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 Unpublished field notes from surveys carried out in the 1940s and in the early 1970s were crucial for drawing up this detailed map, which together with subsurface data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, mesozóicas, paleógenas y neógenas. En
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; Pereia 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.
some of the major extensional faults are the result of the negative inversion of earlier contractional faults (Fontboté, 1954). These contractual 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 (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. Vaque (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 Battle (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, 1949).
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 genera 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; Andón 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 (Andón 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,
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-feldspathic matrix.
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. 5.- (Continuation)
Fig. 5.- (Continuación)
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 Carboniferous rocks 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 imbrications (Figs. 4a, 5a, 5b, 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 dif-
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 subver-
tical 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 in-
dicates the reactivation of the Parc Güell thrust by exten-
sional faults. The Parc Güell thrust truncates all the previ-
ously 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 Carbon-
iferous 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 sedi-
ments 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 di-
ameter 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 an-
gle 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 ret-
rogradation of the granodiorite to chlorite-muscovite as-
semblages. Low angle normal faults were also observed
in the impermanent outcrops of Ordovician rocks as a re-
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 Sil-
urian 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 eleva-
tion 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 super-
imposed on the imbricate structure of Silurian and Devo-
nian units. The normal faults have narrowed and thinned
the limb because of the subtraction of rock units. As a re-
result, these faults place Ordovician rocks in contact with
Devonian limestones, and Silurian black shales in con-
tact 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 nor-
mal fault. In the República Argentina street, a preserved
outcrop shows a fault rock zone, a few metres thick, in-
volving 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 re-
lationship 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-
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
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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