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The Neogene and Quaternary deposits of the Barcelona city through the high-speed train line

J.M. Salvany[1] and J. Aguirre[2]

[1]**Departament d'Enginyeria Civil i Ambiental, Universitat Politècnica de Catalunya**
c/ Jordi Girona 1-3, 08034 Barcelona. E-mail: josepm.salvany@upc.edu

[2]**Departamento de Estratigrafía y Paleontología, Facultad de Ciencias, Universidad de Granada**
Avenida Fuentenueva s/n, 18002 Granada. E-mail: jaguirre@ugr.es

ABSTRACT

A total of 208 boreholes with continuous core sampling, drilled for the construction of the high-speed train line through the city of Barcelona and other nearby infrastructures, were studied. The correlation of the lithologic logs of these boreholes allows identifying five main depositional sequences bounded by sharp erosional surfaces: i) lower Miocene, of alluvial origin; ii) middle Miocene, of deltaic-lacustrine origin; iii) lower Pliocene, of beach-shelf origin; iv) Pleistocene, of alluvial origin and v) Holocene, of deltaic origin. The erosive surfaces that separate these sequences represent important erosive hiatus linked to prolonged sea level falls at regional scale, which eliminated the upper part of each one. Sedimentation took place during decreasing intensity of extensional tectonic activity that mainly affected the Miocene deposits. The Plio-Quaternary units show their original structure apparently without tectonic alterations. Some new biostratigraphic data based on foraminifer assemblages allowed making accurate estimate of the age of the deposits.

KEYWORDS **Neogene. Quaternary. Barcelona. Boreholes. Foraminifera.**

INTRODUCTION

In the first decade of 2000, the high-speed train line through the Barcelona city subsoil ("Linea de Alta Velocidad", LAV) was projected and constructed. It led to the excavation of a tunnel of 10km in length, which begins in the district of El Gornal, in L'Hospitalet del Llobregat village, and extends practically continuously till the neighborhood of La Sagrera, in the North end of Barcelona (Fig. 1).

During the tunnel's project phase, an important number of boreholes were drilled allowing the elaboration of two geological-geotechnical cross-sections: i) from L'Hospitalet to the proximities of Sants railway station (Adif, 2005) and ii) from Sants to Sagrera railway station (Adif, 2007) (Fig. 1). Both sections are separated by an interval of about 500m of length corresponding to Sants station, which has no subsurface information available (the tunnel passes mainly at surface level and no boreholes were drilled). The sections differentiate three main stratigraphic units: the Quaternary (Holocene) of the Llobregat delta, the Quaternary (Pleistocene) of the Barcelona plain, and a Tertiary (Neogene) basement. These units are composed of unconsolidated terrigenous materials ranging from fine to very coarse grain sizes, which give layers of variable development according to the boreholes. This led to interpret a complicated structure of facies lateral changes among the

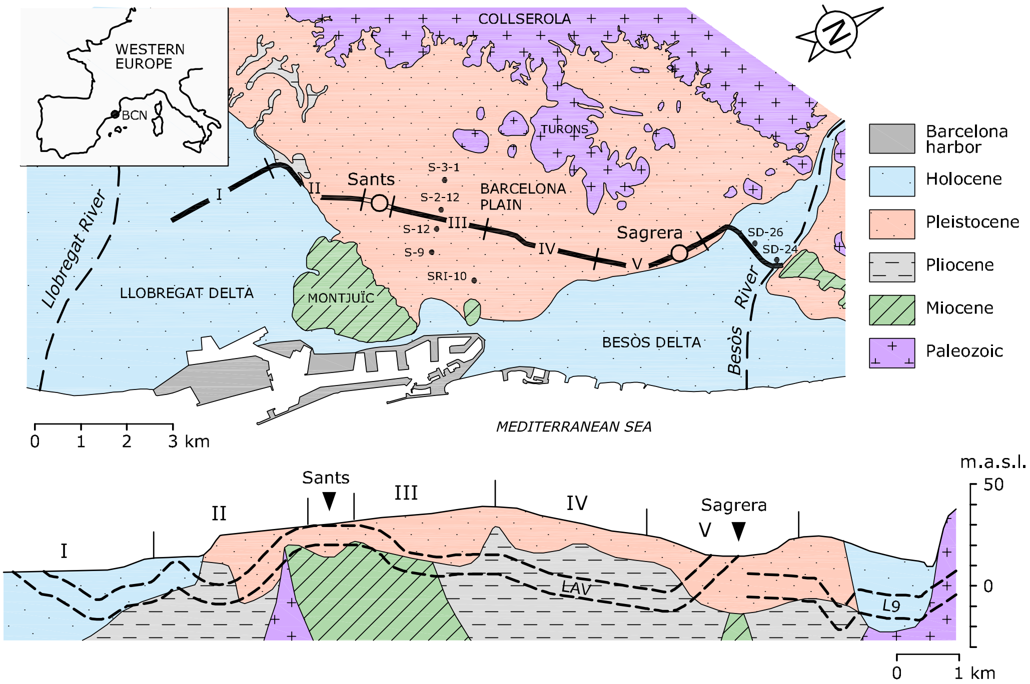

FIGURE 1. Upper part: simplified geological map of the Barcelona area and location of the studied LAV line from the Llobregat delta to Sagrera, L9 lines from Sagrera and Besòs River, and the boreholes of the L8 line and Catalunya Square. I to V are the sections enlarged in Figures 2, 3 and 4. Lower part: simplified geological cross-section and tunnels of the LAV and L9 lines.

different materials, which are difficult to understand from a sedimentary point of view.

During the tunnel's excavation, additional geotechnical and hydrogeological studies were performed in order to better understand some areas of potential constructive problems. Part of these studies were developed to protect some sensitive constructions, such as the world heritage buildings of the Sagrada Familia basilica and Casa Milà (Alonso and Ledesma, 2015; Ledesma and Alonso, 2017; Pujades *et al.*, 2015; Rodríguez and Blanco, 2012). Other studies were performed to understand the ground water behaviour during the construction of several deep enclosures (shafts) linked to the Sants-Sagrera tunnel (Culí *et al.*, 2016; Pujades *et al.*, 2014a, b), the construction of the Sagrera railway station (Candel-Soley and Verbón-Rotllán, 2008; Serrano-Juan *et al.*, 2017), and other parts of the tunnel (Arroyo *et al.*, 2012; Vilarrasa *et al.*, 2008). These studies present local geological layer-cake type models, obtained from correlating sets of close boreholes, sometimes with the help of well-logging (gamma-ray) surveys.

Beyond its constructive purposes, the boreholes of the LAV line have provided an excellent opportunity to better determine the geology of the subsurface of the city, which is still poorly known. With this goal, this paper provides a new Neogene-Quaternary stratigraphic framework and the sedimentary meaning of the Barcelona subsurface based on the revision of a selection of boreholes made during the constructive project and the subsequent tunnel construction of the LAV line, as well as of other nearby infrastructures. More especially, this paper provides criteria to differentiate the Miocene and the Pliocene deposits, commonly difficult to distinguish due to their similar lithological characteristics. Moreover, the paper present new biostratigraphic data that allow constraining the age and the sedimentary environment of the Neogene deposits. Finally, a sedimentary interpretation of the studied units in the context of the Mediterranean Catalan margin is proposed.

GEOLOGICAL SETTING

Barcelona is built on five different geological areas of the Catalan coast: the mountain of Collserola, the Montjuïc hill, the Barcelona plain, and the Llobregat and Besòs deltas (Fig. 1).

The mountain of Collserola, with a height of up to 512m above sea level (Tibidabo), is the part of the Catalan Litoral Range limited by the valleys of the Besòs River to the north and the Llobregat River to the south. It is made up mainly of metamorphic rocks (slates, hornfels, schists, quartzites), as well as sedimentary (limestones, sandstones) and granitic rocks, ranging from Ordovician to Carboniferous age (Enrique, 1990; Gil-Ibarguchi and Julivert, 1988; Julivert and Duran, 1990; Llopis-Lladó *et al.*, 1969; Sunyer-Coma, 2001; Vaquer, 1973). To the southeast, these rocks extend below the Neogene and Quaternary deposits of the Barcelona plain and deltas, thus forming its basement. They are rocks strongly folded and faulted due to Variscan and Alpine tectonics (Santanach *et al.*, 2011), as well as largely weathered from its surface up to some tens of meters deep.

Montjuïc is a gentle coastal relief, up to 175m in height, located between the Barcelona plain and the Llobregat delta. It is mainly composed of marls, sands, gravels, and conglomerates of deltaic origin, with a total thickness of about 200m (Gómez-Gras *et al.*, 2001; Parcerisa *et al.*, 2001; Salvany, 2013; Villalta and Rosell, 1965; among others). Its abundant content of marine fauna led to attribute these deposits to the middle Miocene: Vindobonian, according to ancient paleontological studies (see Via and Padreny, 1972), or Serravallian, according to the more recent one by Parcerisa (2002).

The Barcelona plain constitutes a flat surface that extends in a gentle slope from the foot of the mountain of Collserona to the coastline. This plain constitutes the top of a colluvial-alluvial deposit that ranges from a few meters to 50m in thickness (Llopis-Lladó, 1942; Ribera-Faig, 1945; Solé-Sabarís, 1963; Virgili, 1960). Traditionally, this deposit is attributed to the Quaternary, in a broad sense because it has never been dated. This age is based on its equivalence to the alluvial terraces of the Llobregat River, dated as Quaternary by Solé-Sabaris (1963). Some authors, however, consider it to belong to the late Pliocene to Pleistocene (Riba and Colombo, 2009).

At the end of the Pleistocene, a drainage network going from Collserola to the coast developed in the Quaternary plain (Julià, 1977; Vila, 1977). This caused the downcutting of a creek network known as "rieres". Its last development was greatly conditioned by the growth of the city of Barcelona (Colombo *et al.*, 2013; Riba and Colombo, 2009). Currently this network of creeks is completely buried bellow the buildings and streets of the city.

Two parts of the Barcelona plain can be differentiated: i) the north-western half of the plain, where the Quaternary directly overlies the Paleozoic basement. Part of this basement emerges in different areas forming the so-called "Turons" (the hills) of Barcelona (Santanach *et al.*, 2011). ii) The south-eastern half, where the Quaternary is above the Neogene deposits. With the subsurface information available, it remains unclear the depth at which the Paleozoic basement is located. It is interpreted that both parts are separated by a NE-SW fault, named the Turons fault by Llopis-Lladó (1942). A second fault would be, approximately parallel to that of the Turons, separating the raised block of Collserola with respect to the Turons, named the Tibidabo (or Collserola) fault by the same author. They constitute two normal faults related to the extensional tectonics that affected the western Mediterranean during the Miocene (Bartrina *et al.*, 1992; Roca *et al.*, 1999).

The Neogene below the Quaternary of the Barcelona plain includes Pliocene, middle Miocene and lower Miocene deposits.

Since the former studies by García-Faria (1893) and Rubio and Kindelan (1909) it is assumed that the Pliocene deposits form an almost continuous bed of marls below de Quaternary, up to 140m in thickness according to a deep borehole close to Sagrera station. More recently, the Pliocene has been studied in several excavations and drillings of the city (Alborch *et al.*, 1980; Cabañas, 1986; Gillet and Vicente, 1961; Vicente-Castells, 1979, 1986, 1990; Vicente and Fernández, 1993). However, a precise stratigraphy of this unit remains unknown. This differs from the Pliocene of the neighboring area of the lower Llobregat valley, where a large number of paleontological studies have been carried out (Almera, 1894; Civis, 1972, 1977a, b, 1979; Gibert-Atienza, 1995; Gibert and Martinell, 1992, 1993, 1995; Martinell and Marquina, 1981; Martinell, 1988; Sanz de Siria-Catalán, 1994). These studies have analyzed the outcrops along the valley margins and have established a stratigraphy consisting of a lower unit of gray-blue marls that grade upwards to an upper unit of yellow clay and sand, all of which amounts a few tens of meters in thickness. These materials contain abundant fossils of marine fauna and flora, as well as a great variety of biogenic structures. Despite this rich fossil record, there are discrepancies about the precise age and paleoenvironmental meaning of the Pliocene sediments.

The characteristics of the middle Miocene below the Barcelona plain remains almost unknown. In a broad sense, its contents can be considered equivalent to those found in the Montjuïc hill (Fig. 1).

The lower Miocene deposits are identified in several areas of the subsoil of the Barcelona plain and the Llobregat delta (Filbà *et al.*, 2016; GISA, 2002; Parcerisa *et al.*, 2008). It consists of alluvial deposit mainly composed of reddish clayey gravels unconformably overlying the Paleozoic rocks. Casanovas-Vilar *et al.* (2010) corroborated the early Miocene age based on rodent remains in samples taken from a borehole of the L9 line. The Miocene outcrop at the northern margin of the Besòs delta (Fig. 1) is made up of a reddish conglomerate up to 70m in thickness, of imprecise age (Vicente-Castells, 1957, 1989), which would also correspond to the early Miocene continental episode.

The Llobregat delta has been the subject of numerous sedimentological studies (Cabello *et al.*, 2007; Checa *et al.*, 1988; Gàmez *et al.*, 2009; Gàmez-Torrent, 2007; Lafuerza *et al.*, 2005; Liquete *et al.*, 2008, 2010; Manzano-Arellano *et al.*, 1986-1987; Marqués, 1984). According to Gàmez-Torrent (2007), the Llobregat delta is made by the superposition of four deltaic wedges: the first three (Lower Deltaic Complex) correspond to the Pleistocene, while the fourth (Upper Deltaic Complex) forms the current delta, developed during the Holocene, which was greatly influenced by the growth of the city during the last 2000 years (Marqués, 1984). This youngest delta forms a sequence made up by a basal layer of gravels, a middle layer of silt, and an upper layer of sand and gravel. The basal layer was deposited during the fall of the sea level at the last glaciation and the remaining ones was formed due to the progradation of the delta during the subsequent Holocene transgression that extends to the present day.

The Besòs delta has similar sedimentological characteristics than the Llobregat delta (Velasco *et al.*, 2012). Its later stages of evolution were conditioned by the historical development of the city of Barcelona (Julià-Brugués and Riera-Mora, 2012; Riba and Colombo, 2009).

METHODS

A total of 208 boreholes drilled with continuous core sampling, between 15 and 69 meters in length, were studied: 195 correspond to the LAV line, and the rest to additional nearby projects (see the location of these boreholes in Figs. 1; 2; 3; 4).

Those belonging to the LAV line correspond to different drilling campaigns related to the constructive project of the tunnel between 2002 and 2009, and its subsequent construction up to 2012 (Adif, 2005, 2007, 2009, 2011; GIF, 2001, 2003, 2004a, b; LOSAN, 2008). The other boreholes correspond to the L9 line, between Sagrera station and the Besòs River (GISA, 2002), the L8 line, between Espanya Square and Gràcia neighborhood (GISA, 2012), and Catalunya Square (GISA, 2009). The cores of 38 of these boreholes have been analysed by the authors at naked eye, as well as through thin-sections (see some of them in Figs. 5; 6; 7; 8). This included a detailed observation of the texture (grain sizes, grain shapes, color, type and amount of matrix and/or cement, and sedimentary structures) and the composition of the different lithofacies. The remaining cores are the lithological logs performed by the drilling companies, which are adequate for the purpose of this study. Given the uneven logs provided by the different companies, a standardization of the information, with the aim to facilitate the correlation between boreholes, was established.

In boreholes EI-130, PM, EG, S-2-12, and SRI-10, thirteen samples were collected (see locations of samples in Figs. 6; 7; 8) in order to provide an age estimate of the deposits based on planktonic foraminifers. The samples were sieved and dried at 40ºC; the fraction above 125 microns was studied. In addition, the qualitative analysis of the benthic foraminifer assemblages allows inferring environmental conditions.

LITHOSTRATIGRAPHY

The studied boreholes allow identifying rocks of the Paleozoic basement and five main depositional sequences corresponding to the early Miocene, middle Miocene, Pliocene, Pleistocene, and Holocene, all of them separated by sharp erosive surfaces.

Paleozoic basement

Near the Sants station, the LAV line crosses Paleozoic calcareous rocks that form an isolated small paleorelief buried below Neogene deposits (Fig. 2). Similar calcareous rocks, attributed to the Silurian-Devonian, are crossed by other nearby boreholes (GISA, 2002; Jurado and Salvany, 2016) and are also exposed in Collserola and Turons areas (Juliverd and Duran, 1990; Sunyer-Coma, 2001). Near the Sagrera station, the Paleozoic basement is also identified below the Holocene sediments of the Besòs River through the L9 line (Fig. 1). This is a granitic basement with similar rocks to those outcropping in the lower part of the Collserola mountain, of Permo-Carboniferous age (Enrique, 1990).

Early Miocene

The early Miocene is only identified in the S-3-1 borehole of the L8 line (Fig. 8). In this borehole, the lower Miocene unit forms a monotonous sequence of brown to reddish coarse gravels, located between a depth of 44m and its bottom at 66m depth. Gravels are well graded and rich in clay matrix, of metamorphic composition (mainly shales, hornfels and quartzite), and show mostly angular shapes. Some intervals are of dominant clay composition, although always with variable gravel content.

Middle Miocene

Between the Sants station and borehole EG (Fig. 3), below the Quaternary deposit, the LAV line crosses a cyclic alternation of two sets of layers: clay, silt and fine sand (M1), and coarse-medium sand and gravels (M2). The thickness and vertical location of the M1 and M2 units varies among boreholes, making their correlation complicated. This correlation was resolved considering a gentle synclinal structure crossed by some normal faults.

Near the Sants station (boreholes S1, S2 and S3, Fig. 3), the Miocene forms a thick package of sand and gravel,

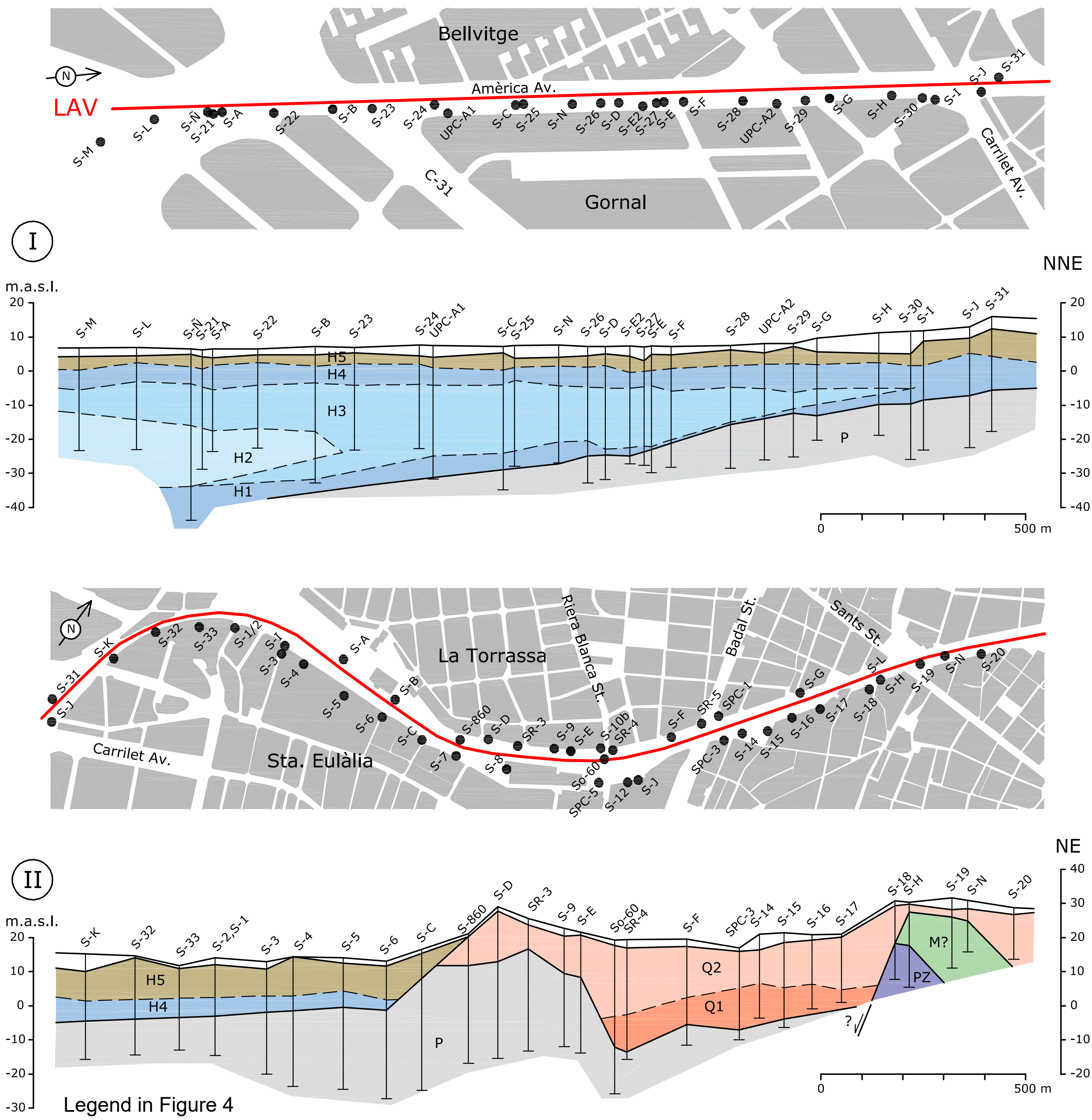

FIGURE 2. Sections I (Hospitalet-La Torrassa) and II (La Torrassa-Sants) of the LAV line. See Figure 1 for location.

up to 27m in thickness and yellowish in color. Gravels are composed by white, well-rounded quartzite grains up to 6cm in size. The sand is mainly coarse grain-sized and composed of quartz-feldspar and mica (reworked weathered granite). The other boreholes indicate similar characteristics for coarse materials, but little can be said about the finer ones.

In S-3-1 borehole (Fig. 8), the middle Miocene forms a single coarsening upward cycle of 10.6m in thickness developed just above the lower Miocene gravels. In borehole S-2-12 two similar cycles are differentiated between 50m in depth and the end of the borehole at 65m in depth. Above these cycles, the middle Miocene succession forms a clay interval up to 20m in thickness (M3). It is a light brown pure clay that intercalates minor layers of gravel (or conglomerate) and sand (or sandstone), leading to finning upwards cycles. These clays are not identified in the Montjuïc hill and seem to constitute the top of the

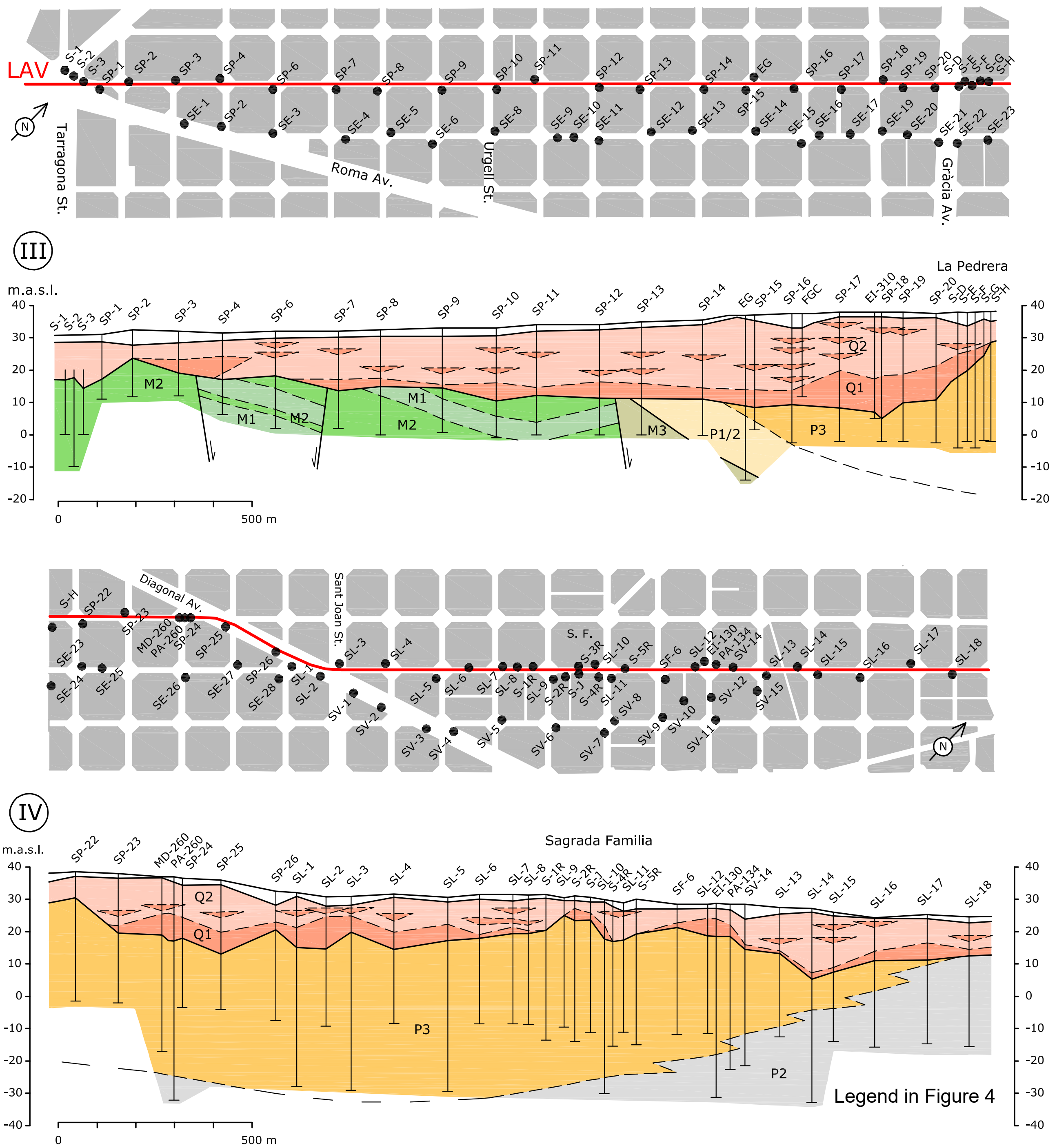

FIGURE 3. Sections III and IV of the LAV line through Provença and Mallorca strets. See Figure 1 for location.

Miocene sequence only preserved in this central part of the Barcelona plain.

In the Sagrera area, below the Quaternary deposits, several boreholes have crossed a thick succession of coarse sand and gravels, of grey to clear brown color, up to 38.7m thick in the S-4 borehole (Figs. 4; 7). Gravels are mainly composed of rounded, well-sorted quartzite grains between 3 and 6cm in size. The sand is of dominant quartz-feldspar composition with scattered gravels and variable amounts of silty-clay matrix. This deposit can be interpreted as a small paleohill of Miocene gravels. This interpretation is supported by the fact that in some boreholes the Pliocene marls separate these gravels from those composing the Quaternary. When both gravels are directly superposed it is difficult to differentiate between them.

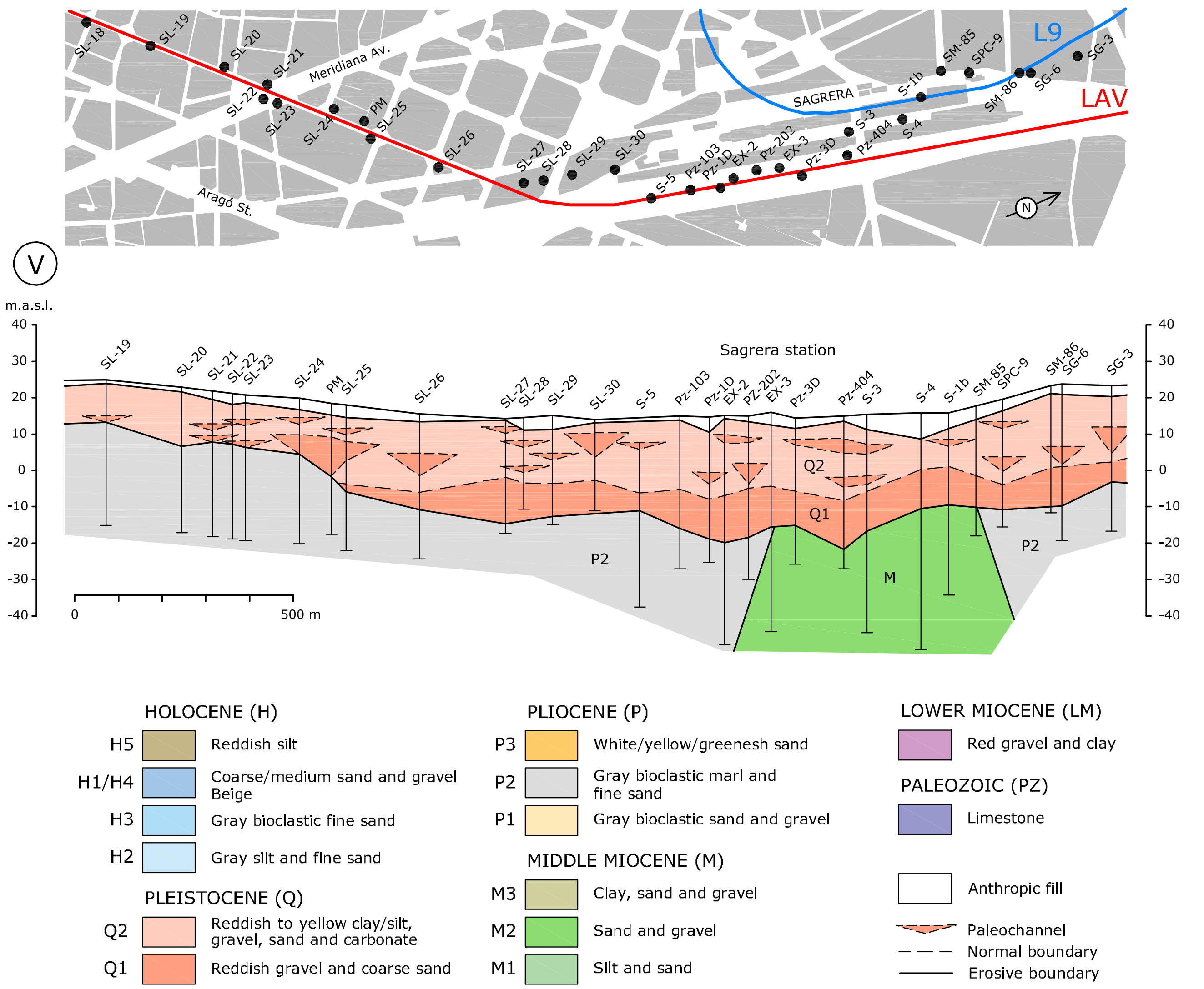

FIGURE 4. Section V of the LAV line through Mallorca Street and Sagrera railway station. See Figure 1 for location.

The equivalence of these materials to those forming the Montjuïc hill, of middle Miocene age, is based on two main facts: i) the cyclic alternation of fine and coarse lithologies, which is a characteristic feature of Montjuïc materials (Gómez-Gras *et al.*, 2001; Salvany, 2013). Moreover, the abundance of gravel levels of large grain size is almost absent in the Pliocene units (see below). These gravels cannot correspond to the lower Miocene or the Quaternary units because their clasts are clearly different in shape and composition. Surprisingly, however, there is a lack of grey marls, which are a frequent component of the Montjuïc cycles. ii) The Pliocene and Quaternary deposits are not affected by faults and folds.

Pliocene

Below the Llobregat delta (Figs. 2; 3) the Pliocene forms a uniform gray marl unit. The study boreholes enter up to 30 meters into the marl. However, some nearby longer boreholes allow to assign to this unit a thickness greater than 100m (Gàmez-Torrent, 2007). In some boreholes, the upper part of this unit forms a yellowish silt interval, of common laminated structure, with some layers of fine sand and sandstone, up to several meters in thickness.

In the Barcelona plain three main units (P1, P2 and P3) are identified:

P1 unit constitutes a basal unit of gravel-bearing sand that contain fragments of marine fauna (mainly bivalves), of 13 meters thick in the EG borehole (Fig. 6). The sand is mainly fine grained and greenish to grey color. Gravels are mainly less than 1cm in grain-size, occasionally up to 4cm, well rounded, and of quartzite composition. Minor sandstone layers up to 15cm in thickness are present in the lower part of this unit. This unit is also present in boreholes

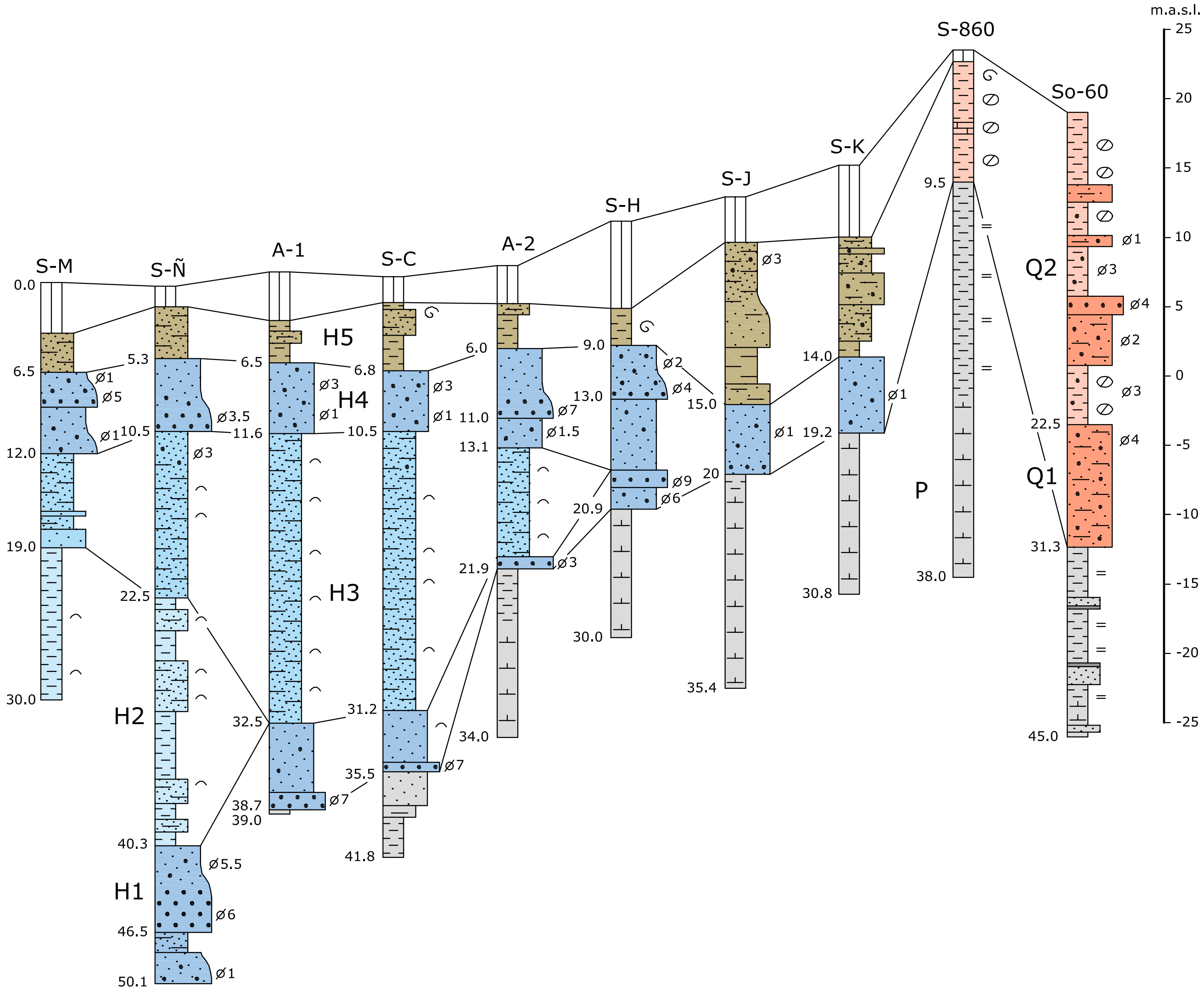

FIGURE 5. Representative boreholes of sections I and II of the LAV line. See Figure 2 for location.

S-2-12 and SRI-10 (Fig. 8) with similar lithological characteristics, being of 8 and 5m in thickness respectively.

P2 unit consists of grey marl with minor layers of sand, rich in marine fauna and bioturbation structures. The sand forms finning upward cycles up to several meters in thickness, of variable development depending on the boreholes (Fig. 7). Marine fauna consists mainly of fragments of mollusc shells (mostly bivalves), as well as abundant foraminifera. The boreholes of the LAV line penetrate up to 30 meters into the marl unit never reaching its base. Exceptionally, borehole SRI-10 allowed a complete section of this unit, which is 23m thick (Fig. 8).

P3 unit constitutes a thick package of sand, up to 40m in thickness. It forms an alternation of layers of coarse, medium and fine sand, of white to yellow color. In all cases, this sand is of dominant siliceous composition. Occasionally it includes small white gravels (mostly less than 1cm in size), well rounded, of quartzite composition. Minor layers of greenish silt are also present. These layers form finning upward cycles of several meters in thickness. The uppermost levels of these cycles, those composed of silt or fine sand, frequently show burrows. The number and degree of development of these cycles vary depending on the boreholes and a clear correlation between them cannot be established.

Pleistocene

The top of the Pliocene and Miocene deposits forms an irregular erosive surface that goes from 10 to more than 40m in depth (Figs. 2; 3; 4). In many boreholes, this erosive surface is associated to a whitish calcareous crust, up to few meters in thickness, affecting the top of the Neogene deposits. Above this erosive surface, the Pleistocene constitutes a heterogeneous deposit composed of two main types of layers: gravel and coarse sand, and clay and silt bearing carbonate levels, all of which show a dominant reddish color.

Gravels mainly form an almost continuous basal layer of very variable thickness, up to 13 meters in the area of Sagrera station (Q1). Upward, gravels form discontinuous layers (paleochannels) of variable development according to the boreholes, of a few meters in thickness, intercalated with the finer sediments. This set of gravels and fine sediments forms an upper unit (Q2), between 7 and 23m in thickness.

Gravels are well graded and contain abundant silt and coarse sand matrix. Gravels are up to 10cm in size, show sub-rounded shapes, and are mainly of metamorphic composition (shales, hornfels, quartzite). The sand also forms layers of variable grain size, with pebbles of the same metamorphic composition. In all cases, quartz-feldspar composition dominates, usually with mica grains, coming from reworking of weathered granite.

The clay and silt are the dominant materials of the upper unit, with reddish, brown and yellow colors. Since the early studies by Virgili (1960) and others, it is assumed that clays are of dominant dark colors (red, brown) while silts are beige or yellow. However, a clear textural differentiation at naked eye between both lithologies is not possible. Moreover, there are not granulometric data available to validate this idea. In reality, lighter colors are related to high carbonate content.

Usually, fine-grained materials contain variable amounts of scattered particles of coarse sand and small gravels, as well as small remains of carbonized organic matter (black small grains). Fragments of shells of continental snails are usually observed in the uppermost levels, but they are absent in the lower levels, probably due to its dissolution.

Carbonate forms whitish levels of nodular structure, normally of less than 1m in thickness. Nodules can be densely packed or scattered into a silty matrix light in color, but also into reddish clay. The size of these nodules can vary from a few millimeters (micronodules) to some centimeters. Less frequently, carbonate forms laminated crusts of a few tens of centimeters in thickness, usually developed on the top of the nodular levels. The number of carbonate levels and their thickness varies highly depending on the boreholes.

As a whole, the Pleistocene forms a fining upwards sequence with a lower part where gravels are the dominant lithology, a middle part where layers of gravels, sand and clay-silt alternate, and an upper part of dominant clay-silt. The carbonates can develop in any level above the basal layer of gravels. The degree of development of these lithologies highly varies according to the boreholes thus preventing a precise correlation between them.

The top of this sequence ends with an anthropic fill of some meters in thickness and a variable development depending on the boreholes. It constitutes a chaotic mixture of sand, clay and gravels with occasional man-made debris. Usually it is not easy to differentiate from the underlying natural deposit.

Holocene

In the Llobregat delta, the Holocene forms a wedge-shaped formation developed above the Pliocene marls that thickens toward the south reaching 50m in thickness (Fig. 2). It is well stratified and consists of five main layers:

A basal layer of gravel (H1), which is composed of polygenic and well-rounded gravels, of up to 7cm in grain size, and coarse sand. These materials form a finning upwards cycle that thickens to the south, usually less than 5m in thickness.

A middle silty layer (H2), which is a dark gray silt with minor layers of fine sand containing small fragments of marine fauna (bivalve). It only develops in the inner part of the delta where it reaches 17.8m in thickness in the S-Ñ borehole (Fig. 5).

A middle layer of bioclastic sand (H3), which forms a uniform package of silty fine sand, rich in marine fragments of fauna (bivalve), of gray color and up to 21m in thickness in the A1 borehole.

An upper layer of sand and gravel (H4), which is composed of clean (without matrix) coarse sand with frequent scattered gravels. Gravels are well rounded, between 1 and 4cm in size, and polygenic. It has a relative uniform thickness between 6 and 10m with finning upwards trend.

An upper silty layer (H5), which is composed of reddish silt with minor layers of sand and small gravels up to 3cm in size. Fragments of continental snail shells are usually present scattered between the silt. The thickness of this interval increases toward the delta margin, from 6 to 15m.

In the study section, the Besòs delta forms a tabular deposit of about 35m in thickness developed above a granitic (Paleozoic) basement (Fig. 7). The stratigraphy is similar to that of the Llobregat delta, with a basal layer of gravel, up to 15m in thickness (H1), a middle layer of gray silt, rich in marine fauna and about 10m in thickness (H2), an upper layer of sand and gravel, up to 25m in thickness,

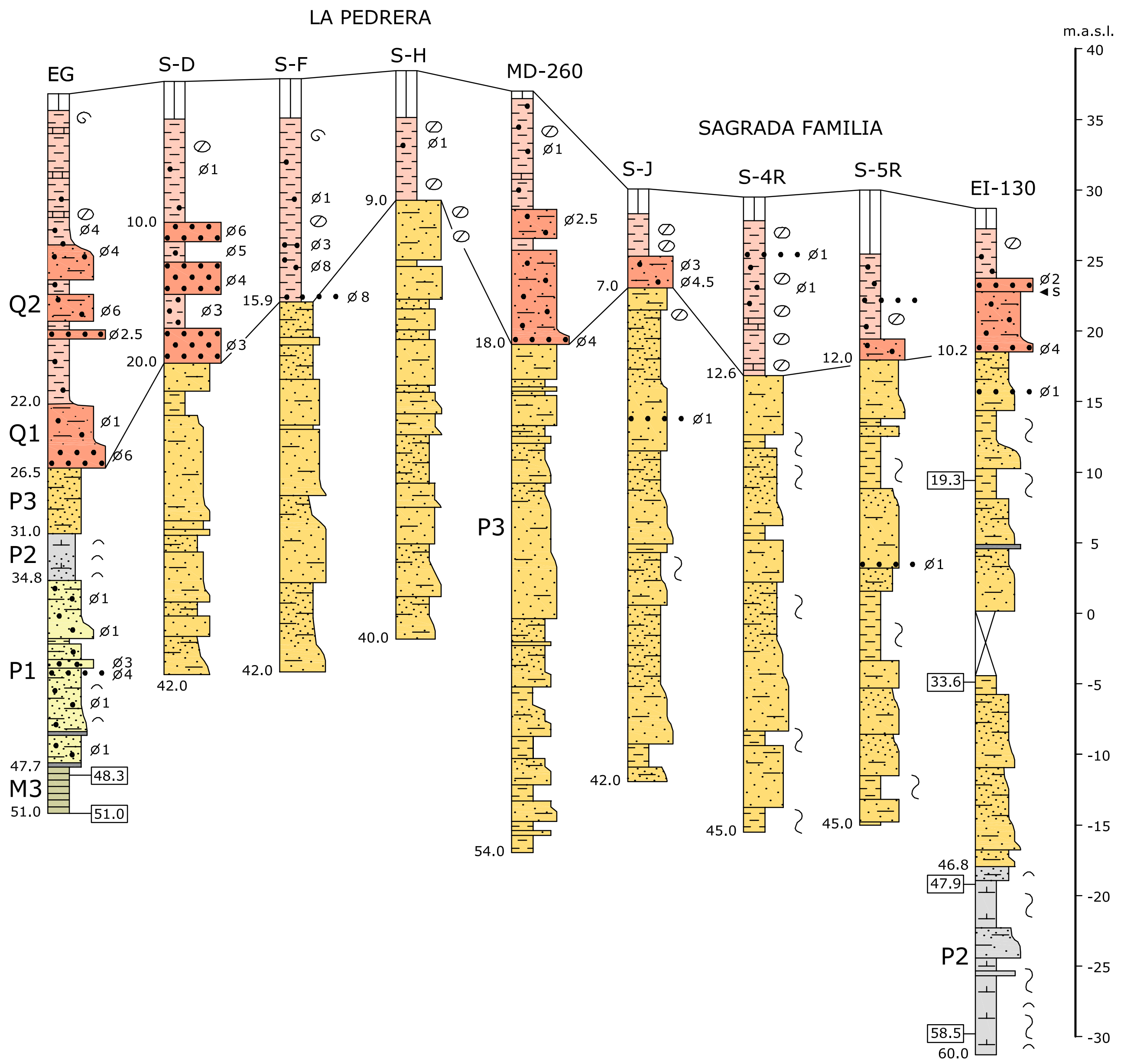

FIGURE 6. Representative boreholes of sections III and IV of the LAV line. See Figure 3 for location.

and an upper silty layer, up to 15m in thickness. In this case, a layer equivalent to H3 is not identified. Gravels are composed of a wide variety of lithologies, including metamorphic, sedimentary (sandstones, carbonates) and granitic rock fragments.

BIOSTRATIGRAPHY

Samples were collected in the Miocene and Pliocene deposits (Figs. 6; 7; 8). The Miocene samples (EG-48.3, EG-51, S2-12-33.7, and S2-12-49.5) cannot be dated due to the lack of planktonic foraminifers. However, it is worth mentioning the presence of pristine ostracod tests in sample S2-12-33.7.

The Pliocene samples are very rich in foraminifers, predominating benthic over planktonic species, with planktonic/benthic (P/B) ratios ranging from 28.5% (sample SRI-10-50.3) to 9% (sample EI-130-47.9). Six samples were collected in the P2 unit (EI-130-58.5, EI-130-47.9, PM-33.2, PM-23.4, SRI-10-50.3, and SRI-10-38.7) and three in P3 unit (EI-130-33.6, EI-130-19.3, and SRI-10-30.2). Planktonic foraminifer assemblages in all these samples are dominated by *Orbulina universa*, *Globigerina* spp, *Globigerinoides* spp, and *Trilobatus* spp, with subordinate

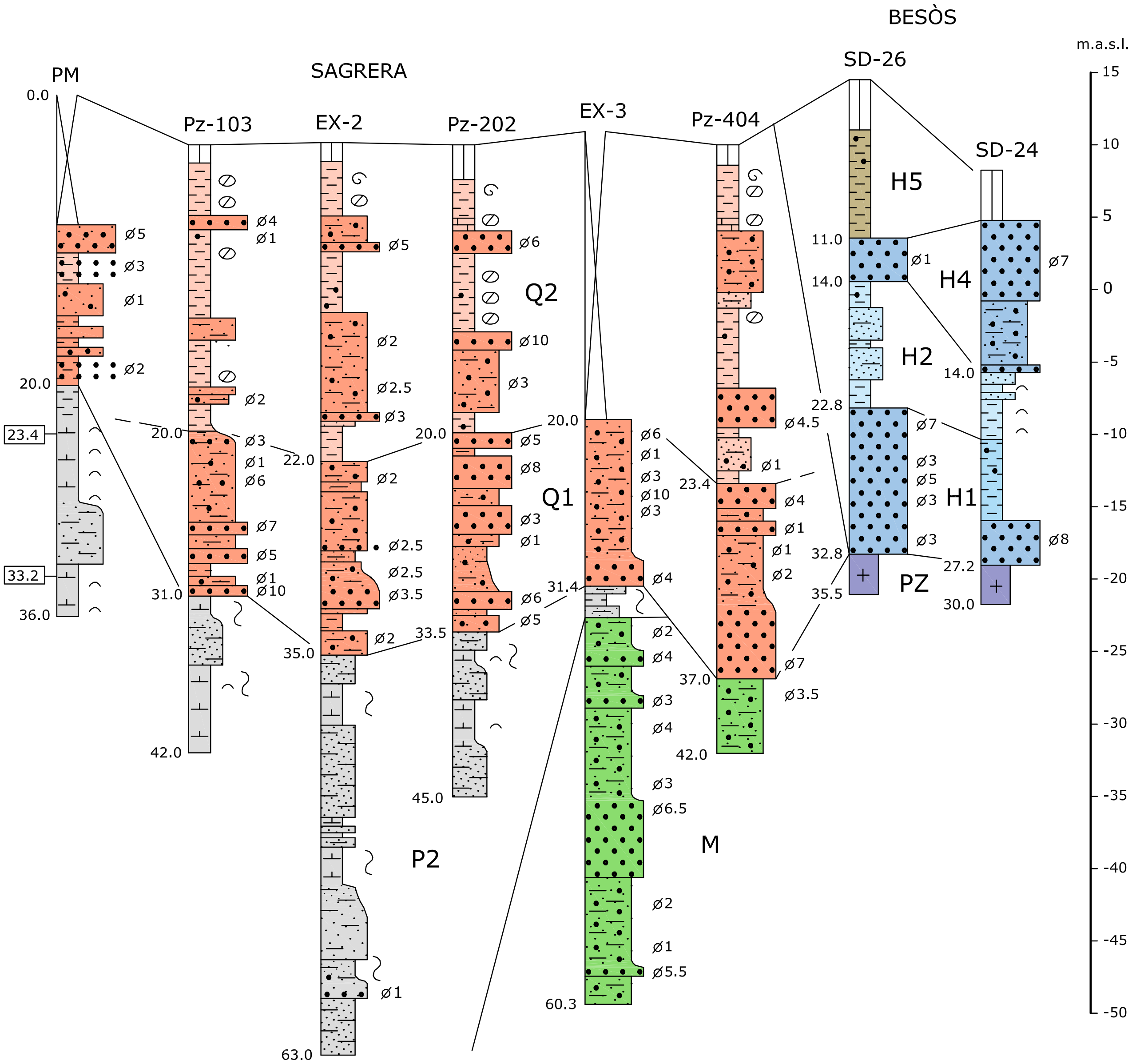

FIGURE 7. Representative boreholes of section V of the LAV and L9 lines. See Figure 4 for location.

neogloboquadrinids. In relation with biostratigraphically significant species, the lowermost samples of P2 unit (EI-130-58.5, PM-33.2, and SRI-10-50.3) show high relative abundance of *Sphaeroidinellopsis* spp (10%, 9% and 14%, respectively). These results allow confidently assigning them to the lowermost early Pliocene biozone of the Mediterranean biostratigraphic scale: the *Sphaeroidinellopsis* acme biozone MPl1 (Lirer *et al.*, 2019).

In the remaining three samples of the upper part of P2 unit (EI-130-47.9, PM-23.4, and SRI-10-38.7), *Sphaeroidinellopsis* is present but its relative abundance is low. These samples contain *Globoturborotalita nepenthes*. The last occurrence of *G. nepenthes* took place at 4.36Ma (Wade *et al.*, 2011). This indicates that the upper part of P2 unit is early Pliocene in age: most likely MPl2 biozone of Lirer *et al.* (2019). For this interval, it would be expected to find *Globorotalia margaritae*, which is the typical biostratigraphic marker for this time interval. Nonetheless, the nominal species has not been found in the study samples, which agrees with previous findings (Alborch *et al.*, 1980; Civis, 1972, 1977a, b, 1979; Martinell, 1988).

Samples from the P3 unit cannot be dated since they do not contain foraminifers or, if present, they are rare and with no biostratigraphic significance. Its stratigraphic position, above the early Pliocene P2 unit and below sediments attributed to the Pleistocene, suggests that P3 unit can be Pliocene in age.

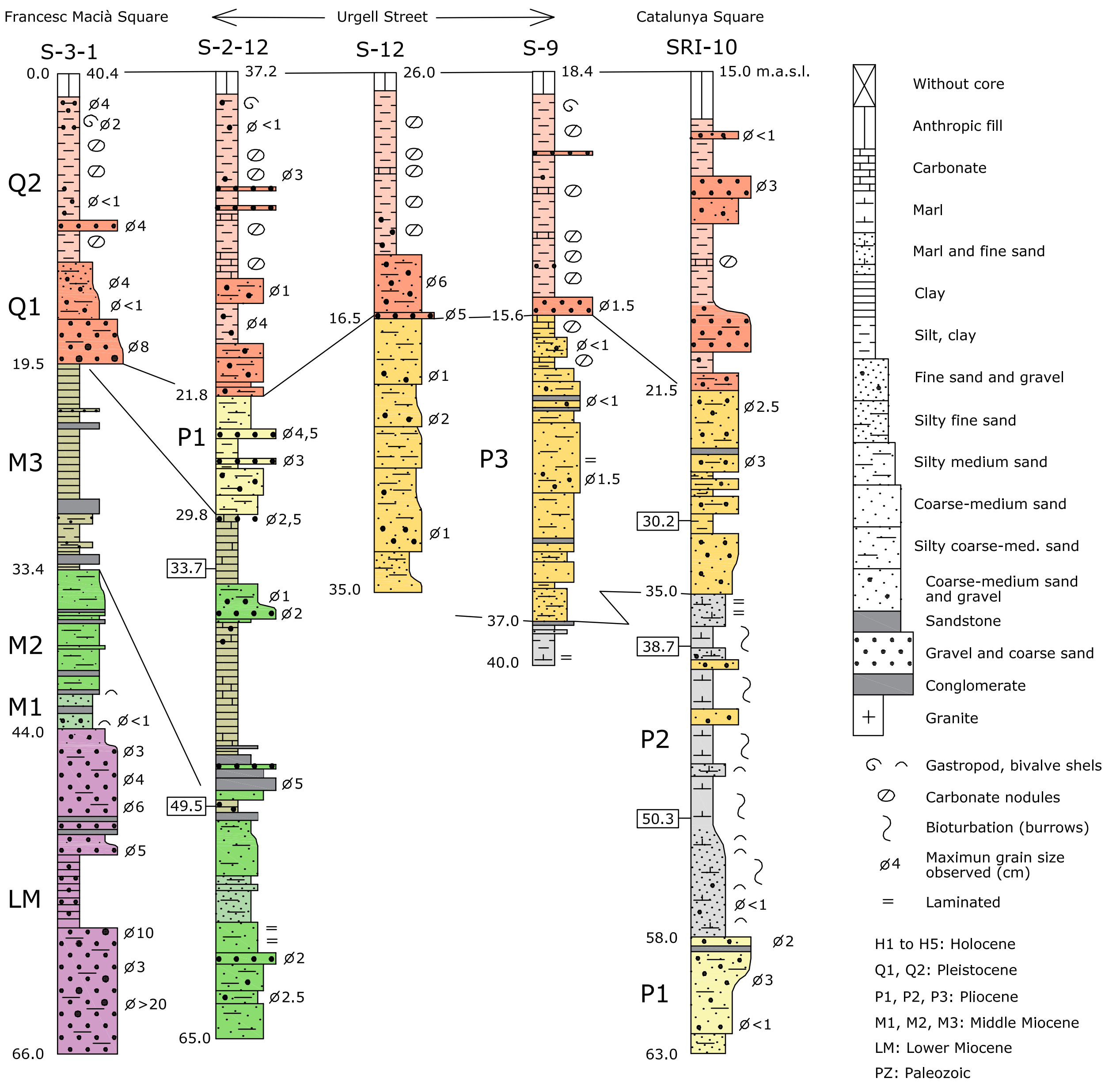

FIGURE 8. Representative boreholes of the L8 line through the Urgell Street, and the Catalunya Square. See Figure 1 for location.

SEDIMENTARY INTERPRETATION AND DISCUSSION

The litho and biostratigraphic data enable providing a sedimentary interpretation that can be stated in the following episodes (Fig. 9):

i) The lower Miocene gravels represent an alluvial deposit linked to the SE slope of Collserola, which was the source area as indicated by the metamorphic composition and the dominant angular shape (short transport) of the gravels. This alluvial deposit would be part of a thick continental sedimentation that took place during the syn-rift stage of the extensional tectonics that affected the Catalan margin since the late Oligocene up to the early Miocene (Roca *et al.*, 1999). However, their uncertain age and partial preservation (for the most part eroded) prevents further interpretations.

ii) The Miocene deposits crossed by the LAV line show similar lithofacies than those outcropping in the Montjuïc hill. However, the available data renders a precise correlation between them impossible. According to Gómez-Gras *et al.* (2001), these deposits would correspond to a deltaic system. The cyclic alternation of fine and coarse terrigenous sediments represents a delta system affected by transgressive-regressive episodes. The paleogeographic reconstruction of this delta is difficult because of the scarcity of data. Probably, the Miocene layers of the LAV line represent the upper part of the deltaic succession. The clay intervals that form the top of the succession can be interpreted as lacustrine deposits developed at the end of the Miocene sedimentation. The presence of ostracods and the absence of foraminifers and other marine fauna support this interpretation.

In the context of the Catalan margin, this deltaic-lacustrine deposit would be part of the depositional sequence of latest Serravallian to Tortonian age, bounded by the Messinian unconformity, which represents a pronounced sea level fall that affected the entire western Mediterranean region (Bartrina *et al.*, 1992). Its deposition took place in an extensional tectonic setting of gradual decreasing activity. This is the post-rift stage of Roca *et al.* (1999), or the thermal subsidence stage of Bartrina *et al.* (1992), developed from the late Burdigalian to the present day.

iii) After the Messinian sea-level fall, the Pliocene begins with a new marine transgression and the restoration of the sedimentation in the Catalan coast. This is the Zanclean transgression, which is well documented in many areas of the western Mediterranean region (Aguirre *et al.*, 2014; Cornée *et al.*, 2014; Duvail *et al.*, 2005; Lancis *et al.*, 2015). In the Barcelona plain, the Pliocene developed above the Miocene deposits previously deformed and eroded. The P1, P2 and P3 units represent a deepening-shallowing cycle.

The P1 bioclastic sands and gravels are interpreted as basal high-energy lag deposits linked to the first stages of the transgression. In the P2 unit, the percentage of benthic foraminifer is higher than the planktonic one (>71%). These values are characteristic of inner platform settings (Murray, 1991, 2006). Presence of fragments of plant remains in the samples agrees with this interpretation. The lower part of the P2 marls present relatively diversified benthic foraminifer assemblages dominated mostly by *Hanzawaia boueana*, followed by low-oxygen taxa, such as *Bulimina* spp, *Uvigerina* spp, *Rectuvigerina* spp, *Bolivina* spp, *Marginulina* spp and *Cassidulina neocarinata*. In addition, deep-water taxa, such as *Melonis* spp, *Siphonina planoconvexa* (Murray, 1991, 2006), are also significant. In the upper part of the unit, low-oxygen inhabitants (*Uvigerina*, *Bulimina*, *Marginulina* and *C. neocarinata*) are also present, but the benthic foraminifer assemblages are almost exclusively dominated by *H. boueana*, followed by *Ammonia* spp. The overabundance of these two taxa is indicative of very shallow waters, most likely shallow inner shelf. This change in the benthic foraminifer assemblages suggests a shallowing upwards trend, consistent with the transition to the highstand system tracts deposits of the P3 unit (see below). The marly and silty nature of the P2 sediments suggests that deposition took place in a very sheltered shallow setting, where low-circulation patterns prevailed and, consequently, low oxygen bottom conditions established. A similar interpretation was proposed by Martinell (1988). Pervasive presence of pyritized foraminifer casts is consistent with these conditions. In these protected environments, ecological factors other than bathymetry were more important controlling the distribution of benthic foraminifer assemblages. In the study case, depleted-oxygen bottom was the key ecological factor. The P3 sands represent beach and foreshore sediments, which laterally, to the east, change into the P2 marls. As demonstrated by biostratigraphic data, the whole sedimentary succession (P1, P2 and P3 units) formed during the Pliocene.

According to the mineral composition of the sands (dominantly quartz and minor amounts of feldspars and micas), the source area of these deposits would be mainly the granitic rocks of the Litoral Range northeastward of the Barcelona plain. Longshore currents, similar to the present-day coastal dynamics, transported the sediment from this source area to the Barcelona plain. The dominant hard siliceous composition of the gravels and their well-rounded shapes point out a high degree of maturation, consistent with the prolonged wave action that these sediments endured through longshore drift. According to Bataller (1922), during the Pliocene transgression, the Montjuïc hill formed initially an island that later, after a progressive accumulation of sand, became a tombolo. This tombolo constituted a barrier that trapped the sand coming from the NE and favoured the beach progradation in the area of Barcelona. At the same time, the tombolo limited the development of beaches in the Llobregat area, where sedimentation was mainly characterized by fine-grained deposits (gray marls and yellow silts). This area formed then a long bay (or ria) that penetrated more than 10km inland, mainly filled up by sediments coming from the surrounding coastal mountains of Collserona and Garraf (Gibert-Atienza, 1995).

The Pliocene succession crossed by the LAV line is similar to that observed in the outcrops of the lower Llobregat valley, also dated as early Pliocene (Civis, 1977a, b, 1979; Martinell, 1988). The P1 unit would be equivalent to the lower breccias above the Paleozoic basement, described by Civis (1977a, b) and Gibert and Martinell (1995). The P2 unit corresponds to the blue clays that mainly compose this succession, and the P3 unit to the upper yellow sands and clays, described by all authors.

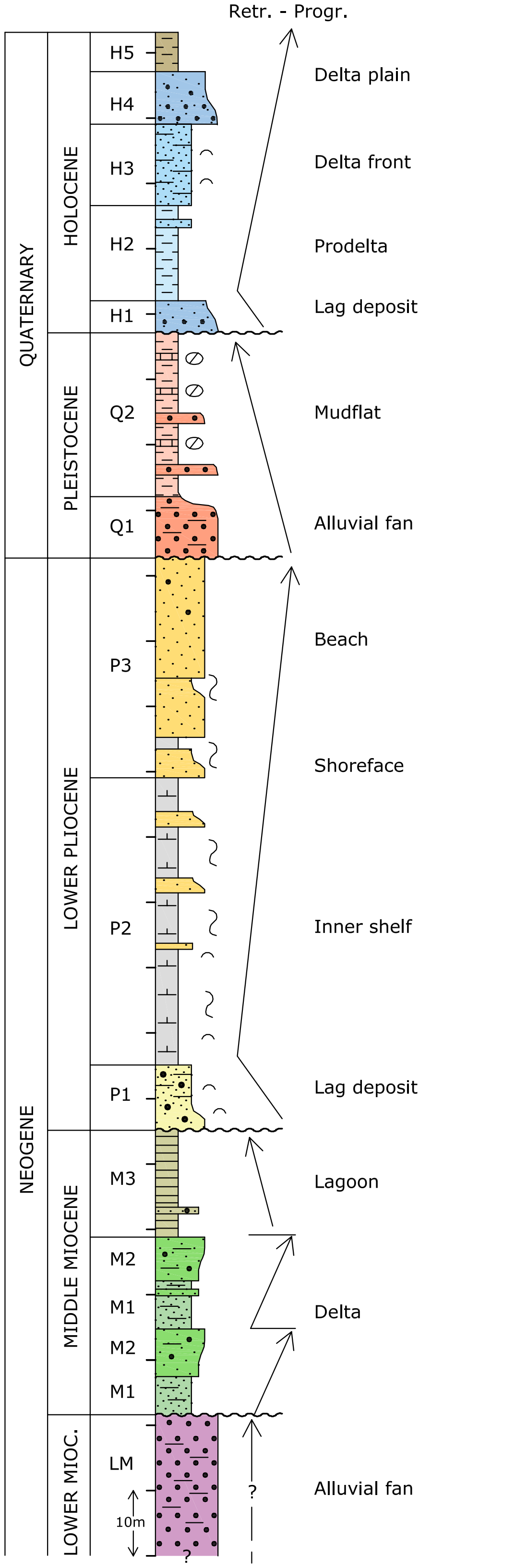

FIGURE 9. Synthetic lithologic log, age and sedimentary environments of the whole Neogene and Quaternary deposits studied.

It remains unknown which materials formed in the late Pliocene. In the Neogene basins of Baix Ebre and Empordà this period is represented by continental (alluvial) sediments that overly a marine succession of early Pliocene age (Arasa-Tuliesa, 1990; Arasa-Tuliesa and Cabrera, 2018; Fleta *et al.*, 1991). In the lower Llobregat, the Pliocene succession also ends with a continental conglomerate although of imprecise age (Gibert and Martinell, 1992). In these cases, the continental materials grade above the marine sediments indicating the beginning of continental sedimentation in a regressive setting. In the area of Barcelona, Riba and Colombo (2009) suggest that a part of the basal gravels of the Quaternary formation could correspond to the late Pliocene (the Plio-Quaternary unit as stated by these authors). However, this is difficult to justify due to the complete lack of paleontological data. The sharp erosive surface that cuts the Pliocene sands (P3) of the Barcelona area seems to indicate that a significant part of the Pliocene succession was eroded. It remains unknown if this lack of upper Pliocene deposits is due to erosion or no sedimentation. Anyway, it is reasonable to consider that the continental succession above this erosive surface would be post-Pliocene. This agrees with Solé-Sabaris (1963) who considered that the pre-Quaternary erosion occurred during the early Pleistocene, while the subsequent sedimentation mainly corresponds to the middle-late Pleistocene.

According to the subsurface data provided by the LAV lines, the Pliocene deposits do not show tectonic deformations. However, many studies of the Barcelona area have described fault systems crossing the Pliocene units (Culí *et al.*, 2016; Gàmez-Torrent, 2007; Riba and Colombo, 2009; Serrano-Juan *et al.*, 2017; Vázquez-Suñé *et al.*, 2016; Velasco *et al.*, 2012). Many of these faults are interpreted to resolve sharp lateral changes of lithologies, without taking into account that those changes may be due to lateral changes of facies typical of the sedimentary environments. At a regional scale, it is obvious that the Pliocene was affected by post-rift extensional tectonics because marine marls are more than 120 meters above the sea level in the outcrops of the lower Llobregat valley, while being 100m below the sea level in the Llobregat delta front. According to Solé-Sabaris (1963), this variation in height supposes a tilting of Pliocene deposits toward the sea along the Llobregat valley caused by an uplift of the Litoral Range.

iv) The erosion that preceded the Pleistocene sedimentation cuts through the Miocene and Pliocene deposits at different levels causing an irregular paleotopography where highs and lows alternate. The carbonate crust that is usually associated to this erosive surface represents a long period of lack of sedimentation and the development of a pedogenetic soil. The finning upward sequence that characterizes the Pleistocene represents the evolution of a retrogradant alluvial system. The basal layer of gravels constitutes a lower stage of major expansion of the alluvial system mainly filling the deeper zones of the basal erosive surfaces. The uppermost sediments represent the development of a relative distal alluvial mud flat crossed by channels of gravel and sand. The dominant metamorphic (Paleozoic) composition of the gravels evidences that the source area was Collserola. The nearly absence of granitic gravels suggests that this lithology, which is well represented in the outcrops of this mountain, would be decomposed by weathering to form the coarse sand found as host material between gravels and producing also sandy layers. Like in the basal erosive surface, the interlayered carbonate levels are paleosols (caliches) that represent periods of alluvial sedimentation inactivity. The irregular arrangement of these paleosols observed in the lithologic logs suggests that they would develop on non-flat surfaces or form discontinuous layers, which makes their correlation very complicated. Some studies suggest that the paleosols and their associated yellow silts correspond to dry and cold climatic periods, while the more dark and reddish clays and gravels without carbonates correspond to humid and warm periods (Ribera-Faig, 1945; Solé-Sabarís, 1963; Virgili, 1960). The yellow silt layers were interpreted as eolian sediments (loess), caused by reworking of alluvial sediments during drier periods (Virgili, 1960). These ancient studies identify up to three main cycles, each one composed by a lower red bed of clay and gravels, an intermediate yellow layer of silt bearing carbonate nodules and an upper calcareous (caliche) layer, which would represent the evolution from a humid-warm to a dry-cold climate. This is the so-called "three cycle" of many geotechnical studies (Ventayol *et al.*, 1978; ICC, 2000). According to Solé-Sabarís (1963), these cycles would represent minor climatic oscillations within the larger interglacial period between the Riss and Würm glacial periods. From the study lithologic logs, it is difficult to give a precise stratigraphy of these cycles because their number and degree of development are highly variable depending on the boreholes.

Like the Pliocene, the Pleistocene of the LAV line seems to be unaffected by tectonics. Roca *et al.* (1999) explain that extensional tectonics decreased along the late Miocene and almost ceased during the Pliocene. However, Llopis-Lladó (1942) has described small faults and folds affecting the Pliocene and Pleistocene deposits in different outcrops and excavations of the Barcelona area. Also, Riba and Colombo (2009) describe faults and folds that have affected the Pleistocene of the Barcelona plain as well as the Holocene deltas. These structures would represent residual neo-tectonics movements still poorly known in the area of Barcelona.

v) The Pleistocene deposit ends again with a new erosive surface caused by the sea level fall at the end of this period, with regards to the last glacial maximum (Gàmez *et al.*, 2009). In the Llobregat and Besòs areas, this erosion eliminated almost completely the Pleistocene deposit and part of the Pliocene materials. In the Barcelona plain, the network of creeks that represents this erosion only affected the upper part of the Pleistocene sequence. During the subsequent marine transgression (the Flandrian transgression), the Llobregat and Besòs deltas developed simultaneously. The H1 layer represents a lowstand alluvial sediment that preceded the marine transgression. During the transgression, this alluvial sediment was reworked by marine waves and formed a retrogradant beach system (Filbà *et al.*, 2016). The H2 to H5 layers represent the gradual progradation of the deltas during the high stand sea level.

The level of the present-day deltaic plains is several meters below the plain of Barcelona. This has given rise to an almost continuous topographic step that encircles all the plain of Barcelona. This step is the highest part of the pre-Holocene erosion not buried by the deltaic sedimentation. In the LAV section, this step is just crossed in La Torrassa area (Fig. 2). In the NE margin of the Barcelona plain, the step is less evident because it has been significantly modified by the mouth of several creeks and the growth of the city (Casassas and Riba, 1992). The polygenic composition of gravels comprising the Llobregat and Besòs deltas points out that the source area extended inland beyond the coastal ranges. This represents an important change with respect to the precedent deposits that were only supplied by rocks of the Litoral Range. In the Barcelona plain, the creeks were filled up with sand and gravels also belonging to Collserola, or to the reworking of the neighboring Pleistocene deposit, as well as anthropogenic fills (Ventayol *et al.*, 1978). Despite the fact that the LAV line crosses transversally the whole creek network, a clear identification of its sediments was not possible.

CONCLUSIONS

i) The Neogene and Quaternary deposits crossed by the LAV line and some nearby infrastructures (L8, L9 lines) form five main depositional sequences corresponding to the early Miocene, middle Miocene, Pliocene, Pleistocene and Holocene. The first one forms a coarse continental (alluvial) deposit of uncertain sequential trend and age, identified only in one of the study boreholes. The middle Miocene sequence forms a deltaic to lacustrine deposit also with uncertain age, presumably corresponding to the uppermost part of Miocene sequence. The Pliocene forms a coastal prograding sequence that goes from shallow inner shelf to beach sediments, of early Pliocene age according to the biostratigraphic (foraminifera) data. The Pleistocene forms a new continental sequence of retrograding trend that goes from coarse proximal alluvial deposits to fine mudflat sediments bearing carbonate levels, of imprecise age. The Holocene forms again a coastal prograding sequence of deltaic sediments that extend to the present day.

ii) Each sequence starts above a sharp erosional surface that cuts through part of the older deposits leading to significant erosional hiatus. These erosions can be attributed to prolonged periods of sea level fall. The unconformity that preceded the Pliocene sequence corresponds to the Messinian sea level fall. This, in turn, would cause the erosion of the late Miocene (Tortonian) deposits, which are not identified in the area of Barcelona. The unconformity that preceded the Pleistocene sequence corresponds to a new sea level fall that eroded the upper Pliocene sediments, also not identified in the area of Barcelona. Finally, the pre-Holocene erosion removed the whole Pleistocene sequence in the delta areas, as well as a minor part of the same sequence in the Barcelona plain. Little can be said about the effects of the pre-early Miocene and pre-middle Miocene erosions due the scarce available litho and biostratigraphic data.

iii) The sedimentation of these sequences occurred in an extensional tectonic setting of gradual decreasing activity. The Miocene deposits were deformed by faulting and gentle folding. However, the Plio-Quaternary deposits show their original sedimentary structures apparently without tectonic alterations.

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