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# Stratigraphy and petrology of the Miocene Montjuïc delta (Barcelona, Spain)

## Estratigrafía y petrología del delta mioceno de Montjuïc (Barcelona, España)

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## ABSTRACT

The Neogene rift in the Catalan Coastal Ranges, which is located in the NE part of the Eastern Iberian Margin, corresponds to a system of grabens formed at the north-western edge of the Valencia Trough. In the central part of the Catalan Coastal Ranges are the Vallès-Penedès half-graben in the onshore and the Barcelona half-graben in the offshore, which are separated by the Garraf and the Collserola-Montnegre horsts. Montjuïc hill is a tilted block, which is located to the S of the Barcelona city, between the Collserola-Montnegre horst and the Barcelona half-graben.

The Middle Miocene section of Montjuïc is constituted by an alternation of conglomerate, sandstone, mudstone and marlstone beds. The Montjuïc section was divided into four lithostratigraphic units from base to top: (1) The Morrot conglomerate and sandstone Unit, interpreted as delta plain deposits; (2) the Castell conglomerate, sandstone and mudstone Unit considered as proximal delta front deposits; (3) the Miramar marlstone Unit attributed to prodelta deposits; and (4) the Mirador conglomerate, sandstone and mudstone Unit interpreted as delta front deposits.

As regards the foraminifera association, the Miocene of Montjuïc may be attributed to the N9-N10 zones of Blow, indicating a Serravallian age. The palaeobotanical record suggests that the climate during the deposition of the Miocene of Montjuïc was temperate-warm and humid.

The sandstones and conglomerates are litharenites and lithorudites; they show variable amounts of matrix and are well cemented. The main framework components are quartz, rock fragments and K-feldspar. The Collserola mountain, where Palaeozoic materials crop out is the deduced source area. Montjuïc sandstones are characterized by an early silicic cementation consisting of K-feldspar overgrowths, quartz overgrowths, mesoquartz intergranular cement and a microquartz transformation of a former detrital matrix. A surface cementation is considered for these cements in the absence of compaction and the geological setting.

*Key words:* Stratigraphy. Sedimentology. Petrology. Litharenites. Serravallian. Barcelona.

## RESUMEN

La Cordillera Costero Catalana se sitúa en el NE del margen ibérico. Constituida por un sistema de semi-grabens neógenos, esta cordillera presenta un conjunto de fallas de zócalo con orientación NE-SW a ENE-SWS, las cuales actuaron como fallas compresivas durante la orogenia Alpina y, algunas de ellas, como fallas normales durante la extensión neógena (falla del Vallès-Penedès, falla de Camp). También aparece un conjunto de fallas direccionales con orientación NW-SE que, en algunos casos, afecta a las fallas NE-SW.

En la parte central de la Cordillera Costero Catalana se encuentran los semi-grabens del Vallès-Penedès y de Barcelona, separados por los horsts de Collserola-Montnegre y del Garraf. El sector de Montjuïc, al S de la ciudad de Barcelona, se sitúa entre el horst de Collserola-Montnegre y el semi-graben de Barcelona y constituye un pequeño bloque basculado adosado al graben de Barcelona.

La sucesión de Montjuïc tiene 200 m de potencia, está formada por una alternancia de lutitas, margas, areniscas y conglomerados y se subdivide en cuatro unidades litostratigráficas: (1) Areniscas y conglomerados del Morrot (84 m), que se interpretan como depósitos de llanura deltaica. (2) Lutitas, areniscas y conglomerados del Castell (100 m), organizados en 5 secuencias grano y estratocrecientes, y que corresponden a depósitos de frente deltaico proximal. (3) Margas de Miramar (15 m) con bivalvos, equinodermos, restos de plantas y bioturbaciones, que son interpretadas como depósitos pro-deltaicos. (4) Conglomerados, areniscas y lutitas del Mirador (20 m) con fósiles marinos, que corresponden a depósitos de frente deltaico.

Considerando las especies de foraminíferos planctónicos que se han encontrado, estos sedimentos pertenecen a las biozonas N9-N10 de Blow y su edad es Serravalliense. El registro paleobotánico sugiere un clima cálido-templado y humedo durante la sedimentación del Mioceno de Montjuïc.

Del análisis petrológico de las muestras se deduce que las areniscas de Montjuïc son textural y composicionalmente inmaduras, con un contenido en matriz variable (0-20%) y una gran cantidad de granos fácilmente alterables. El esqueleto está formado por cuarzo (35%), fragmentos de roca (20%) de una gran variedad litológica (granito, filita, aplita, pegmatita, radiolarita, ...) y feldespato potásico (9%). Se pueden clasificar como litoarenitas o como grauvacas líticas, dependiendo de su contenido en matriz, procedentes de la erosión de las formaciones paleozoicas del horst de Collserola. Las areniscas de Montjuïc se caracterizan por una cementación silícica temprana que comporta el desarrollo de sobrecrecimientos de feldespato potásico y cuarzo, cemento intergranular de mesocuarzo y la transformación de la matriz detrítica a microcuarzo. Debido a la cementación temprana los efectos de la compactación mecánica son muy limitados. Por otro lado, la situación de la montaña de Montjuïc dentro del contexto tectónico regional es la causante de que no se haya producido un notable enterramiento y, por lo tanto, la diagénesis es de carácter superficial.

*Palabras clave:* Estratigrafía. Sedimentología. Petrología. Litoarenitas. Serravalliense. Barcelona.

## INTRODUCTION

The geology of the Valencia Trough has been the focus of considerable attention in the last ten years and a number of papers on geophysics, geodynamic evolution, stratigraphy and other aspects have been published (Soler et al., 1983; Fontboté et al., 1990; Clavell and Berastegui, 1991; Banda and Santanach, 1992a; Roca and Guimerà, 1992; Roca and Desegaulx, 1992; Roca, 1994; Álvarez-de-Buergo and Meléndez, 1994) in addition to two monographs as special issues (Banda and Santanach, 1992b; Cabrera, 1994). Although the geology of the Vallès-Penedès depression has been well known for a number of years, new studies have been carried out (Agustí et al., 1985; Cabrera et al., 1991; Bartrina et al., 1992; Garcés et al., 1996; Cabrera and Calvet, 1996). The geology of the offshore Barcelona half-graben is also well known (Bartrina et al., 1992; Roca and Guimerà, 1992; Álvarez-de-Buergo and Meléndez, 1994; Bitzer et al., 1997; Sans et al., 1998).

By contrast, the link zone between the Collserola Mountain (western part of the Collserola-Montnegre

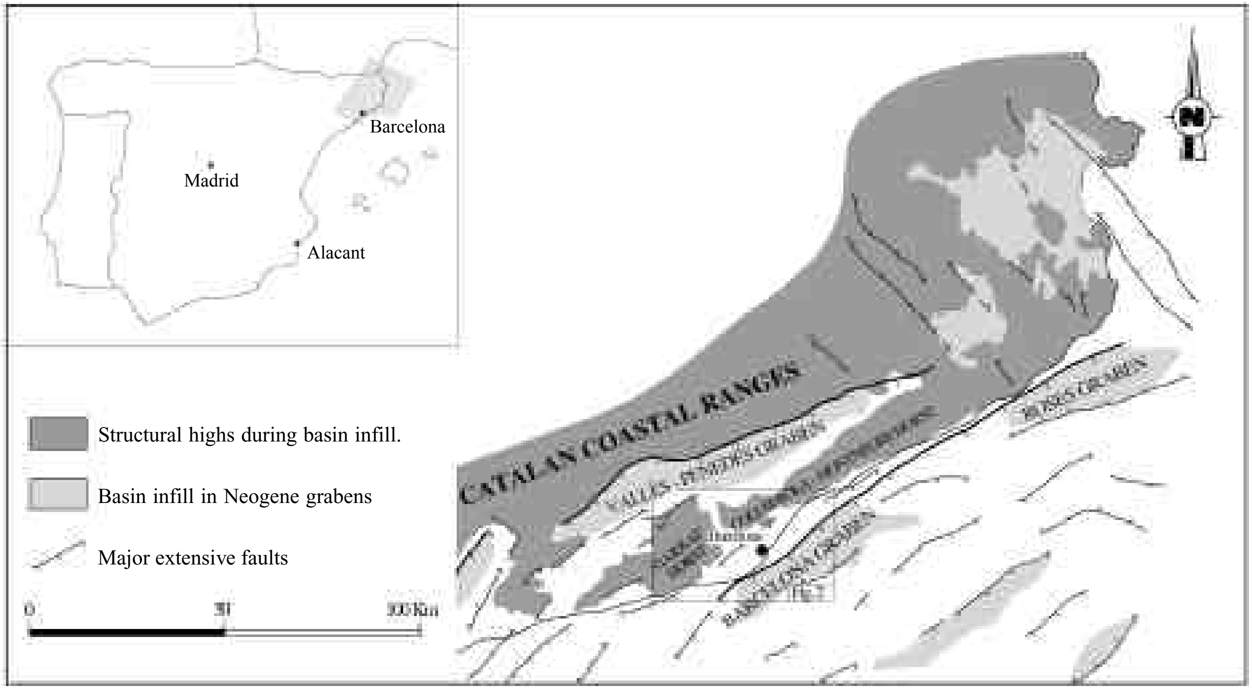


Figure 1. Structure of the catalan margin of the Valencia trough (modified from Bartrina et al., 1992).

Figura 1. Estructura del margen catalan del surco de Valencia (modificado de Bartrina et al., 1992).

horst) and the Barcelona half-graben has received scant attention. This paper is focused on the most important Miocene outcrop, the Montjuïc tilted block, which is situated in this link zone. In particular, this work deals with the lithostratigraphical, chronostratigraphical and petrological aspects of the Middle Miocene (Serravallian) deltaic deposits of the Montjuïc tilted block.

## GEOLOGICAL SETTING

The Neogene rift in the Catalan Coastal Ranges, which is located in the NE part of the Eastern Iberian Margin (Fig. 1), corresponds to a system of grabens along the north-western edge of the Valencia Trough (Roca and Guimerà, 1992; Roca, 1994). The structure of the range is dominated by longitudinal, near vertical basement faults which trend from NE-SW to ENE-WSW. During the Alpine Palaeogene compressive phase, these faults moved sinistrally with local transpression. In the course of the Neogene extension, some of these faults (Vallès-Penedès fault, Camp fault) were reactivated as normal faults trending ENE-WSW. There is another set of strike-slip faults trending NW-SE, such as the Llobregat fault, which in some places displaces the longitudinal faults.

The Catalan Coastal Ranges are composed of a Hercynian basement which is unconformably overlain by Mesozoic and Cenozoic cover rocks. The basement is made up of metamorphic Palaeozoic rocks and late Hercynian granites. The Mesozoic (Triassic, Jurassic and Cretaceous) sediments are basically calcareous rocks (limestones and dolomites) and locally siliciclastic and evaporitic rocks.

There are two neogene half-grabens in the central part of the Catalan Coastal Ranges: the Vallès-Penedès half-graben, which is onshore and the Barcelona half-graben, which is offshore. These are separated by the Garraf and the Collserola-Montnegre horsts (Fig. 1). Between the Collserola-Montnegre horst and the Barcelona half-graben there is a link zone where the Montjuïc tilted block is located.

### The Vallès-Penedès and Barcelona half-grabens

The Vallès-Penedès half-graben is approximately 100 km in length and between 10 and 14 km in width (Fontboté, 1954; Bartrina et al., 1992). The western margin of Vallès-Penedès half-graben is downfaulted 3.000 m by

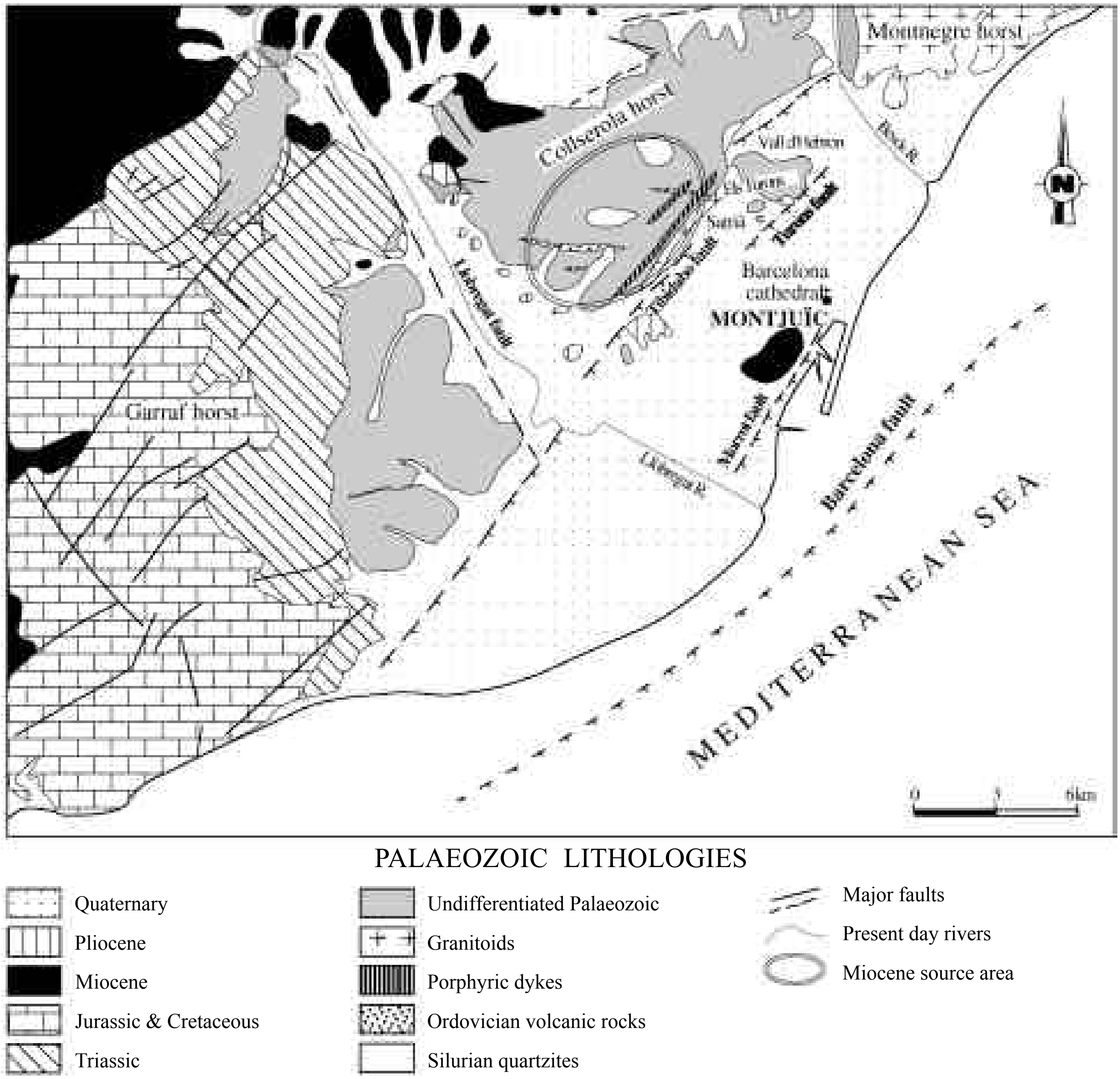


Figure 2. Geological map of the Collserola and Garraf horsts and Barcelona graben link zone.

Figura 2. Mapa geológico de los horsts de Garraf y Collserola y del Llano de Barcelona.

means of the Vallès-Penedès fault, which is oriented ENE-WSW to NE-SW (Fig. 1). The eastern margin, which is related to the Garraf and the Collserola-Montnegre horst, is faulted by normal hectometric faults oriented NE-SW.

The Miocene in the Vallès-Penedès half-graben has been divided into four lithostratigraphic complexes (Cabrera et al., 1991), which from base to top are: 1) Lower continental complexes Aquitanian?-Early Burdigalian in age; 2) Continental and transitional complexes with reefal carbonate platforms Langhian in age; 3) Continental and transitional complexes with mixed carbonate-siliciclastic shelves which are Lower Serravallian in age and 4) Upper continental complexes. This unit consists of thick red bed sequences deposited on alluvial fan environments. The age of this unit is Late Aragonian-Turolian (Garcés et al., 1996) and is equivalent to Middle-Upper Serravallian-Tortonian age in marine successions. The Messinian is represented by a regional erosive surface affecting the underlying deposits.

The Barcelona half-graben is up to 60 km long and 16 km wide. It is bounded in the NW by a SE dipping extensional listric fault with a displacement of up to 6 km and in the SE margin by several hectometric normal faults (Bartrina et al., 1992; Álvarez-de-Buergo and Meléndez, 1994).

The Barcelona half-graben filling consists of the following lithostratigraphic units (Bartrina et al., 1992): 1) Palaeogene-Aquitanian? units, which are constituted by red-bed sequences, evaporites and carbonate coal-bearing beds; 2) Early-Middle Miocene units (Aquitanian?-Early Serravallian) made up of basically terrigenous shelf to slope deposits and locally coralgal carbonate platforms; and 3) Late Serravallian-Tortonian units,which present marine shales and transitional sandstones.

### The Collserola-Montnegre and Garraf horsts

The Collserola-Montnegre and the Garraf horsts are oriented NE-SW. The two horsts are separated by the Llobregat fault, which is oriented NW-SE (Fig. 2).

The Collserola-Montnegre horst is up to 75 km long and up to 20 km wide (Figs. 1 and 2). The SW part of this horst is called the Collserola Mountain. The Collserola Mountain consists of palaeozoic rocks from Upper Ordovician to Carboniferous, and granitoids (Vaquer, 1973; Gil Ibarguchi and Julivert, 1988; Julivert and Durán, 1990). The Ordovician and Silurian materials, which are well represented in this area, present a wide variety of low-middle grade regional metamorphic rocks (slates, phyllites, quartzites) with interlayered volcanic rocks (Durán et al., 1984). The granitoids, which form part of an important calc-alkaline batholith (Enrique, 1990), are very homogeneous and are made up of quartz, plagioclase, K-feldspar and biotite (Vaquer, 1973). The granitoid intrusion affected the previous regional metamorphic materials up to 2 km from the contact, where there is also a wide variety of hornfels lithologies (San Miguel de la Cámara, 1929; Vaquer, 1973 and Gil Ibarguchi and Julivert, 1988). The granitoid batholith and the metamorphic rocks are cross-cut by porphyric, pegmatitic and aplitic dikes.

The Garraf horst, which is up to 50 km long and 20 km wide (Fig. 2), consists of Mesozoic materials (Triassic, Jurassic and chiefly Cretaceous limestones) and locally Palaeozoic materials (igneous and metamorphic rocks).

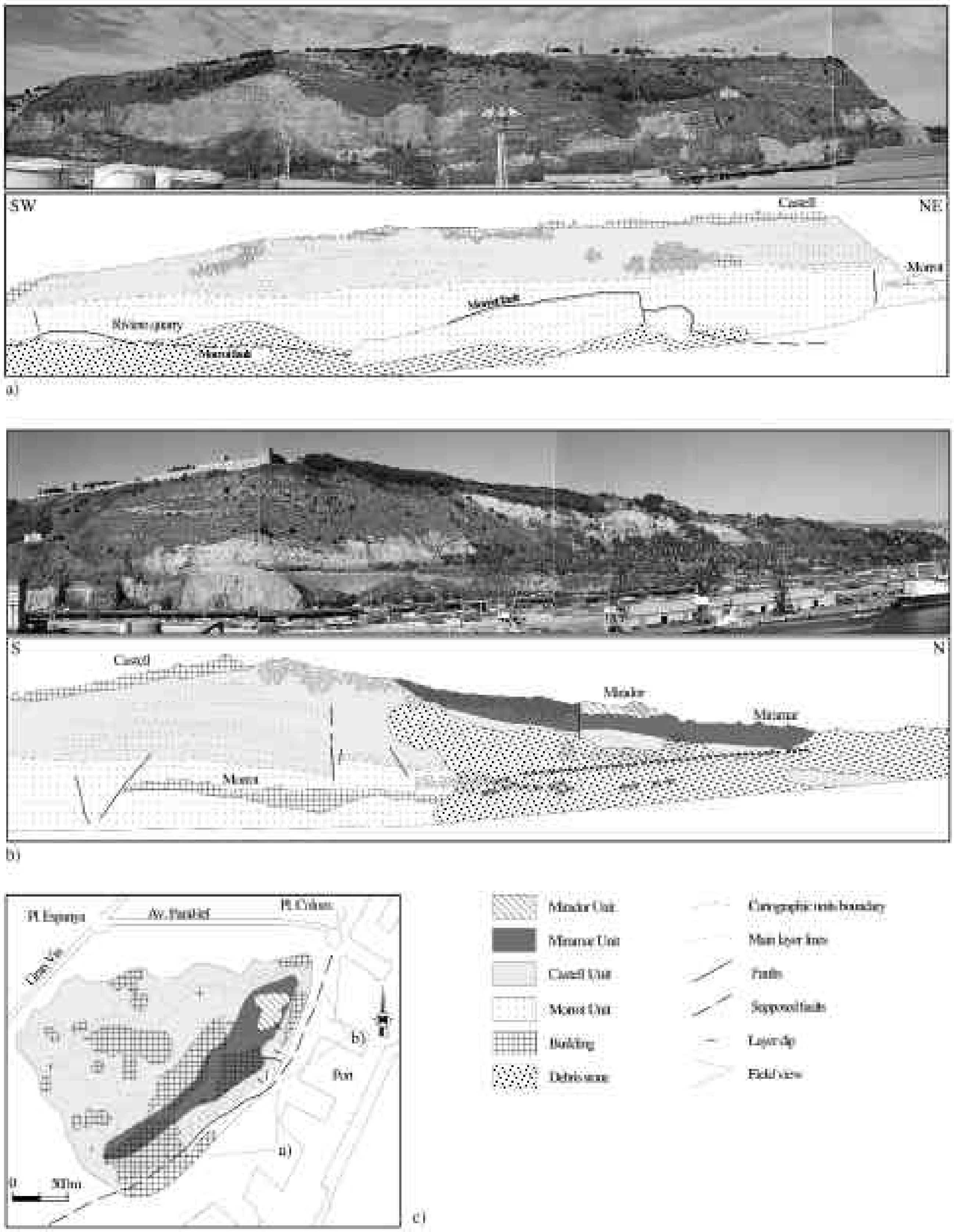
### Collserola mountain and Barcelona half-graben link zone

The geological structure of the link zone is relatively complex (Fig. 2) and is constituted by several minor tectonic units which are progressively affected by different faults: the Tibidabo fault, the Turons fault, the Barcelona fault and the Morrot fault. These faults are orientated NE-SW and are downfaulted up to 300 metres (Llopis, 1942b; Solé Sabarís, 1963; Medialdea Vega and Solé Sabarís, 1973; Alonso et al., 1977; Roca and Casas, 1981).

The link zone from the Collserola Mountain to the Mediterranean sea presents the following tectonic units: 1) The Vall d'Hebron and Sarrià minor depressions (Llopis, 1942b) located at the base of the Collserola Mountain and probably controlled by the Tibidabo fault. These two minor depressions are separated by the Els Turons tilted block complex and are filled with quaternary deposits; 2) The Turons (Monteroles, Putxet, Vallcarca, Carmelo) tilted block complex, which is constituted by Ordovician and Silurian metamorphic pelitic rocks and Silurian-Devonian calcareous rocks; 3) The Barcelona city depression is up to 300 m thick. This depression is controlled by the Els Turons fault along the northern edge and by the Barcelona fault along the southern edge (Llopis, 1942b; Roca and Casas, 1981). The Barcelona city depression is filled with marine Pliocene and Quaternary continental deposits (Almera, 1894; Llopis, 1942b; Solé Sabarís, 1963; Alonso et al., 1977; Roca and Casas, 1981); and 4) The Montjuïc tilted block is bounded to the south by the Morrot fault and to the north by a minor fault oriented E-W (Roca and Casas, 1981). The Montjuïc tilted block probably shows a certain structural continuity to the NE (towards the old city centre), where the pliocene deposits crop out below the historic buildings, forming the hypothetical Mont Taber tilted block.

## STRATIGRAPHY AND GENERAL SEDIMENTOLOGICAL FEATURES

A number of stratigraphic studies have been carried out in the Miocene of Montjuïc and some of these were


SW
Castell
NE
Morrot
Morrot fault
Riviera quarry
Morrot fault
a)
S
Castell
Mirador
Miramar
Morrot
N
b)
Pl. Espanya
Av. Paral·lel
Pl. Colom
Gran Via
b)
Port
a)
0
300 m
c)
Mirador Unit
Miramar Unit
Castell Unit
Morrot Unit
Building
Debris stone
Cartographic units boundary
Main layer lines
Faults
Supposed faults
Layer dip
Field view

published during the nineteenth century (La Marmora, 1834; Vezian, 1856; Carez, 1881; Maureta and Thos, 1881; Almera, 1880, 1899). Subsequent studies were conducted by San Miguel de la Cámara (1912), Suñer Coma (1957), Villalta and Rosell (1965), Magné (1978) and Álvarez (1987). Broadly, the stratigraphic section presented in this paper coincides with the stratigraphy carried out by Villalta and Rosell (1965).

The Middle Miocene (Serravallian) section of Montjuïc, with a thickness exceeding 200 m, is constituted by an alternation of dominant conglomerate and sandstone units with minor mudstone units. The conglomerate and sandstone layers are generally well-cemented and present a massive aspect owing to the intensity of the diagenetic processes which obliterated almost all the original sedimentary structures. Generally, the mudstone units are made up of grey siltstone and marlstone layers, which can be traced laterally for distances of over 1-1.5 km (the width of available outcrops) without loss of thickness (Figs. 3a and 3b). The Miocene deposits of the Montjuïc tilted block are divided into four lithostratigraphic units, which from base to top are (Figs. 3 and 4): (1) The Morrot conglomerate and sandstone Unit; (2) The Castell conglomerate, sandstone and mudstone Unit; (3) The Miramar marlstone Unit, and (4) The Mirador conglomerate, sandstone and mudstone Unit.

### The Morrot conglomerate and sandstone Unit

This unit is up to 84 m thick and consists of two decametric sets of well-cemented, massive layers of conglomerates and sandstones (30 and 33 m thick, respectively) separated by a drab-coloured marly level (10 m thick). These two sets are overlain by 11 m of siltites and fine sandstones. Bedding is mainly horizontal and can be distinguished by broad granulometric changes with a high lateral continuity. The upper part of the second set is formed by 20 m thick sandstones and conglomerates with erosive surfaces and channel incisions. Some of the conglomerate pebbles have an intraformational origin, proceeding directly from the erosion underlying beds. The last 11 m of this unit are constituted by bioturbated siltites and fine sandstones with mollusc and foraminifera fauna and are characterized by a differential cementation, with strong-cemented red-coloured zones leaving weak-cemented ochre-coloured patches. At four meters from the top, there is a key bed of carbonate cemented sandstones (50 cm thick) which was frequently reworked, forming carbonate cemented intraclasts. This unit is capped by a mainly siliciclastic conglomerate key bed 30 cm thick, which can be traced along the available exposures. This layer contains pebbles of quartz, plutonic rock fragments, phyllite rock fragments, chert and some bioclasts (bivalves, balanus...).

The materials of this unit are interpreted as delta plain deposits. These deltaic sediments were formed close to the highlands (Collserola Horst) in association with tectonic escarpments (Tibidabo and Turons faults; see Fig. 2) and consist of channelled coarse-grained facies with a relatively high lateral continuity. These deposits could result from the progradation of a flood-related braided alluvial plain into the sea. All these features can be attributed to a fan delta system, after Nemec and Steel (1988). The last 11 m of this unit are formed by shore deposits, where the reworked carbonate cemented sandstones represent a ravinement surface and the siliciclastic conglomerate key bed a chennier deposit.

### The Castell conglomerate, sandstone and mudstone Unit

This unit is 100 m thick and is characterized by an alternation between grey-coloured siltstones and mudstones and well-cemented sandstones and conglomeratic sandstones, arranged in thickening and coarsening upward cycles from 15 to 25 m in thickness. The lower part of the cycles is formed by mudstones and siltstones with fauna of gastropods, bivalves, some carbonaceous remains and pyritized pellets, which grade upwards to sandstones presenting occasionally cross-stratification and ripple lamination. In the middle part of the cycles, sandstones consist of 3-8 m thick beds with local cross-stratification and erosive truncation surfaces, displaying a uniform medium or coarse grain size. At the top, the conglomeratic sandstones are composed of 1.5-5 m thick fining upward beds ranging from conglomerates to very fine sandstones. These beds have erosive bases

Figure 3. Disposition of the Miocene lithostratigraphic units in Montjuïc hill. a) Field view of the SE side of the hill. b) Field view of the E side of the hill. c) Cartographic sketch of miocene units in Montjuïc hill.

Figura 3. Disposición de las unidades litostratigráficas miocenas de Montjuïc. a) Vista del flanco SE. b) Vista del flanco E. c) Cartografía de las unidades miocenas de Montjuïc.

which may truncate underlying sandstones. Although these conglomeratic sandstones are commonly massive, they also display cross-bedded and planar laminated facies. The cycles are frequently capped by a burrowed and ferruginous level. Overlying the uppermost cycle are 5.2 m of massive sandstones and conglomerates arranged in 3 fining upward beds with sharp erosive bases, and finally 5.1 m of bioturbated calcisiltites with abundant fauna of oysters and gastropodes interbedded with grey marlstones. There is a ferruginous crust at the top of this unit.

The Castell Unit is interpreted as progradational delta-front deposits where the ferruginous burrowed sharp tops on the cycles are the consequence of subaerial exposure. The boundary between the cycles represents a flooding surface by lobe abandonment. The overlying massive sandstones and conglomerates correspond to channels in a delta plain environment and the calcisiltites and marlstones are interpreted as shoreface deposits.

### The Miramar marlstone Unit

This unit consists of 15 m of grey to green marlstones with abundant fauna of bivalves, echinoderms, planktic foraminifera, ferruginous burrows and plant remains in the two first meters of the unit. Given this distinctive lithological character, which facilitates mapping of Montjuïc Hill, the Miramar Unit was individualized as a lithostratigraphic unit, despite being part of the progradational deltaic system.

The marlstone deposits of this unit are attributed to prodelta deposits.

### The Mirador conglomerate, sandstone and mudstone Unit

This unit outcrops discontinuously and has a minimum thickness of about 20 m. Conglomerates and sandstones have a massive aspect and are arranged in thickening and coarsening upward cycles. The stratification and sedimentary characteristics resemble those of the Castell Unit, marine fossils such as oysters and possible coral fragments being frequent (Cabrera, 1973). The top of this unit is constituted by marls.

The facies of this unit are interpreted as proximal delta-front deposits.

### Proposal of sequence stratigraphy subdivision

The main variations in relative sea-level can be inferred from the facies distribution. Three depositional sequences (Van Wagoner et al., 1990) are distinguished in the Miocene marine section of Montjuïc (Fig. 4).

A relative sea-level rise (Transgressive System Tract) is indicated by the marly level and the decrease in grain size at the top of the first conglomeratic set in the Morrot Unit. Under this T.S.T. there is a Lowstand System Tract (L.S.T.), whose lower limit does not crop out. The end of the transgression is marked by an iron-bearing crust at the top of a thin and fine-grained sandstone bed in the marly level and this could be interpreted as the maximum flooding surface (M.f.s). Subsequently, a Highstand System Tract (H.S.T.) was developed by delta-plain progradational facies.

The L.S.T. of the second sequence is evidenced by channel incisions with intraformational conglomerates which occur in the lower part of the Morrot Unit. The transgressive surface (T.s.) is related to the decrease in grain size of the shore siltites and fine-grained sandstones of the last 11 m of this unit, where the ravinement surface appears. The maximum flooding surface is marked by the chennier deposits of the conglomerate key bed which is located at the top of the Morrot Unit. A thick H.S.T., which is characterized by progradational delta-front facies (Castell Unit), developed subsequently.

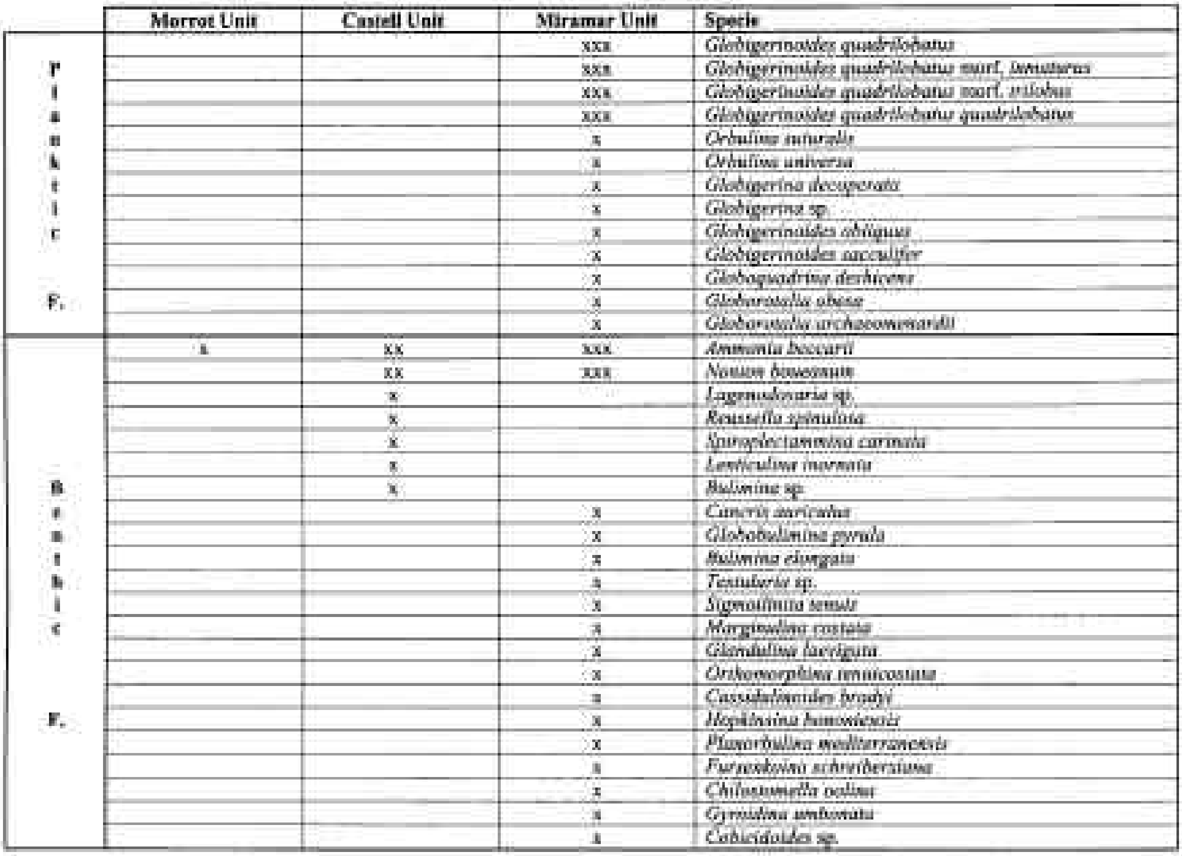
The decrease in grain size and the occurrence of calcarenites with abundant marine fauna in the upper part of the Castell Unit indicates the occurrence of a third sequence with a retrogradational T.S.T. The maximum flooding surface could be represented by the maximum average of planktic foraminifera in the middle of the Miramar Unit. The H.S.T. is made up of the Miramar and Mirador units. In this sequence, the presence of a Lowstand System Tract is not clear.

## BIOSTRATIGRAPHY AND CHRONOSTRATIGRAPHY

A number of paleontological studies have been carried out in the Miocene of Montjuïc (Maureta and Thos, 1881; Mallada, 1892; Almera, 1899; Faura y Sans, 1908, 1917; Colom and Bauza, 1945; Magné, 1978). The chronostratigraphy of these deposits has not been well defined, despite having been assigned an Upper Helvecian-Tortonian age by a number of authors (Almera, 1899; Deperet, 1898; San Miguel de la Cámara, 1912; Faura y Sans

Table 1. Miocene foraminifera fauna in Montjuïc hill.

Tabla 1. Foraminíferos encontrados en el Mioceno de Montjuïc.



| | Morrot Unit | Castell Unit | Miramar Unit | Specie |
|---|---|---|---|---|
| **Planktic F.** | | | xxx | *Globigerinoides quadrilobatus* |
| | | | xxx | *Globigerinoides quadrilobatus morf. immaturus* |
| | | | xxx | *Globigerinoides quadrilobatus morf. trilobus* |
| | | | xxx | *Globigerinoides quadrilobatus quadrilobatus* |
| | | | x | *Orbulina suturalis* |
| | | | x | *Orbulina universa* |
| | | | x | *Globigerina decoperata* |
| | | | x | *Globigerina sp.* |
| | | | x | *Globigerinoides obliquus* |
| | | | x | *Globigerinoides sacculifer* |
| | | | x | *Globoquadrina dehiscens* |
| | | | x | *Globorotalia obesa* |
| | | | x | *Globorotalia archaeomenardii* |
| **Benthic F.** | x | xx | xxx | *Ammonia beccarii* |
| | | xx | xxx | *Nonion boueanum* |
| | | x | | *Lagenodosaria sp.* |
| | | x | | *Reussella spinulosa* |
| | | x | | *Spiroplectammina carinata* |
| | | x | | *Lenticulina inornata* |
| | | x | | *Bulimina sp.* |
| | | | x | *Cancris auriculus* |
| | | | x | *Globobulimina pyrula* |
| | | | x | *Bulimina elongata* |
| | | | x | *Textularia sp.* |
| | | | x | *Sigmoilinita tenuis* |
| | | | x | *Marginulina costata* |
| | | | x | *Glandulina laevigata* |
| | | | x | *Orthomorphina tenuicostata* |
| | | | x | *Cassidulinoides bradyi* |
| | | | x | *Hopkinsina bononiensis* |
| | | | x | *Planorbulina mediterranensis* |
| | | | x | *Furzenkoina schreibersiana* |
| | | | x | *Chilostomella oolina* |
| | | | x | *Gyroidina umbonata* |
| | | | x | *Cibicidoides sp.* |

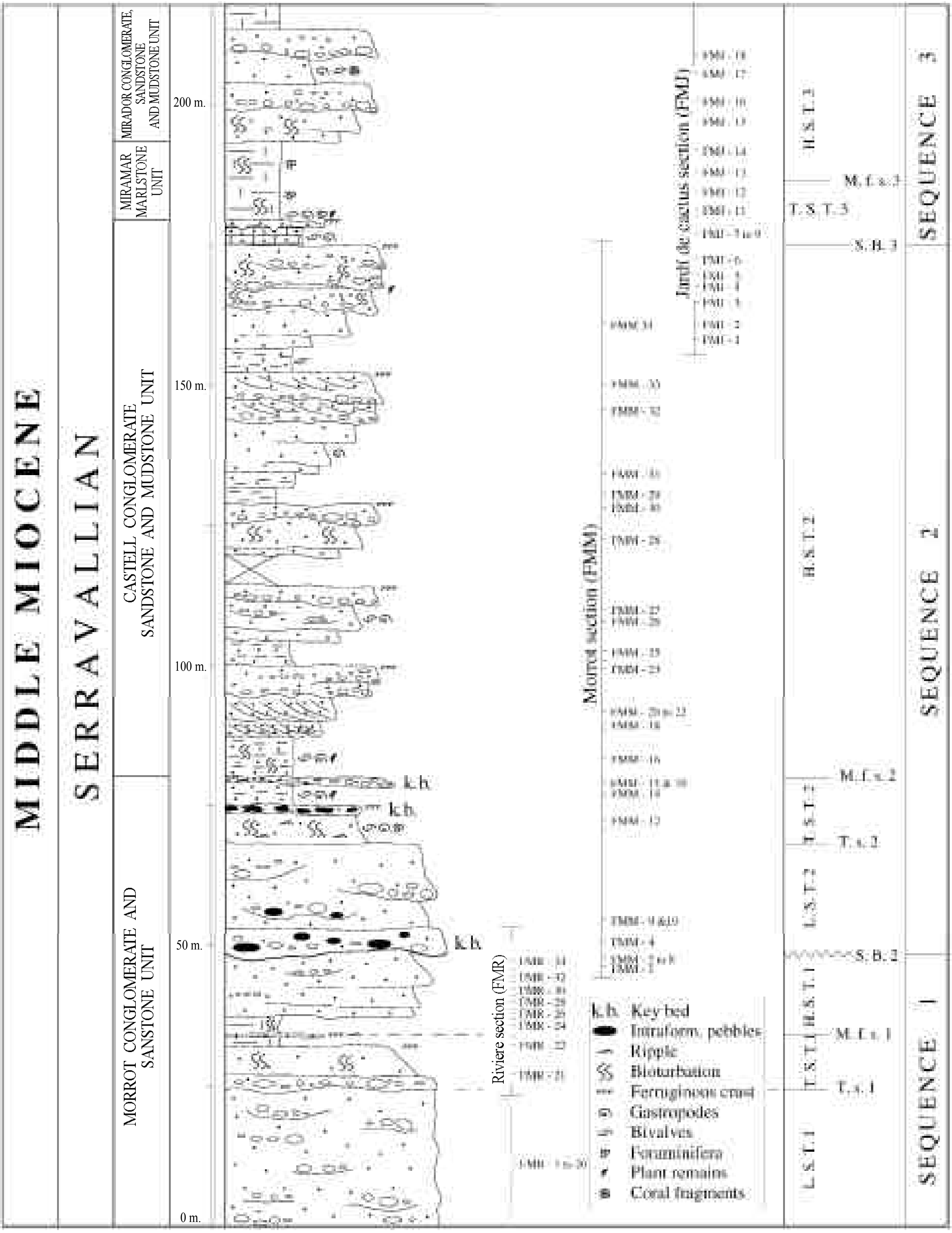
1917 and a Vindobonian age by other authors (Llopis, 1942a; Suñer Coma, 1957). Magné (1978) attributed an Upper Serravallian-Tortonian age on the basis of microforaminiferal dating. New foraminifera and palynological studies were carried out to determine the chronostratigraphy of the Miocene of Montjuïc on the basis of 7 samples collected from the marly and lutitic layers of the different units.

## Foraminifer a

The foraminifera content of the Miocene of Montjuïc was studied by Colom and Bauza (1945) and Magné (1978). Colom and Bauza (1945) reported 29 species, indicating the prevalence of *Bulimina ovata*, *Rotalia beccarii* (= *Ammonia beccarii*) and *Nonion boueanum* as well as several planktonic foraminifera (*Globigerinoides trilocularis*, *Globigerinoides sacculifera*, *Globigerina helicina*, *Globigerina bulloide*s and *Globigerinella aequilateralis*). Magné (1978) reported 14 species of planktonic foraminifera and a large number of benthic foraminifera. According to this author the presence of *Globorotalia* cf. *cultrata menardii*, *Globigerinoides cf. bulloideus*, *Orbulina universa*, *Virgulinella floridana* and *Ammonia punctatogranosa* association could be attributed to the N16 zone of Blow (1969), suggesting an Upper Serravallian-Tortonian age.

The samples were collected from the following units (Fig. 4): i) The Morrot Unit, in the marlstone layer located in the middle (FMR-24 sample) and in the upper part (FMM-14 sample); ii) The base of the second thickening and coarsening upward cycle of the Castell Unit (FMM-25 sample), and iii) The Miramar Unit (FMJ-11, FMJ-12, FMJ-13 and FMJ-14 samples).

Some specimens of *Ammonia beccarii* were found in the marly level of the Morrot Unit and the Castell Unit contains benthic foraminifera (*Ammonia beccarii* and


MIDDLE MIOCENE
SERRAVALLIAN
MIRADOR CONGLOMERATE, SANDSTONE AND MUDSTONE UNIT
MIRAMAR MARLSTONE UNIT
CASTELL CONGLOMERATE SANDSTONE AND MUDSTONE UNIT
MORROT CONGLOMERATE AND SANSTONE UNIT
200 m.
150 m.
100 m.
50 m.
0 m.
k.b.
k.b.
k.b.
Jardí de cactus section (FMJ)
FMJ - 18
FMJ - 17
FMJ - 16
FMJ - 15
FMJ - 14
FMJ - 13
FMJ - 12
FMJ - 11
FMJ - 7 to 9
FMJ - 6
FMJ - 5
FMJ - 4
FMJ - 3
FMJ - 2
FMJ - 1
Morrot section (FMM)
FMM 34
FMM - 33
FMM - 32
FMM - 31
FMM - 29
FMM - 30
FMM - 28
FMM - 27
FMM - 26
FMM - 25
FMM - 23
FMM - 20 to 22
FMM - 18
FMM - 16
FMM - 15 & 10
FMM - 14
FMM - 12
FMM - 9 &10
FMM - 4
FMM - 2 to 8
FMM - 1
Riviere section (FMR)
FMR - 34
FMR - 32
FMR - 30
FMR - 28
FMR - 26
FMR - 24
FMR - 22
FMR - 21
FMR - 1 to 20
k.b. Key bed
Intraform. pebbles
Ripple
Bioturbation
Ferruginous crust
Gastropodes
Bivalves
Foraminifera
Plant remains
Coral fragments
H.S.T.3
M. f. s. 3
T. S. T. 3
S. B. 3
H.S.T.2
M. f. s. 2
T. S. T.2
T. s. 2
L.S.T.2
S. B. 2
H.S.T.1
M. f. s. 1
T.S.T.1
T. s. 1
L.S.T.1
SEQUENCE 3
SEQUENCE 2
SEQUENCE 1

*Nonion boueanum*) without any chronostratigraphic significance. Benthic and planktic foraminifera are present in the Miramar Unit. Planktic foraminifera percentage (relative to total foraminifera content) averages 36% at the bottom, 69% in the middle portion and 23% at the top of this unit. The main planktic foraminifera are represented by *Globigerinoides quadrilobatus, Globigerinoides quadrilobatus morf. inmaturus, Globigerinoides quadrilobatus morf. trilobus, Globigerinoides quadrilobatus quadrilobatus*. Different foraminifera species of each unit are shown in Table 1.

The presence of *Orbulina universa* and *Globorotalia archaeomenardii* in the Miramar Unit determines the N9 and N10 biozones of Blow (1969) implying a Langhian age according to this author. But, according to Bolli and Saunders (1985) and Iaccarino (1985) the presence of *Orbulina universa* and *Globorotalia archaeomenardii* indicates a Serravallian age. Nevertheless, materials below the Miramar Unit could be Langhian or Serravallian in age.

According to the foraminifera results, the Serravallian deltaic deposits of Montjuïc have been regarded as equivalent to those of the offshore Sandstone Castelló Group Unit (Soler et al., 1983; Clavell and Berastegui, 1991; Bartrina et al., 1992; Álvarez-de-Buergo and Meléndez, 1994).

### Plant remains and palynology

The presence of plant remains in the Miocene deposits of Montjuïc was reported by Almera (1899), Faura y Sans (1917), San Miguel de la Cámara et al. (1928), Menendez Amor (1950), Bataller (1931; 1951), Vicente (1988) and Sanz de Siria (1994) among others. The Miramar marlstone Unit is especially rich in plant remains and, probably the plants cited by Almera (1899), were found in this unit whereas the plants cited by Vicente (1988) were found at the top of the fifth cycle of the Castell Unit. These authors suggest a Middle Miocene age and a subtropical climate with temperature averages of 18-19ºC.

Five samples, which were used in the foraminifera characterisation (FMM-14, FMJ-11, FMJ-12, FMJ-13, FMJ-14), were employed to determine the palynological association (Fig. 4). Results are shown in Table 2.

A number of assumptions can be made from the plant remains found in Montjuïc: 1) The presence of the Gymnospermae group with some Pteridophyta yields information about the vegetation of the source area (Collserola-Montnegre horst). The flora of the source area is dominated by *Pinus* owing to its great pollen productivity and ease of dispersion; 2) The presence of *Typha*, *Sparganium*, *Nuphar*, *Myriophyllum* and Pteridophtyta spores suggests a marsh and palustrine vegetation related to the delta plain environments. The occurrence of Taxodiaceae, *Alnus*, *Pterocarya*, *Populus* and Ulmaceae and Chlorophyceae algae (*Circulisporites*) is also typical of fresh waters; 3) A temperate-warm and humid climate is indicated by the terrestrial flora. Dinocystes, especially *Selenopemphix nephroides*, is a warm water species indicator (Santarelli, 1997); and 4) This flora suggests a Miocene age.

The taxons as *Pterocarya*, *Engelhardtia*, *Liquidambar*, *Tsuga* and *Pinus* type *haploxylon* group are actually extinct in the Iberian Peninsula.

## PETROLOGY

### Detrital composition

Despite the large number of studies on the Miocene of Montjuïc, the petrology of the Montjuïc sandstones has been described by very few authors (Faura y Sans, 1917; San Miguel and Masriera, 1970; and more recently Álvarez, 1988 and Gómez-Gras et al., 1998).

The Montjuïc sandstones show a great diversity of grain size from silt to gravel. The clasts have medium to high roundness and a variable but usually high sphericity. Sandstones with a large amount of matrix and poorly sorted (texturally immature) prevail in the lower lithostratigraphic units, whereas the amount of matrix decreases and sorting increases towards the upper units.

As regards composition, these sandstones are immature, with a significant content of rock fragments and feldspars. The sandstones have a siliciclastic composition and can be classified as litharenites (Fig. 5) or lithic

Figure 4. Stratigraphic section of the Miocene of Montjuïc hill.

Figura 4. Sección estratigráfica general del Mioceno de Montjuïc.

Table 2. Miocene palynological association in Montjuïc hill.

Tabla 2. Contenido palinológico del Mioceno de Montjuïc.

| | **Family** | **Genus** | **Morrot Unit** | **Miramar Unit** |
|---|---|---|---|---|
| PTERIDOPHYTA | Lycopodiaceae | *Lycopodium* | | x |
| | Selaginellaceae | *Selaginella* | | x |
| | Schizaeaceae | *Lygodium* | | x |
| | | indet. | | x |
| | | indet. | x | x |
| | | indet. | | x |
| GIMNOSPERMAE | Abietaceae | *Abies* | | x |
| | | *Pinus* type *diploxylon* | xx | xx |
| | | *Pinus* type *haploxylon* | xx | xx |
| | | *Cedrus* | | x |
| | | *Tsuga* | | x |
| | Taxodiaceae | *Sequoia* | | x |
| | | *Sciadopytis* | | x |
| | Gnetaceae | *Ephedra* | | x |
| ANGIOSPERMAE | Fagaceae | *Quercus* | x | |
| | | *Quercus* type *ilex-coccifera* | | x |
| | Betulaceae | *Alnus* | x | |
| | | *Betula* | x | |
| | | indet. | | x |
| | Juglandaceae | *Juglans* | | x |
| | | *Engelhardtia* | | x |
| | | *Pterocarya* | x | x |
| | | indet. | | x |
| | Ulmaceae | type *Ulmus-Zelkova* | x | x |
| | | *Celtis* | | x |
| | Salicaceae | *Populus* | | x |
| | Caprifoliaceae | *Sambucus* | | x |
| | Myricaceae | *Myrica* | | x |
| | Oleaceae | *Fraxinus* | | x |
| | Anacardiaceae | *Pistacia* | | x |
| | Aquifoliaceae | indet. | | x |
| | Hamamelidaceae | *Liquidambar* | | x |
| | Eleagnaceae | *Hippophäe* | | x |
| | Ericaceae | indet. | | x |
| | Convolvulaceae | cf. *Calystegia* | | x |
| | Boraginaceae | indet. | | x |
| | Campanulaceae | *Campanula* | | x |
| | Umbelliferae | indet. | | x |
| | Papilionaceae | indet. | | x |
| | Amaranthaceae-Chenopodiaceae | indet. | | x |
| | Poaceae | indet. | | x |
| | Asteraceae Cichorioideae | indet. | | x |
| | Asteraceae Asterodeae | indet. | | x |
| | Caryophyllaceae | indet. | | x |
| | Nymphaeaceae | *Nuphar* | | x |
| | Halorrhagaceae | *Myriophyllum* | | x |
| | Thyphaceae | *Thypha latifolia* | | x |
| | Sparganiaceae | *Sparganium* | | x |
| | DINOCYST | Spiniferites group | x | x |
| | | *Lingulodinium machaerophorum* | x | x |
| | | *Selenopemphix nephroides* | | x |
| | | *Tuberculodinium vancampoae* | | x |
| | | *Capillicysta fusca* | | x |
| | | *Melitasphaeridium* sp. | | x |
| | | *Dapsilidinium* sp. | | x |
| | | cf. *Fibrocysta* | x | x |

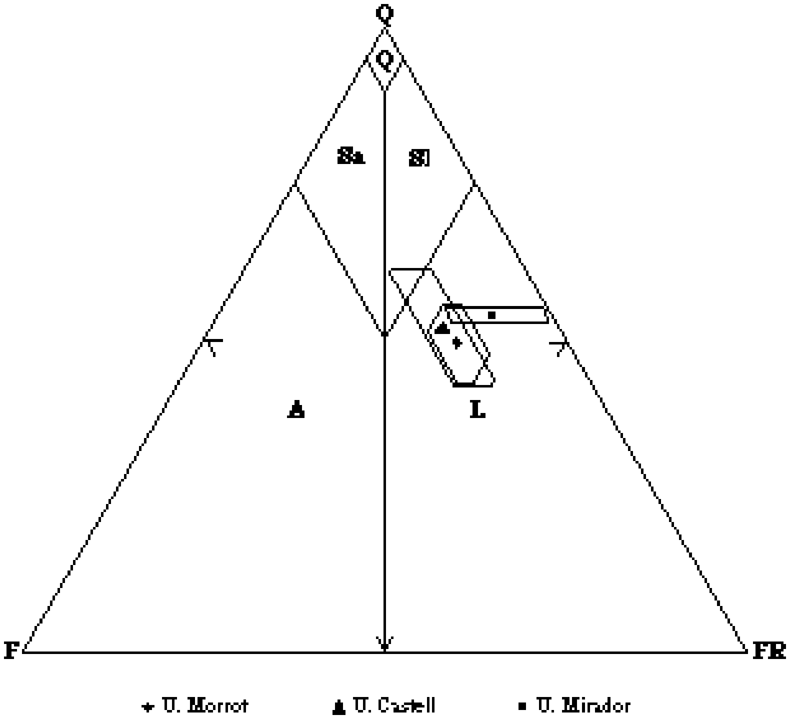


Figure 5. Detrital composition of free-matrix sandstones plotted in Dott (1964). Q: Quartzarenite. Sl: Sublitharenite. L: litharenite. Sa: Subarkose. A: Arkose.

Figura 5. Proyección de las areniscas sin matriz en el diagrama triangular de Dott (1964) para la clasificación de areniscas. Q: Cuarzoarenita. Sl: Sublitoarenita. L: Litoarenita. Sa: Subarcosa. A: Arcosa.

wackes, depending on whether the amount of matrix exceeds 15% (Dott, 1964).

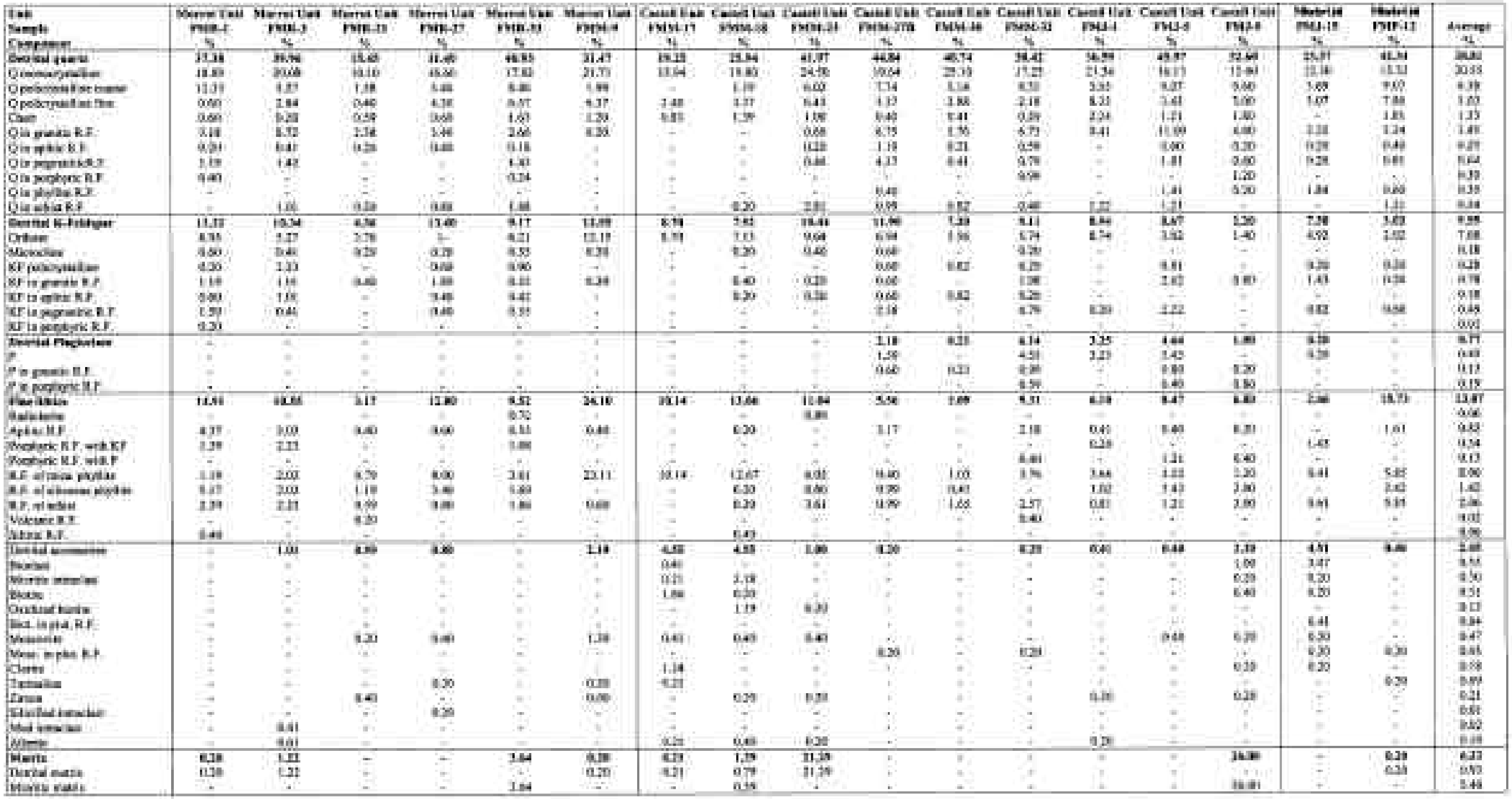
Modal analyses of Montjuïc sandstones (Table 3) quantified according to the Gazzi-Dickinson method (Ingersoll et al., 1984) showed that the framework is composed of quartz (38.8%), monocrystalline grains prevailing over polycrystalline ones; rock fragments (13.9%), which include a high diversity of lithologies (granitoid and granitoid porphyries, quartzites, phyllites, schists, aplites, pegmatites and radiolarites); K feldspar (9.5%, dominantly orthoclase) and plagioclase (0.8%)(Fig. 6a). Accessory minerals are biotite, muscovite, zircon, chlorite, tourmaline, mud intraclasts and silica cemented intraclasts. In marly sections and shore deposits, interbedded sandstones display bioclasts (0%-3.1%) and micritic grains (0%-2.2%).

Detrital K feldspar shows a strong differential alteration, from unaltered to totally altered to illite (2.4%), and occasionally to kaolinite (0.1%). The detrital plagioclase in the lower units occurs only in the rock fragments where it is altered to kaolinite or vermiculite. In upper units plagioclase content may be significant (6.1% in FMM-32). Mica content is scarce in the entire stratigraphic section. The scarcity of plagioclase and mica contrasts with their abundance in the Palaeozoic basement lithologies (Vaquer, 1973).

The framework composition is not uniform and there are differences between fine and medium-coarse sizes (Table 3): The metamorphic fragments prevail in the fine sandstones (6.7%-23.7%). In order of abundance they are: micaceous phyllites (7.9%), schists (2.1%) and siliceous phyllites (1.2%). The plutonic fragments may be significant too (3.8%-8.7%). In order of abundance they are: granites (1.8%), aplites (1.5%), granitoid porphyries (0.4%) and pegmatites (0.2%). The plutonic fragments predominate in medium-coarse sandstones (6.3%-21.1%), i.e. granites (6.2%), pegmatites (2.9%), aplites (2.7%) and granitoid porphyries (1.5%). Metamorphic fragments are: siliceous phyllites (2.2%), schists (2%) and micaceous phyllites (2%).

Table 3. Representative and average modal compositions of miocene Montjuïc sandstones.

Tabla 3. Composición modal media y de muestras representativas de las areniscas miocenas de Montjuïc.

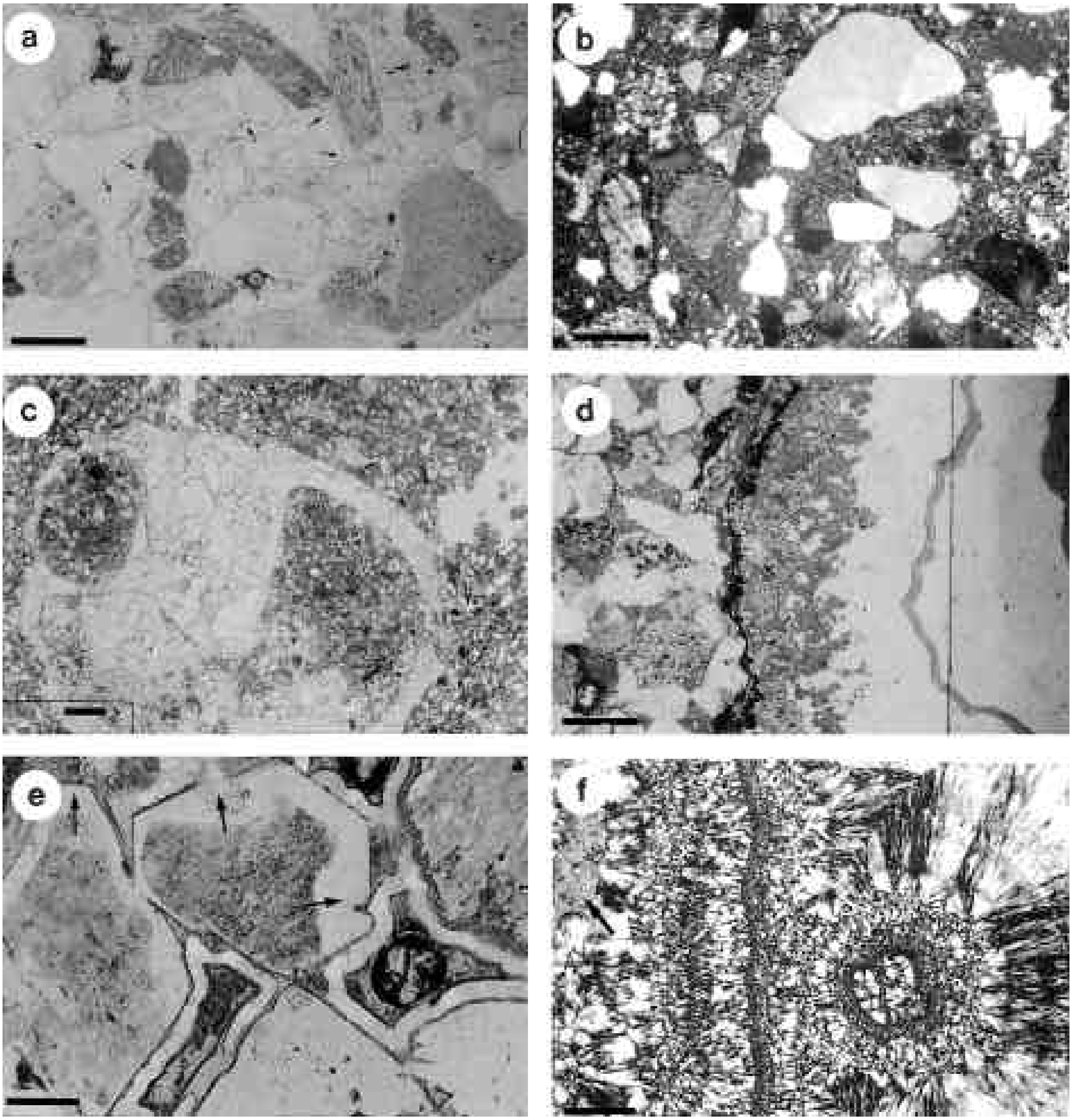


| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total diagenetic** | 12.41 | 33.47 | 78.84 | 46.60 | 31.40 | 18.85 | 39.49 | 45.76 | 11.89 | 34.23 | 46.91 | 31.48 | 38.84 | 27.62 | 27.24 | 58.61 | 39.84 | 41.86 |
| Pseudomatrix in (Q, R.F.) | 0.40 | 8.41 | - | 1.00 | 0.40 | 4.98 | - | 0.20 | 2.01 | - | - | - | - | - | - | - | - | 1.18 |
| Calcite intergranular | - | - | - | - | - | - | 32.70 | 26.54 | - | - | 14.20 | 0.20 | - | - | 11.80 | 29.30 | - | 12.87 |
| Neomorphic Ct | - | - | - | - | - | - | 0.21 | - | - | - | - | - | - | - | 2.20 | 24.80 | - | 2.56 |
| Ct in Q grain | - | - | - | - | - | - | 12.63 | - | - | - | 1.65 | - | - | - | - | - | - | 1.22 |
| Ct in KF grain | - | - | - | - | - | - | 4.97 | 0.80 | - | - | 1.65 | 0.20 | - | - | - | 0.61 | - | 0.54 |
| Ct in R.F. | - | - | - | - | - | - | 2.26 | - | - | - | 5.70 | 0.20 | - | - | 1.00 | 1.23 | - | 0.84 |
| Ct in glide | - | - | - | - | - | - | 1.45 | - | - | - | - | - | - | - | - | - | - | 0.14 |
| Matrix transf. to Microquartz | 3.17 | - | 73.98 | 26.40 | 13.13 | - | - | - | - | - | - | - | - | - | - | - | - | 3.93 |
| MicroQ cement in Q grain | - | - | - | 1.40 | 0.38 | - | - | - | - | - | - | - | - | - | - | - | - | 0.06 |
| MicroQ intergranular cement | 1.39 | 0.81 | - | 0.20 | 0.73 | 0.60 | - | - | - | - | - | - | 1.22 | 1.41 | - | - | 1.60 | 0.48 |
| Q overgrowth | 3.37 | 11.30 | 0.20 | 1.40 | 8.33 | 2.79 | - | 8.39 | 5.00 | 13.31 | 5.39 | 18.02 | 18.50 | 15.12 | - | 0.20 | 13.51 | 3.74 |
| Radial MicroQ | 9.14 | 4.02 | 0.99 | 1.00 | 1.33 | 1.00 | - | - | - | 12.50 | - | 4.59 | 9.19 | 4.84 | - | - | 10.98 | 3.13 |
| Q cement in KF | 0.20 | - | 0.40 | 0.40 | - | - | - | - | - | - | - | - | - | - | - | - | - | 0.06 |
| KF overgrowth | 2.78 | 3.66 | - | 1.40 | 1.33 | 0.20 | - | 3.96 | 0.60 | 5.16 | 2.00 | 4.75 | 0.58 | 2.02 | - | - | 1.00 | 1.67 |
| KF cement in detrital KF | - | 0.20 | - | 0.20 | - | - | - | - | - | - | - | - | - | 0.26 | - | - | 0.20 | 0.04 |
| Illite intergranular | - | - | - | - | - | 0.40 | - | - | 0.20 | - | - | - | 0.20 | - | - | - | 0.20 | 0.11 |
| Illite in pore-lining | - | - | - | - | - | - | 0.21 | - | 0.40 | - | - | - | - | - | - | - | - | 0.03 |
| Illite in KF | 4.07 | 5.08 | 0.40 | 3.00 | 0.40 | 0.60 | - | 0.99 | 1.61 | 2.78 | 1.65 | 0.40 | 1.22 | 0.60 | 3.20 | 0.61 | 1.23 | 1.07 |
| Illite in KF in plut. R.F | 1.59 | 0.61 | 0.20 | 1.20 | - | - | 0.83 | - | 0.20 | 0.99 | - | - | 0.20 | 0.26 | 0.80 | 0.20 | 0.20 | 0.46 |
| Kaolinite in KF | - | - | - | - | 1.55 | - | - | - | 0.20 | 0.40 | - | - | - | - | - | - | - | 0.08 |
| Kaolinite in KF in plut. R.F. | - | - | - | - | 0.40 | - | - | - | - | - | - | - | - | - | - | - | - | 0.02 |
| Sericite in P | - | - | - | - | - | - | - | - | - | 0.60 | - | 2.57 | 2.03 | 1.01 | - | - | - | 0.21 |
| Fe oxides in Q | - | - | - | - | - | - | - | - | - | - | 0.42 | - | - | - | - | - | - | 0.02 |
| FeO in phyllite R.F | - | - | - | - | - | - | - | - | - | - | 1.50 | - | - | - | - | - | - | 0.12 |
| FeO in Mica | - | - | - | 0.20 | - | - | - | - | - | - | - | - | - | - | - | - | - | 0.01 |
| FeO in KF | 0.60 | 0.80 | 0.59 | 1.00 | 1.27 | 0.20 | - | - | 1.00 | 0.20 | 1.03 | - | - | 0.20 | - | - | - | 0.28 |
| FeO in KF in plut. R.F | - | 0.61 | - | 0.20 | - | - | - | - | - | - | - | - | 0.20 | 0.60 | - | - | - | 0.05 |
| FeO in pore-filling | 0.20 | 0.81 | 16.63 | - | 1.51 | 1.59 | - | 6.73 | 4.02 | - | 4.94 | 0.20 | 0.41 | - | - | 0.82 | - | 2.15 |
| FeO coating | - | - | 2.77 | - | - | - | - | - | - | - | 4.70 | - | - | - | - | - | - | 0.37 |
| Barite intergranular | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 0.83 | 0.08 |
| Chalcedony intergranular | - | - | - | - | 0.36 | - | - | - | - | - | - | - | - | - | - | - | - | 0.02 |
| Hematite | - | - | - | 1.00 | - | 1.39 | - | 0.79 | - | 0.20 | 0.82 | - | 0.20 | 0.20 | - | - | 1.03 | 0.32 |
| Oxidized pyrite | - | - | - | - | - | - | 0.41 | - | - | - | - | - | - | - | - | - | - | 0.04 |
| Glauconite | - | - | - | - | - | - | 0.21 | - | - | - | - | - | - | - | 1.20 | 0.82 | - | 0.14 |
| **Porosity** | 3.78 | 3.40 | 0.59 | 1.00 | 5.26 | 15.94 | 1.46 | 2.77 | 2.01 | 1.19 | 1.85 | 5.59 | 4.08 | 4.23 | 3.00 | 3.28 | 6.47 | 6.39 |
| Intergranular | 0.40 | 1.22 | - | 0.40 | 3.63 | 10.96 | 0.81 | 0.40 | 2.01 | 0.60 | 1.63 | 2.78 | 2.24 | 2.82 | 1.25 | 0.82 | 6.27 | 4.08 |
| Intragranular in KF | 0.80 | 2.03 | - | 0.40 | 0.66 | 0.60 | - | 0.59 | - | 0.60 | - | - | - | 0.20 | 0.40 | 1.84 | - | 0.63 |
| Intra. in KF in plut. R.F | 0.20 | 0.20 | - | - | 0.24 | 2.99 | - | - | - | - | - | - | - | - | - | 0.41 | - | 0.16 |
| Intra. in P | - | - | - | - | - | - | - | - | - | - | - | 1.19 | 2.04 | 0.20 | - | - | - | 0.13 |
| Intra in R.F | - | - | - | - | - | - | - | 0.20 | - | - | - | 0.20 | - | - | 0.40 | - | - | 0.11 |
| Intra. indeterminated | 0.40 | - | 0.59 | 0.20 | 0.73 | 2.39 | 0.82 | 1.58 | 0.40 | - | 0.21 | 0.20 | 0.20 | - | - | 0.20 | 0.20 | 0.82 |
| **Grain volume (%)** | 74.79 | 72.23 | 25.74 | 68.40 | 65.83 | 81.47 | 65.63 | [illegible] | 73.48 | 70.24 | 62.02 | 68.13 | 61.59 | 72.08 | 31.60 | 65.24 | 63.31 | 75.39 |
| **Replaced volume (%)** | 12.42 | 7.71 | 53.23 | 24.60 | 17.21 | 6.89 | 22.36 | 1.39 | 3.01 | 4.96 | 13.38 | 3.37 | 3.66 | 4.40 | 6.00 | 27.40 | 1.60 | 13.29 |
| **Cemented volume (%)** | 19.48 | 23.32 | 20.29 | 4.80 | 13.78 | 7.77 | 31.15 | 44.10 | 6.22 | 29.17 | 31.33 | 28.12 | 36.18 | 23.19 | 19.20 | 31.18 | 28.21 | 27.43 |
| **Intergranular volume (%)** | 25.25 | 27.79 | 71.49 | 31.60 | 34.17 | 18.13 | 34.36 | 45.90 | 29.02 | 29.78 | 39.23 | 31.86 | 28.41 | 27.02 | 44.80 | 31.97 | 36.69 | 41.54 |
| **Por$^a$ destroyed comp.*** | 30.68 | 39.33 | - | - | 31.82 | 33.09 | 13.36 | - | - | 23.60 | 24.28 | 39.30 | 3.96 | 32.46 | - | 30.08 | 8.27 | 13.96 |
| **Por$^a$ destroyed cement.*** | 48.31 | 83.29 | - | - | 52.73 | 19.42 | 82.82 | - | - | 72.92 | 83.23 | 78.30 | 86.40 | 57.06 | - | 57.07 | 91.86 | 56.40 |
| **Granulometry** | M to C | M to C | VF to M | F to C | VF to C | VF to F | VF | M | F to C | C to Vc | M to Vc | M to Vc | F to M | M to Vc | VF to Vc | M to Vc | C to Vc | |
| **Sorting** | M | M | Vg | P | M | G | G | G | P | M | M | M | G | M | P | Vp | G | |

Granulometry → VF.: Very fine, F.: Fine, M.: Medium, C.: Coarse, Vc.: Very coarse.
Sorting → Vp.: Very poor, P.: Poor, M.: Moderated, G.: Good, Vg.: Very good.
* Only in fine matrix samples (grain supported).

There are several types of matrix: (1) pseudomatrix (1.2%), mainly formed by deformation of micaceous phyllite fragments; (2) depositional micritic protomatrix, which may be abundant in fine sandstones (26% in FMJ-9) and (3) detrital protomatrix (21.3% in FMM-23). Detrital matrix is composed of quartz, feldspar, clays and micas and frequently it has transformed to opal and microquartz (Fig. 6b) with variable amounts of feldspar and clay mineral remains. This transformed matrix is significant in the Morrot Unit (19.7%) but non-existent in the upper units.

The analysis of the different fragments shows that the framework of the Montjuïc sandstones is exclusively formed by Palaeozoic material. Therefore, the source area must be the Collserola mountain, where Palaeozoic material crops out, in particular, the Tibidabo-Vallvidrera area, where granitoid porphyries crop out.



## Sandstone diagenesis

Authigenic mineral formation has been an essential process in the lithification of the Montjuïc sandstones, which involves an early silicic cementation, an opal/ microquartz replacement of the original matrix and a calcite precipitation (Fig. 6c). These processes have considerably modified the original sediment, giving it a hard consistency and a massive appearance (Almera, 1880, 1899; Llopis, 1942b; San Miguel and Masriera, 1970).

In free matrix sandstones, cementation appears as mainly authigenic overgrowths on detrital K-feldspar and quartz grains (Fig. 6a). These overgrowths enclose the macrocrystalline grains and intersect to form polygons leaving little or no residual porosity. Apparent concave-convex and sutured intergranular contacts are polygonal contacts among the overgrowths. The mesoquartz cement usually fills the larger pores of these sandstones.

In sandstones with variable amounts of detrital matrix (Fig. 6b), the matrix prevents the development of authigenic overgrowths on quartz and K-feldspar grains. In such rocks, the matrix is usually replaced by opal/microcrystalline quartz, which contains variable amounts of clay and feldspar remnants and diagenetic iron/titanium oxides and alunite.

### *K-Feldspar*

Authigenic K-feldspar forms euhedral overgrowths (Fig. 6a and e) showing one or two coating layers that partially or completely cover the K-feldspar grains. The interfaces between the detrital cores and overgrowths are defined by a slight optical discontinuity which is caused by compositional differences between the grain and the cement (Kastner and Siever, 1979). Overgrowths are controlled by the presence or absence of detrital matrix. The feldspar overgrowths average 3.2% in free matrix sandstones and have a thickness of 10 µm to 150 µm, whereas the feldspar overgrowths in sandstones with matrix have a range of 0.3% and a thickness of 10 µm to 50 µm. K-feldspar also develops in pores that are derived from the dissolution of the most altered detrital K-feldspar. Chemically, K-feldspar grains contain variable amounts of BaO and $Na_2O$. Conversely, authigenic K-feldspars are pure end-members.

### *Silica*

Authigenic quartz (Fig. 6a) forms overgrowths on detrital quartz grains and quartzitic rock fragments. Macrocrystalline quartz grains develop euhedral overgrowths in optical continuity, whereas microcrystalline grains develop microcrystalline bladed overgrowths that evolve to drusy pore-fillings in the largest pores (mesoquartz). The maximum development of quartz overgrowths occurs in free matrix sandstones (8.3%) and are 20 µm to 160 µm in thickness. In sandstones with variable amounts of matrix, quartz overgrowths average 0.5% and the overgrowths are poorly developed with a maximum thickness of 20 µm. The detrital matrix may be replaced by opal/microquartz (6.2%) with clear feldspar and clay remnants (Fig. 6b). Matrix replacement causes some quartz overgrowths to exhibit an irregular surface owing to interpenetration with intragranular matrix.

Figure 6. a) Very coarse-grained sandstone of the Morrot unit with a siliciclastic framework of quartz, feldspar (stained) and rock fragments (plutonic, metamorphic and chert) cemented by quartz overgrowths (arrows). Plane-polarized light. Scale 0.5 mm. b) Early silica cementation of a Montjuïc sandstone by transformation of a former argilaceous matrix into microquartz. Crossed polars. Scale 0.5 mm. c) Equant calcite cement in moldic porosity. Plane-polarized light. Scale 0.2 mm. d) The fracture is filled with a first stage consisting of barite crystals (arrows) and oxides and a second stage made up of an alternance of opal/microquartz and chalcedony. Plane-polarized light. Scale 0.5 mm. e) Spherulitic, isopachous void cutans of chalcedony filling the residual porosity of sandstones. This cementation is related to fractures. Note the early polygonal feldspar overgrowths (arrows). Plane-polarized light. Scale 0.2 mm. f) Different generations of opal/microquartz, checkerboard chalcedony and chalcedonite (Fibrous radiating spherulites) precipitated in fracture wall. Note the barite crystal (arrow). Crossed polars. Scale 0.2 mm.

Figura 6. a) Arenisca de la unidad del Morrot con cuarzo, feldespato (teñido) y fragmentos de roca, cementada por sobrecrecimientos de cuarzo (flechas). Luz polarizada plana sin analizador. Escala 0.5 mm. b) Cementación de una arenisca de Montjuïc por transformación de la matriz arcillosa original a microcuarzo. Nícoles cruzados. Escala 0.5 mm. c) Cemento de calcita en mosaico rellenando porosidad móldica. Luz polarizada plana sin analizador. Escala 0.2 mm. d) Fractura cementada por precipitación de baritina (flechas) y óxidos, a continuación aparece una alternancia de ópalo/microcuarzo y calcedonia. Esta cementación afecta también a la porosidad residual de la arenisca. Luz polarizada plana sin analizador. Escala 0.5 mm. e) Cemento de calcedonia rellenando la porosidad residual en una arenisca de Montjuïc. Esta cementación está relacionada con fracturas. Nótese los sobrecrecimientos poligonales primarios de feldespato (flechas). Luz polarizada plana sin analizador. Escala 0.2 mm. f) Diferentes generaciones de ópalo/microcuarzo, calcedonia "checkerboard" y calcedonita (esferulitos fibrosos) en una fractura. Nícoles cruzados. Escala 0.2 mm.

### *Calcite spar cement*

The calcite spar cements generally fill moldic porosity (bivalves and gastropods) and interparticle porosity and locally fill intraparticle porosity (gastropods, briozoans and cirripeds). Moldic porosity presents two calcite cement generations. The first generation has a discontinuous rim disposition which is up to 400 µm thick. The second generation presents euhedric to subhedric crystals with a clear to brownish aspect, varying in size from 50 µm to 2 mm. Locally, the calcite cements filling moldic porosity grade to neomorphic calcite crystals. The calcite spar cements filling interparticle pores present clear to dirty crystals with a subhedric to anhedric habit, varying in size from 21 to 90 µm.

The calcite spar cements filling moldic porosity present the following characteristics: i) The values of the magnesium content are variable from below the detection limit to 5.520 ppm. ii) The values of the manganese content range from below the detection limit to 5.060 ppm. iii) The iron content varies from below the detection limit to 15.070 ppm. iv) The strontium and sodium content is always below the detection limit. Thus, the calcite spar cement may be interpreted as having a meteoric origin. The high values of manganese and iron are due to the siliciclastic host-rock influence.

### *Iron /Titanium oxides*

Iron oxides (2.9%) appear as spherical nodules (10 µm-50 µm) of goethite in the transformed matrix, surrounding the detrital K-feldspar and in metamorphic rock fragments. The iron oxides exhibit an opaque core with brown edges in XPL. Iron oxides account for the general red to purple colour of the Montjuïc sandstones, showing locally an irregular banding. Titanium oxides are found as pseudomorphic remains due to mica solution.

### *Alunite*

Alunite is scarce and occurs as disseminations commonly associated with an opal and microquartz transformed matrix and consists of discrete euhedral or subhedral cubes ranging from 1 to 5 µm across. This occurrence was detected by X-ray diffraction and microprobe analyses, which show small amounts of P in all alunite crystals.

## Joint diag enesis

The Miocene deposits (especially sandstones and conglomerates) present abundant fractures (faults and joints). Joints mainly affect the silicified rock. Joints in unsilicified rocks are filled with calcite or gypsum, whereas joints in silicified rocks are filled with several generations of different cements that show an evolution from the host rock to the joint surface wall (Fig. 6d).

The general stratigraphic fracture filling from the border to the centre presents the following stages: 1) Microquartz-barite fringe. In the vicinity of the joint wall there is a net fringe of microquartz and barite (5 - 10 µm) precipitation. Occasionally microquartz cement displays a network of intersecting blades with polyhedral cavities filled with a mosaic of irregular microquartz. Some isolated remains of quartz or feldspar grains with their overgrowths show serrated surfaces. 2) Barite crystals, iron oxides and microquartz. The barite crystals are euhedral, prismatic and are roughly perpendicular to the fracture wall. There is a mixture of small microquartz and barite crystals among the barite megacrystals, and also an opaque band of iron oxides that surrounds the barite megacrystals. 3) Opal, microquartz and chalcedony. This stage is primarily isopachous, developing sequentially from irregular botryoids of brown opal to microquartz and spherulites of checkerboard chalcedony with double optical elongation. The last phases to crystallize in the voids by means of fibrous radiating spherulites of length-fast chalcedony (Fig. 6f). Barite is partially replaced by chalcedony.

There is an opal cement which in some places is neomorphised to chalcedony or microquartz (Fig. 6e) in the residual primary porosity of the host rock. Barite in euhedral, prismatic crystals coexists with opal. The framework grains of the host rock and their overgrowths have an irregular shape owing to their growth in previously filled intergranular volume.

Some joints show infilling breccias made up of very angular silica cemented clasts from adjacent rocks. Breccia cementation shows illuvial features. Opal occurs at the base of the pores and the clasts are frequently capped with microquartz laminae 10 to 50 µm in thick. Finally, there is a precipitation of length-fast chalcedony with rhythmic extinction banding.

Mineralogically, barite crystals have large amounts of SrO. Opal spherulites have considerable quantities of $Al_2O_3$, CaO and $K_2O$, whereas chalcedony is very poor in cations.

## Diagenetic evolution of sandstones

The regional tectonic setting of the Montjuïc tilted block suggests that burial does not play an important role in the Montjuïc sandstones. Textural criteria of mechanical compaction are infrequent because of early cementation. Only some phyllite fragments are deformed into pseudomatrix. There is no evidence of chemical compaction. The early cementation has preserved an intergranular volume (30.5%) in the free-matrix sandstones, whereas primary intergranular porosity averages 4.1%. The secondary porosity is intragranular averaging 2.3% and is principally caused by the dissolution of altered K feldspar (1.2%) and rock fragments.

The relationship of cement percentage versus intergranular volume percentage of Montjuïc sandstones in a Housecknecht diagram chart (Fig. 7) shows that cementation was more important than compaction and that the high intergranular volume is preserved by an extensive cementation. This distribution pattern suggests that early cementation was the main mechanism of lithification.

## CONCLUSIONS

The principal conclusions of this paper are summarized as follows:

*Lithostratigraphy*. The Middle Miocene section of Montjuïc hill with a thickness exceeding 200 m was divided into four lithostratigraphic units from base to top (Fig. 3 and 4): (1) The Morrot conglomerate and sandstone Unit; (2) The Castell conglomerate, sandstone and mudstone Unit; (3) The Miramar marlstone Unit, and (4) The Mirador conglomerate, sandstone and mudstone Unit.

*Sedimentology*. Montjuïc hill is interpreted as a delta body made up of prodelta deposits (marlstones with planktic foraminifera), delta front deposits (mudstones, siltstones, sandstones and conglomeratic sandstones arranged in thickening and coarsening upward cycles) and delta plain deposits (sandstones and conglomerates arranged in fining upward beds with sharp erosive bases).

*Chronostratigraphy*. According to the foraminifera association, the age of the deposits of Montjuïc hill is Serravallian (Middle Miocene). The Montjuic deposits are related to the offshore Sandstone Castelló Group Unit.

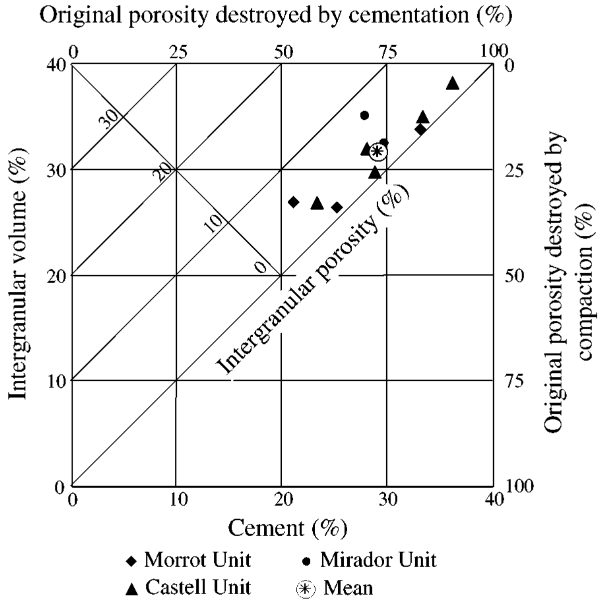


Figure 7. Plot of cement % versus intergranular volume % (cf. Housecknecht, 1987), for 10 sandstone samples of Montjuïc hill.

Figura 7. Relación % cemento - % volumen intergranular (cf. Housecknecht, 1987) de 10 muestras de Montjuïc.

*Paleoclimatology*. The palynological data and the plant remains suggest a temperate-warm and humid climate for the period of the Montjuïc delta deposition.

*Petrology*. The Montjuïc sandstones and conglomerates are mostly litharenites/rudites and lithic wackes containing siliciclastic fragments essentially made up of quartz, rock fragments and K-feldspar. The source area of the detrital framework is the Collserola mountain, where Palaeozoic materials crop out in particular in the Tibidabo-Vallvidrera area, located in the southern part of the horst.

The Montjuïc delta formation and its petrofacies are strongly related to the tectonics of the Catalan margin of the Valencia trough. The Montjuïc tilted block is related to the post-rifting stage defined by Sans et al. (1998).

*Diagenesis*. The formation of authigenic cement minerals played an essential part in the Montjuïc sandstones (Fig. 7).Two stages of cementation are present: 1) An early cementation that involved the development of a cementation sequence made up of K-feldspar overgrowths, quartz overgrowths and mesoquartz intergranular cement; occasionally, the detrital matrix is transformed into opal/microquartz; 2) A joint cementation arranged in a specific succession.

Despite a classical burial diagenetic origin proposed for these cements, a surface cementation is considered for these cements in the absence of compaction and the geological setting.

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