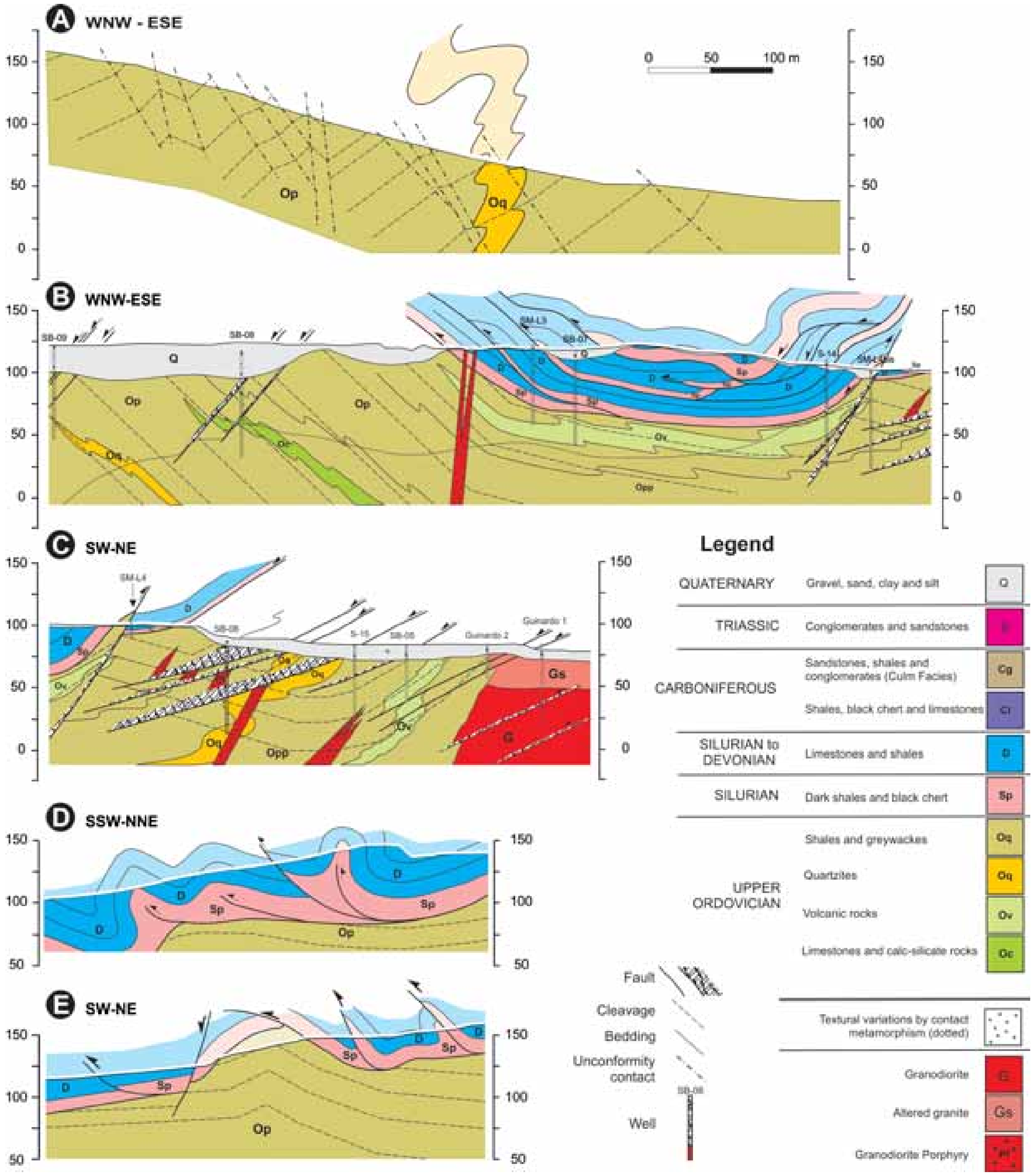

Fig. 5.- Cross sections of the Barcelona hills: a) El Guinardó hill; b) and c) El turó de la Rovira hill; d), e) and f) Cross-sections of the southern slope of the El Carmel hill; g) Cross section of the El Coll syncline and h) Cross section of the El Putget hill. See figure 4 for location.

Fig. 5.- Cortes geológicos de las colinas de Barcelona: a) El Guinardó; b) y c) El turó de la Rovira; d), e) y f) Cortes de la vertiente sur del Carmel; g) Corte del sinclinal del Coll y h) Corte del turó del Putget. Situación en la figura 4.

quartz, orthoclase, biotite and, locally, hornblende. The rock has a granular texture, with idiomorphic zoned plagioclase, biotite and hornblende. Pegmatites and aplites crop out in small dykes (1-4 m in width) or in irregular masses at the top of the granodiorite intrusion near the contact with the country rock. Contacts of the granodiorite with the country rock are sharp and a contact metamorphic aureole occurs in the host-rock surrounding the granodiorite up to 3 km from the contact (Vaquer, 1972; Gil Ibarguchi and Julivert, 1988). Contact metamorphic minerals overgrow the regional ones, thus indicating that the granodiorite intruded subsequently. A NE-SW linear dyke swarm cuts the pre-Variscan rocks and the Barcelona granodiorite. The dykes range from metres to several hectometres in length and have a metric thickness. They are constituted by granodioritic to granitic porphyries composed of plagioclase, orthoclase, quartz and biotite phenocrysts in a microcrystalline quartz-feldspatic matrix.

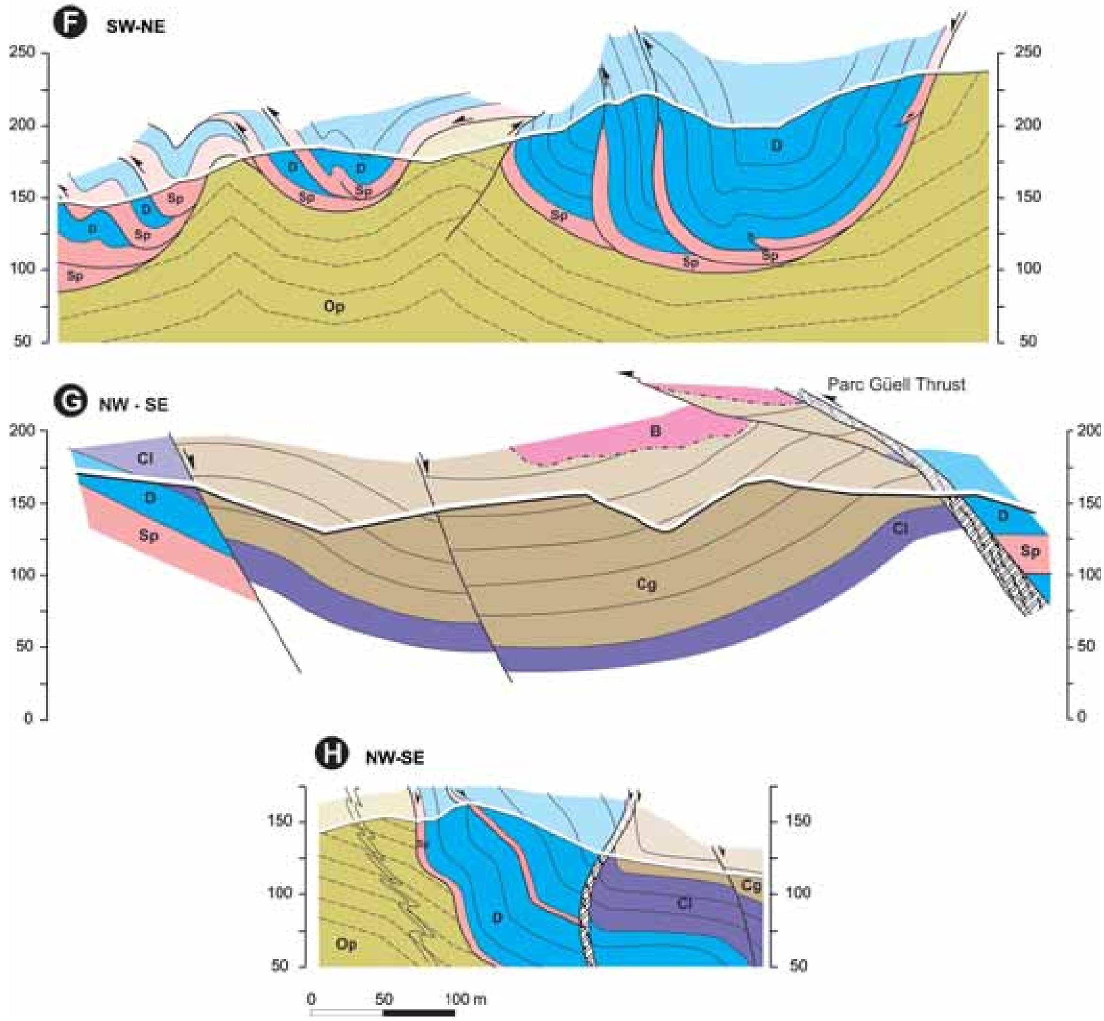

Fig. 5.- (Continuation)
Fig. 5.- (Continuación)

4.3. Post-Variscan rocks

Small outcrops of Triassic red beds of the Buntsandstein facies lie unconformably over the Culm sequence or are in fault contact with the Paleozoic basement (Almera, 1903; Riba, 1949; Cabrera and Santanach, 1979). They are made up of conglomerates, sandstones with cross-bedding and shales.

Quaternary alluvial detrital sediments are mainly composed of layers of red clay, yellow silt, and minor sand and gravel. The clays and silts are rich in calcium carbonate nodules which locally constitute 1m thick layers. The thickness of the alluvial detrital sediments is variable, attaining 20 m in the creeks.

5. Structure

The general structure of the hills of Barcelona is a NNE-SSW trending asymmetric synclinorium that plunges towards the SSW. The rock units involved, from outer to inner, are the Barcelona granodiorite; the Upper Ordovician shales and quartzites; the Silurian black shales; the Siluro-Devonian limestones and shales and the Carboniferous rocks that form the core of the synclinorium. Triassic red conglomerates and sandstones of Buntsandstein facies unconformably overlie the Carboniferous detrital rocks in the core of the synclinorium (Fig. 4a). The western limb of the synclinorium consists of a narrow strip of Silurian and Devonian rocks between the Ordovician and Carboniferous metasediments. In this limb, beds of Siluro-Devonian limestones and faults dip to the east at a high angle. In spite of the irregularities due to the superposition of folds, this limb roughly trends NNE-SSW. The eastern limb of the synclinorium trends NW-SE and its attitude is roughly subhorizontal, and consequently, the outcrop of Silurian and Devonian rocks is wide (Figs. 4a and 4b). The structure of the study area is characterized by the superposition of several sets of folds and different generations of faults that have resulted in an intricate map pattern (Fig. 4a). A description of the structures from the

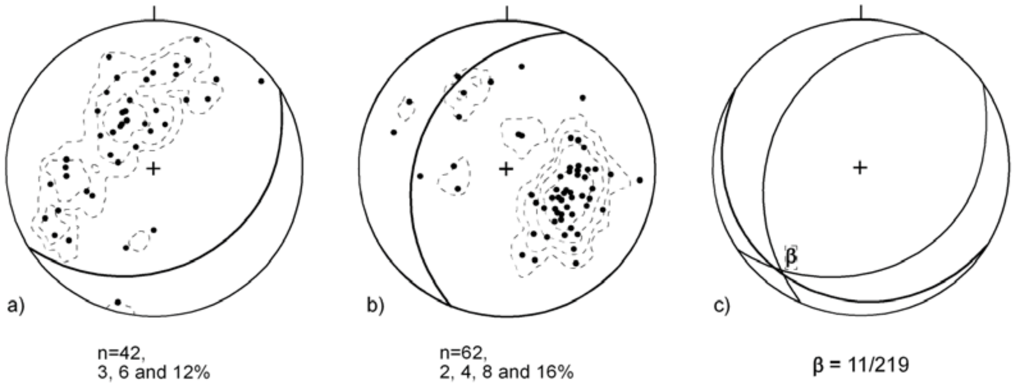

Fig. 6.- a) and b) Equal-area lower hemisphere stereoplots showing the foliation arrangement on the western and eastern limbs of the synclinorium; c) Attitude of the foliation of both limbs of the synclinorium after the rotation of the long limbs of the late folds. See text for explanation. "n" indicates the number of measurements.

Fig. 6.- a) y b) Estereogramas, en el hemisferio inferior, que muestran la disposición de la foliación en los flancos occidental y oriental del sinclinorio; c) Disposición de la foliación en ambos flancos del sinclinorio después de efectuar una rotación de los flancos largos de los pliegues tardíos. Explicación en el texto. "n" indica el número de medidas.

lower structural levels to the higher ones and from the older to the younger is given below.

Ordovician rocks show a pervasive foliation that is folded. Although syn-foliation folds are not visible in outcrop, they have been deduced from bedding/foliation relationships. They have been interpreted as tight to isoclinal folds verging southwards. Foliation exhibits a different attitude in both limbs of the synclinorium. In the northeasternmost outcrops of the eastern limb, foliation of the Ordovician rocks dips moderately to the NW whereas bedding shows a subvertical attitude (Fig. 5a, 6a). Late folds, open to tight, with steep axial surfaces affect the foliation. In the western limb of the synclinorium, foliation shows a different attitude, dipping moderately mainly to the SE, but also to the NE (Fig. 6). The former orientation would correspond to the long limb of the late folds and the latter to the short limbs. If a rotation of the long limbs of these late folds were performed to unfold the synclinorium, the foliation of both limbs of the synclinorium would acquire a new attitude, gently dipping to the SW (Fig. 6a). This suggests that the synclinorium is younger than the late folds.

Above the Ordovician rocks, the Silurian, Devonian and Carboniferous sediments show a different tectonic style. This style is characterized by thrusts and folds some of which are fault-related folds whereas others post-date thrusting. Bedding is the reference surface and cleavage is irregularly developed, mainly in the incompetent rocks of the sedimentary succession. Thrusts form an imbricate fan system with numerous imbrications of Silurian black shales and Siluro-Devonian limestones (Figs. 4a and 5b). Thrusts are directed towards the S and SW according to the observed fault/bedding cutting relationships. The floor thrust of the system is detached at the bottom of the Silurian black shales (Figs. 5c, 5d, 5d, and 5f). Folds affecting Silurian and Siluro-Devonian beds show different trends depicting a complex pattern (Fig. 4a).

Some of the NW-SE to N-S oriented folds affect the thrusts as well as their basal detachment (Figs. 5d, 5e, and 5f), and are therefore interpreted as also affecting the foliation and the bedding of the Ordovician. The detailed structure of the easternmost syncline, the La Rovira syncline, involving both the imbricated Silurian and Devonian rocks and the Ordovician rocks, is well constrained because it was drilled during the construction of the La Rovira road tunnel (Fig. 5b). In this location a small number of granodiorite dykes intrude into the folded Silurian and Siluro-Devonian limestones and the Ordovician rocks, crossing the basal detachment. The La Rovira syncline has a NW-SE trend and extends along strike for more than one kilometre.

A system of E-W trending folds is clearly visible in the central part of the mapped area in both limbs of the synclinorium (Fig. 4a). These folds also affect the basal detachment and are superimposed on the E-W to NW-SE trending folds related to the thrust ramps of the imbricates (Figs. 4a, 5d, 5e, and 5f).

The Carboniferous rocks cropping out in the core of the synclinorium show a complex structure constituted by two left stepped en échelon synclines separated by one of the aforementioned E-W anticlines (Fig. 4a). Devonian rocks crop out in the core of this anticline across the hinge zone of the synclinorium. Triassic red-beds crop out locally in the core of the northern syncline. The bedding of the biggest Triassic outcrop dips slightly to the SSW as does the fold axis of the synclinorium, whereas the bedding of the Carboniferous rocks below has a different orientation. This is interpreted as the folded post-Variscan unconformity.

A major thrust, termed the Parc Güell thrust, is observed in the middle of the study area along the western edge of the eastern limb of the synclinorium (Fig. 4a). It trends NE-SW in the north, NNE-SSW in the middle and NW-SE in the south. This fault dips towards the ESE or is subvertical and throws up the eastern block with the result that, in most cases, the rocks of the eastern limb thrust over the Carboniferous rocks in the core of the synclinorium (Fig. 5g). The Parc Güell thrust crops out at the western entrance of the Güell Park where a fault rock zone with breccias and gouges up to 15 m thick is visible. In this zone the attitude of the cleavage and small-scale folds indicates the reactivation of the Parc Güell thrust by extensional faults. The Parc Güell thrust truncates all the previously described structures: the thrust imbricates composed of Silurian-Devonian rocks and their floor detachment, the thrust related folds, and the folds post-dating the floor detachment. Buntsandstein rocks are cut in the footwall of the Parc Güell thrust and are involved in an imbricate fan of thrusts together with the Carboniferous rocks (Figs. 4a and 5g). The NW-SE segment of the Parc Güell thrust was characterized thanks to the data supplied by the wells drilled for the future Line 9 of the Barcelona underground (Fig. 4a). These wells, drilled in the area of the future Muntanya underground station, penetrated few metres into the Devonian and Silurian sediments and the Ordovician rocks below. They also traversed fault gouges and Carboniferous sandstones and shales. The position of the wells in relation to the outcropping trace of the thrust provides evidence of its subvertical attitude. This dip together with the lenses of Carboniferous sediments between older sediments suggests that the NW-SE segment of the Parc Güell thrust could be a lateral to oblique ramp with a significant strike-slip component of displacement (Fig. 4a).

Apart from the thrust imbricates and the Parc Güell thrust, other faults (contractional, extensional, strike-slip or unknown) affect the entire series. Most of these faults have developed a fault rock zone of considerable thickness as observed in many outcrops and in the cores of the wells.

In the eastern part of the study area, a hole 25 m in diameter and several tens of metres in depth drilled for the construction of the future Guinardó underground station of Line 9 revealed the existence of a system of low angle normal faults affecting the granodiorite. These faults form fault rocks including gouges up to 20 cm thick which show a transport direction towards the south (between SSE and SSW). They trend from ENE-WSW to SE-NW and dip towards the South (Fig. 7). The low angle normal faults truncate two systems of high angle faults dipping towards the NW and NNE. The older faults, involving granodiorite dykes, show a fabric defined by foliated cataclastic rocks and quartz veins and give rise to the retrogradation of the granodiorite to chlorite-muscovite assemblages. Low angle normal faults were also observed in the impermanent outcrops of Ordovician rocks as a result of the construction of the new Hospital de Sant Pau and at the intersection of the Ronda del Guinardó and Cartagena streets. In this location, these faults partially reactivated the basal detachment at the bottom of the Silurian black shales.

High angle normal faults crosscut the basal detachment in the eastern limb of the synclinorium. A set of NW-SE trending high angle normal faults displace the detachment in the southeastern part of the mapped area as deduced from the information supplied by the high density net of wells (Fig. 4a). The NE-SW trending normal faults cut the Silurian-Devonian imbricates and separate them from the Ordovician rocks to the North. Both fault systems have a morphological expression when the digital elevation model is analysed. The data available did not allow us to determine the relationship between these high angle normal faults and the aforementioned low angle ones.

In the western limb of the synclinorium, normal faults, approximately parallel to the trend of the limb, are superimposed on the imbricate structure of Silurian and Devonian units. The normal faults have narrowed and thinned the limb because of the subtraction of rock units. As a result, these faults place Ordovician rocks in contact with Devonian limestones, and Silurian black shales in contact with sediments of the Culm facies (Figs. 4a and 5h). In the northernmost part of this area the whole imbricate structure has been subtracted and the Ordovician rocks are separated from the Carboniferous detritics by a normal fault. In the República Argentina street, a preserved outcrop shows a fault rock zone, a few metres thick, involving Silurian shales, Devonian limestones and reddish shales of unknown age. In this outcrop, thrusts and strike slip faults are truncated and reactivated by low angle and high angle normal faults, with no single cross-cutting relationship between the normal faults.

A dextral en échelon array of normal faults oriented parallel to the synclinorium limb (NNE-SSW) constitutes the contact between the granodiorite and the Ordovician rocks (Fig. 4a).

6. Discussion

6.1. Variscan structures

The granodiorite and its related porphyry dykes cut the deformed Ordovician rocks as well as the detachment fault and the thrust fault imbricates constituted by Silu-

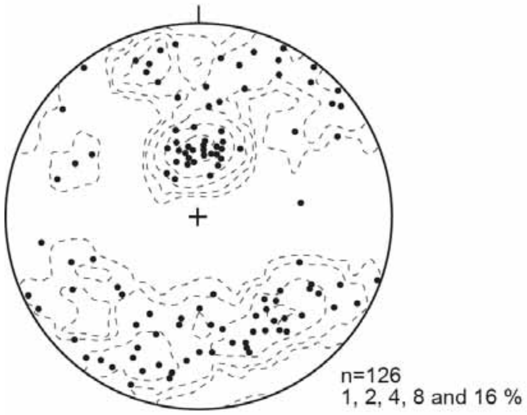

Fig 7.- Equal-area lower hemisphere stereoplot of the faults observed at the future Guinardó underground station. "n" indicates the number of measurements.
Fig. 7.- Estereograma, en el hemisferio inferior, de las fallas observadas en la futura estación del metro de Guinardó. "n" indica el número de medidas.

rian and Devonian units. Since the granodioritic batholith of the Catalan Coastal Range yielded an age close to the Carboniferous/Permian limit (Solé *et al.*, 1998, 2002), these structures should be Carboniferous in age and should correspond to the Variscan orogeny. The Variscan structure is therefore represented by the folding structure associated with pervasive foliation of the Ordovician rocks and by the South directed imbricates affecting Silurian and Devonian limestones detached above the Silurian black shales. A similar structural grain has been described in other areas of the Catalan Coastal Ranges, where south facing folds with an axial planar cleavage develop in the infra-Silurian rocks (Benet, 1990; Durán, 1990; Serra, 1990; Julivert and Durán, 1990b) whereas an imbricate stack repeats the Siluro-Devonian rocks (García-López *et al.*, 1990). This different signature of the main Variscan deformation in the infra- and the supra-Silurian rocks has also been documented in the Pyrenees (Guitard, 1967; Hartevelt, 1970; Santanach, 1972; Domingo *et al.*, 1988; Casas *et al.*, 1989; Poblet, 1991, and references therein).

Foliation in the Ordovician rocks of the mapped area shows an attitude different from that observed in the Collserola Range, where the main foliation dips to the NNE at moderate to high angles (Julivert and Durán, 1990b). This difference could be mainly the result of the Paleogene-Neogene folding and tilting events, which is discussed below. It should be pointed out that the effect of late Variscan folding cannot be ruled out. Unfortunately, the reduced extension of the Ordovician rocks in the hills studied and the small number of outcrops prevented the characterization of the folds affecting the main foliation.

The folds observed in the imbricates of Silurian and Devonian rocks could have different origins. Some of them could be Variscan thrust related folds whereas others affecting the basal detachment could be related to the late-Variscan folding phases and/or to the Paleogene Alpine compression.

The high angle faults described at the Guinardó underground station, which at present show NNE-SSW and NW-SE trends, are probably late Variscan in age since they are associated with granodiorite dykes and low temperature retrograde metamorphism.

6.2. Mesozoic and Cenozoic evolution

There are no age constraints for the low angle normal faults that truncate all the previously described Variscan structures. Nevertheless, some hypotheses may be advanced if we assume that these normal faults have a listric geometry. Should this be the case, low angle faults would represent deeper fault sections than high angle faults, implying that uplifting and erosion of the basement occurred before the formation of the high angle faults during the Neogene. According to the geological history of the region (Roca, 1994; Gaspar-Escribano *et al.*, 2004), erosion of the basement occurred during the Paleogene as a result of the topography that developed in response to the contractional tectonics. Thus, the low angle normal faults would represent deep parts of the Mesozoic normal faults that would subsequently be uplifted during the Alpine compression and preserved in the hangingwall blocks of the Neogene normal faults. Block rotation and uplift during Neogene extension would also have led to a decrease in the dip angle of older extensional faults. Alternatively, the low angle of the observed extensional faults could be the result of the reactivation of earlier low angle anisotropies or the result of the rotation during extensional deformation (domino faults). The former possibility must be ruled out because the granodiorite was deformed by the faults. In the latter case, these rotated domino faults would imply a significant amount of extension.

The general structure of the study area, which is characterized by the NNE-SSW trending synclinorium and the Parc Güell thrust, is the result of the Paleogene contractional deformation as evidenced by the Triassic rocks involved in both structures. Thus, these structures form part of the contractional system of the Catalan Coastal Ranges and probably developed during the Eocene, immediately before or synchronously with the Prelittoral thrust (Fig. 1). The synclinorium and the thrust follow approximately the same trend, varying from NW-SE in the south to NE-SW in the north, which differs from the regional trend of the Catalan Coastal Ranges near Barcelona (Fig. 1). Nevertheless, this trend is compatible with a NW-SE shortening or transport direction as evidenced by the thrusts of the Prelittoral Chain (Fig. 1), which is consistent with the documented regional N-S shortening in northeastern Iberia during the Paleogene (Guimerà, 1984). Another striking feature of the synclinorium is its vergence towards the SE (the interior of the chain), which suggests the existence of another contractional structure (either an antiform or a SE vergent thrust) further to the NW of the mapped area. If we considered the regional kinematics during the Paleogene contractional deformation, the NW-SE trending portion of the Parc Güell thrust would represent a lateral ramp with a left-lateral strike-slip movement. The verticalized Variscan thrusts and the detachment at the bottom of the Silurian shales in the western limb of the synclinorium could also have been reactivated obliquely to the shortening direction as left-lateral strike slip faults. This anomalous oblique to transverse trend of the contractional structures could be attributed to the reactivation of transfer faults of the Mesozoic extensional fault system. The left stepped en échelon folds observed in the hinge area of the synclinorium would be compatible with the left-lateral strike slip component of these faults. However, it may be proposed that the geometry of the folds results from the superposition of the synclinorium on previously developed E-W folds. Some of these folds are the E-W trending anticline cored with Devonian limestones between the stepped synclines of Carboniferous rocks and the anticlines cored by the Ordovician rocks cropping out between Devonian and Silurian sediments in the eastern limb (Fig. 4a). The age of these E-W trending folds is uncertain. They could be late Variscan or Paleogene in age given that they fold the basal detachment.

The high angle normal faults could be subsequent to the Alpine compression since they affect the subvertical western limb and the folded Upper Carboniferous core of the synclinorium. They could be Neogene in age and coeval with the formation of the extensional basins in the Catalan Coastal Ranges (Vallès-Penedès, Barcelona Plain, Barcelona basin, etc.). The different orientation of these faults would result from the earlier orientation of all the older structures. Thus, in the western limb of the synclinorium they predominantly show a NNE-SSW trending direction following the main anisotropies despite truncating previously developed faults and folds (Fig. 4a). Neogene extensional faults can show a low angle geometry locally if they reactivate earlier faults, such as the thrusts observed in the outcrop of the República Argentina street

7. Conclusions

The Upper Paleozoic rocks of the hills of Barcelona have been preserved owing to the combined effect of their general synclinorium disposition and their location on the hangingwall block of the Collserola fault, one of the high angle Neogene normal faults that separate the Littoral Chain from the Littoral Plain. Near Barcelona, the presence of the Upper Paleozoic rocks is scarce, and only the outcrops of Santa Creu d'Olorda and the Montcada hills remain. The internal structure of these Paleozoic rocks consists of an interference refold structure resulting from the superposition of Variscan and Paleogene folds. These folds have been deformed, rotated and truncated by different fault sets: late Variscan faults, Mesozoic extensional faults, Paleogene thrusts and strike-slip faults, and Neogene extensional faults. These faults may have changed their initial attitude by folding and tilting or may have already developed with different orientations because of the intricate pattern of previous mechanical anisotropies. As a result of the long structural evolution and the superposition of different fault systems, fault rock zones are fairly common in the hills of Barcelona. Wide fault rock zones have been observed in most of the preserved outcrops and drilled by many wells during exploratory campaigns for engineering works. They may range in thickness from few centimetres to hectometres and may have a strong impact not only on the stability of the terrain but also on other geological parameters such as hydrological systems.

Structural and geological analyses of the compiled surface and subsurface data reveal a complex structural evolution. These findings complement the regional geological knowledge and provide further insight into the tectonic history of the Catalan Coastal Ranges and the Neogene extensional basins. Our results highlight the importance of an ongoing geological survey of Barcelona given the impermanent nature of the outcrops and the unavailability of the subsurface data. Our findings also reinforce the need for an efficient management of the geological information in urban areas with a complex geology such as that of Barcelona. Furthermore, a better understanding of the subsurface geology of cities would have far reaching social and economic consequences.

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