LATE NEOGENE TO RECENT CONTINENTAL HISTORY AND EVOLUTION OF THE GUADIX-BAZA BASIN (SE SPAIN)

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Abstract: The Guadix-Baza basin is a 100 km long, NE-SW elongated depression within the Betic Cordillera (SE Spain). It has a 500 m-thick uppermost Miocene-Pleistocene continental succession that can be divided into five tectonosedimentary units separated by unconformities and/or paraconformities. The first one consists of alluvial conglomerates/sands and lacustrine marls. The second is made up of lacustrine marls and marl-limestone interbeds. The third unit consists of coarse alluvial sediments, and lacustrine lutites and lutites/marls intercalated with carbonates and gypsum. The fourth is represented by lacustrine marl-limestone interbeds, and the fifth unit consists of coarse-detrital alluvial deposits. Cyclicity studies associate the marl-limestone interbeds to obliquity/precession cycles. Gypsum-lutite/marl alternations reflect very high-frequency cyclicities. The continental history of the Guadix-Baza basin is here found to be related to the activity of the NE-SW, Negratín dextral strike-slip fault system. During the late Turolian and early Alfambrian the basin, stretching NE-SW, was relatively limited in extent. In the Villanian it experienced considerable NW-SE extension at two different points, the Guadix and Baza subbasins, NE and SW of the former NE-SW elongated depression.

Key words: Guadix-Baza basin, lacustrine sedimentation, high-frequency cyclicity, strike-slip faulting, basin analysis, Plio-Pleistocene.

Resumen: La cuenca de Guadix-Baza (Cordillera Bética, España) tiene unos 100 km de longitud y una disposición NE-SW, con dos depocentros marcados (los de las subcuencas de Guadix y de Baza, localizados respectivamente al SW y NE). Dicha cuenca muestra un relleno inicialmente marino y luego continental. Este último es suceptible de dividirse en cinco unidades tectosedimentarias separadas por paraconformidades y/o discordancias. La primera de ellas, de edad Turoliense superior y unos 170 m de potencia, está constituida por conglomerados y arenas aluviales, de procedencia norte (Zonas Externas, Cordillera Bética), que cambian lateralmente a margas lacustres. La segunda unidad (75 m) es de edad Alfambriense-Villaniense inferior. Es exclusivamente lacustre y tiene una parte inferior margosa y otra superior constituida por alternancias de margas y calizas que se relacionan con ciclos de oblicuidad y precesión. La tercera unidad (250 m) es de edad Villaniense-Pleistoceno inferior. Está constituida por sedimentos aluviales detríticos gruesos procedentes de Sierra Nevada y Sierra de Baza (Zonas Internas, Cordillera Bética), acumulados en la subcuenca de Guadix, y lutitas, carbonatos y yesos de origen lacustre, depositados en la subcuenca de Baza. Las calizas y yesos intercalan a su vez entre finos lechos de lutitas/margas. Las alternancias yeso-lutitas/margas reflejan ciclicidades de muy alta frecuencia (de 500 a 1800 años). La cuarta unidad, representada sólo en la subcuenca de Baza, corresponde a un delgado depósito lacustre (8 m), de edad Pleistoceno medio, constituido por alternancias de calizas y margas. La quinta unidad (15 m) es de edad Pleistoceno medio-superior y está constituida predominantemente por sedimentos aluviales detríticos gruesos procedentes de Sierra Nevada. La historia continental de la cuenca de Guadix-Baza se relaciona estrechamente con el sistema de fallas de desgarre del Negratín, de carácter dextroso y orientación NE-SW, que aflora actualmente sólo en el margen norte de la cuenca. En relación con dicho sistema se abrió una pequeña cuenca de pull-apart, alineada NE-SW, en el Turoliense superior. Tras una interrupción en el proceso de sedimentación de ~600 ka, se reabrió la cuenca en el Alfambriense inferior. En el Villaniense, y tras otra interrupción en la sedimentación de unos 400 ka, la cuenca experimentó extensiones notables de dirección NW-SE en dos zonas diferentes (subcuencas de Guadix y Baza), situadas respectivamente al NE and SW de la cuenca inicial.

Palabras clave: Cuenca de Guadix-Baza, sedimentación lacustre, ciclicidad de alta frecuencia, tectónica de desgarre, análisis de cuencas, Plio-Pleistoceno.

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The Guadix-Baza basin is a NE-SW aligned, intermontane depression, approximately 100 km long, located along the boundary between the Internal and the External Zone of the Betic Cordillera (Fig. 1). At present, the basin has two well-marked depocentres, the Guadix and Baza subbasins, divided by a high formed in part by basement outcrops. This basin exhibits the thickest (around 500 m) and most continuous uppermost Miocene-Pleistocene continental sedimentary record in the Iberian Peninsula. Tectonic control of the basin is very evident, with prominent faults trending N50-70E and N150-170E (Fig. 2). The most important fault is the "Falla del Negratín", a NE-SW, dextral strike-slip fault cutting across the basin and extending from Cádiz to Alicante, localities situated some 600 km apart at opposite ends of the Betic Cordillera (Sanz de Galdeano, 1983). This fault is here considered to be part of a strike-slip fault system limiting the basin at both its northern and southern margins, currently intersecting the ground surface only at the northern part of the basin.

The sedimentary record of the basin consists of materials ranging in age from the uppermost Oligocene-lower Aquitanian to the Pleistocene (Fig. 2). It comprises a 2000 m-thick, mainly Miocene (uppermost Oligocene/lower Aquitanian to Tortonian) marine succession, cropping out at the basin margins, and a 500 m-thick, upper-Turolian to upper-Pleistocene continental succession, occupying most of the basin (Fig. 2). Two intervals are distinguished within the continental deposits, one upper Turolian and the other Plio-Pleistocene. The latter can be subdivided into two parts: a lower one of lacustrine origin (the *Gorafe-Huélago Formation*), and an upper one consisting of an alluvial formation (the *Guadix Formation*) passing laterally to a lacustrine formation (the *Baza Formation*) (Fig. 2). Vera (1970) was the first author to recognize these three formations and to formally name them. He also considered the *Gorafe-Húelago Formation* to change laterally to the *Guadix Formation*. Nevertheless, field relationships and recent biostratigraphic datings (see below) make it completely clear that the *Gorafe-Húelago Formation* underlies the *Guadix Formation*.

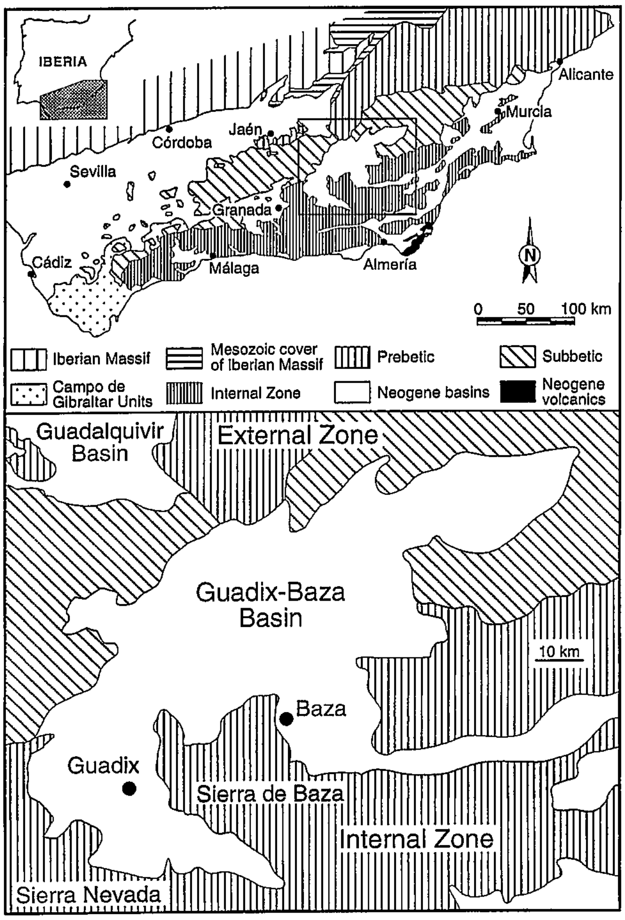


Figure 1.- Geographical and geological location of the Guadix-Baza basin.

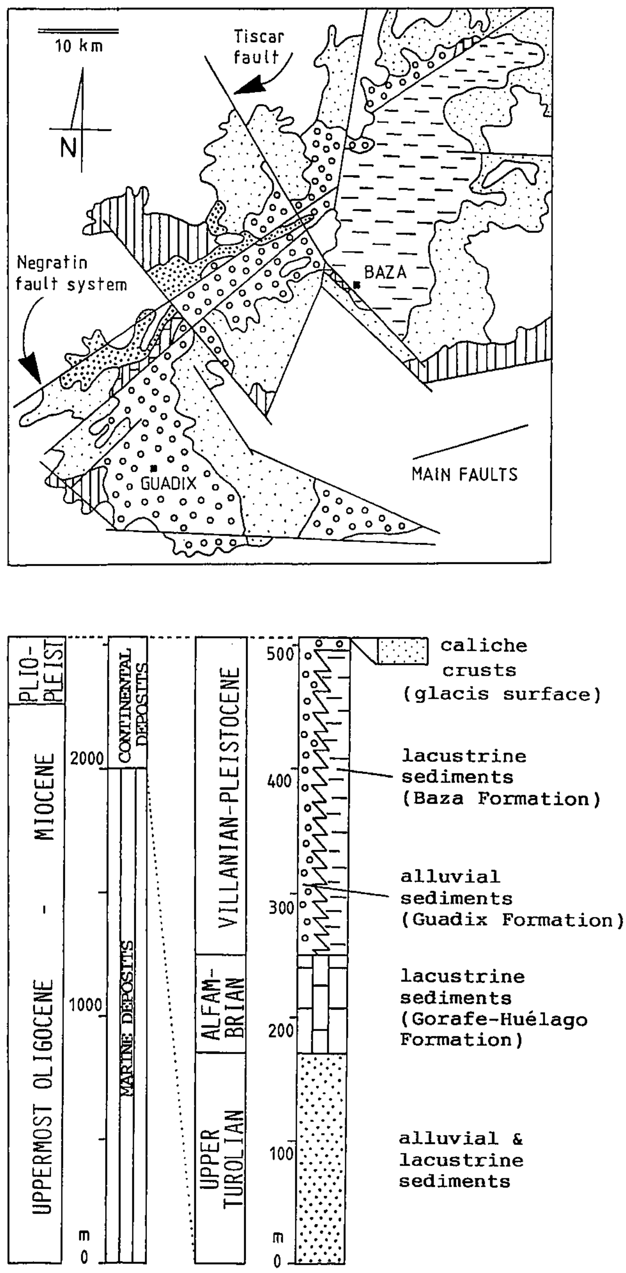


Figure 2.- Simplified geological map outlining the main mapping units and faults (modified from García Aguilar, 1997), and simplified stratigraphic scheme of the Guadix-Baza basin (modified from Vera, 1970, and García Aguilar, 1997).

BIOZONE	FOSSIL SITES IN GUADIX SUBBASIN	FOSSIL SITES IN BAZA SUBBASIN
MP20	a-Cueva Horá (15)	
MP19	b-Solana del Zamborino (4)	c-Cúllar Baza (1,3,11) d-Loma Quemada (1,9) e-Huescar (1,9,10) f-Puerto Lobo (1,9) g-Caniles (8)
MP18		h-Cortes de Baza (19) i-Orce (1,9) j-Venta Micena-Barranco del León (1,6,7,9) k-Fuente Nueva-Barranco de Conejos (1,2,16) l-Cañada de Múrcia-Fuentecilla (1,9) m-Cortijo Yeseras-Don Alfonso (1,9,16) n-Cañada Balmáez (1,9,16) o-Cortijo Don Diego (1,9,16)
MN17	p-Cortijo de las Sabinas (3) q-Cortijo de Tapia (3) r-Cerro de los Pinos (3) s-Barranco de Cañuelas (3) t-Huélago (3)	u-Cortes de Baza (15) v-Fuentenueva (1,9) w-Bardaes (3) x-Areba (8) y-Orce (1,9) z-Alquería (1,9,16) aa-Nuca-Agua (12) ab-Fuentecilla (1,9) ac-Cañada de Múrcia (1,9,10,16)
MN16	ad-Tollo de Chiclana (19) ae-Moreda (9)	af-Galera (1,9,16) ag-Aguila Roa (19) ah-Zújar (19) ai-Cañada del Castaño (1,9,16)
MN15	aj-Belerda (19) ak-Barranco de Cañuelas (15) al-Cortijo de Muros (3) am-Fonelas (3) an-Moreda (9) ao-Rambla del Conejo (3) ap-Gorafe (1,9)	aq-Cómodo (8) ar-Cañada del Castaño (1,9,16) as-Santa (8) at-Barranco de Quebradas (3,10) au-Huescar (1,9,10) av-Nuca (12) aw-Galera (1,9,16)
MN14	ax-Gorafe (1,9,13) ay-Yeguas (17)	az-Aljibe (8) ba-Colorado (8) bb-Cuzco (8)
MN13	bc-Abla (5) bd-Pino Mojón (14)	be-Botardo (3,9) bf-Colorado (8) bg-Bacochas (3)
MN12	bh-Salinas (18)	

Figure 3.- Temporal distribution of the most important fossil-vertebrate sites known in the Guadix and Baza subbasins. Note lowercase lettering code (a to bh) to the left of each site, starting from the stratigraphically highest (youngest) outcrop (Cueva Horá). References: 1: Agustí, 1985. 2: Agustí *et al.*, 1987. 3: Alberdi and Bonadonna, 1989. 4: Casas *et al.*, 1975. 5: Cuevas *et al.*, 1984. 6: Gibert *et al.*, 1983. 7: Gibert *et al.*, 1993. 8: Guerra Merchán, 1992. 9: Martín Suárez, 1988. 10: Mazo *et al.*, 1985. 11: Ruiz Bustos, 1976. 12: Ruiz Bustos, 1991. 13: Ruiz Bustos *et al.*, 1984. 14: Sesé Benito, 1989. 15: Sesé Benito, 1994. 16: Soria, 1986. 17: Soria and Ruiz Bustos, 1991. 18: Soria and Ruiz Bustos, 1992. 19: Martín Suárez, pers. comm., 1999.

Objectives

The main purpose of this paper was to reconstruct the continental history of the basin and to establish a dynamic evolutionary model. Therefore, a detailed study of the stratigraphy of the continental record has been made, referring in some detail to the cyclicity and sedimentology of the lacustrine deposits. The tectonic evolution of the basin is also discussed.

Detailed studies on the sedimentology and stratigraphy of the Plio-Pleistocene continental deposits of the Guadix-Baza Basin have been carried out by different authors (Vera, 1970; Peña, 1979; Cuevas *et al.*, 1984; Peña, 1985; Anadón *et al.*, 1986; Arribas *et al.*, 1988; Ruiz Bustos, 1991; Viseras, 1991; Fernández *et al.*, 1993; García Aguilar, 1995; Fernández *et al.*, 1996; and Soria *et al.*, 1998, amongst others). Most of these works refer specifically to small areas within the basin, or to precise intervals of its continental history. Only a few of them (Vera, 1970; Peña, 1979, 1985; Viseras, 1991; Fernández *et al.*, 1993, 1996; Soria *et al.*, 1998) have a broad, general approach. Viseras (1991) made a comprehensive study of the Guadix subbasin concentrating on the sedimentology of the alluvial deposits. Vera's (1970) and Peña's (1979, 1985) works deal with general aspects of the basin but the conclusions are somewhat basic and as such incomplete. More recently, Fernández *et al.* (1996) and Soria *et al.* (1998) proposed an evolutionary model of the Guadix-Baza basin during the Pliocene-Pleistocene. The stratigraphic scheme presented by these latter authors, which follows that of Viseras (1991), has, however, proved to be partly incorrect (see below). A more accurate stratigraphic framework is here presented and the continental history of the basin is reconstructed accordingly.

Methods

Detailed logging has been carried out to make a synthetic stratigraphic scheme of the Plio-Pleistocene continental record of the basin. The available palaeontological information has been taking into account (Fig. 3), as well as the palaeomagnetic data (Garcés, 1993; Garcés *et al.*, 1997; Parés and Dinarès Turell, 1997; Oms *et al.*, 1999) (Fig. 4), and the information provided by some previous stratigraphic works (Peña, 1985; García Aguilar, 1986; Soria, 1986; Viseras, 1991; Sanz de Galdeano and Vera, 1992; Soria, 1993; Anadón *et al.*, 1995; Fernández *et al.*, 1996; and García Aguilar, 1997, amongst others). Stratigraphic correlation is aided by the exceptional quality of the outcrops and the persistent lateral continuity of most of the horizontal to gently-dipping strata. A detailed geological map of the basin is presented in figures 5A and B.

Cyclicity studies of the lacustrine deposits were carried out with the "CYSTRATI" program (Pardo Igúzquiza et al., 1994). The program has been specifically designed for the spectral analysis of stratigraphic successions, including five of the most classic approaches in Earth Sciences: Blackman-Turkey, Thompson multitaper, classic periodogram, maximum entropy approach and Walsh's spectral analysis. This computer program uses ANSI standard Fortran-77 language, with different processing options for the treatment of a variable (bed thickness in this case) and power-spectrum estimates. Temporal calibration of the cycles obtained by power spectrum analysis is calculated on the basis of the average sedimentation rate of the succession (in cm/ka). Sedimentation rates have been deduced considering the time involved and the thickness of the deposits.

The provenance of coarse detrital (sand and conglomerate) sediments has been determined by analysing clast composition. External Betic Zone-derived clasts are mainly from Jurassic and Cretaceous limestones and dolostones, with minor chert. Internal Betic Zone-derived clasts are mostly from Palaeozoic and older (?) metamorphic rocks (quartzites, micaschists, gneisses, amphibolites, serpentinites, marbles, etc.), together with abundant quartz (found in the source area mainly as vein-filling), and metamorphosed Triassic carbonates (limestones and dolostones). Mineralogical studies of the lacustrine deposits were perfomed using a Philips PW 1710 X-Ray Diffractometer with CuKα radia-

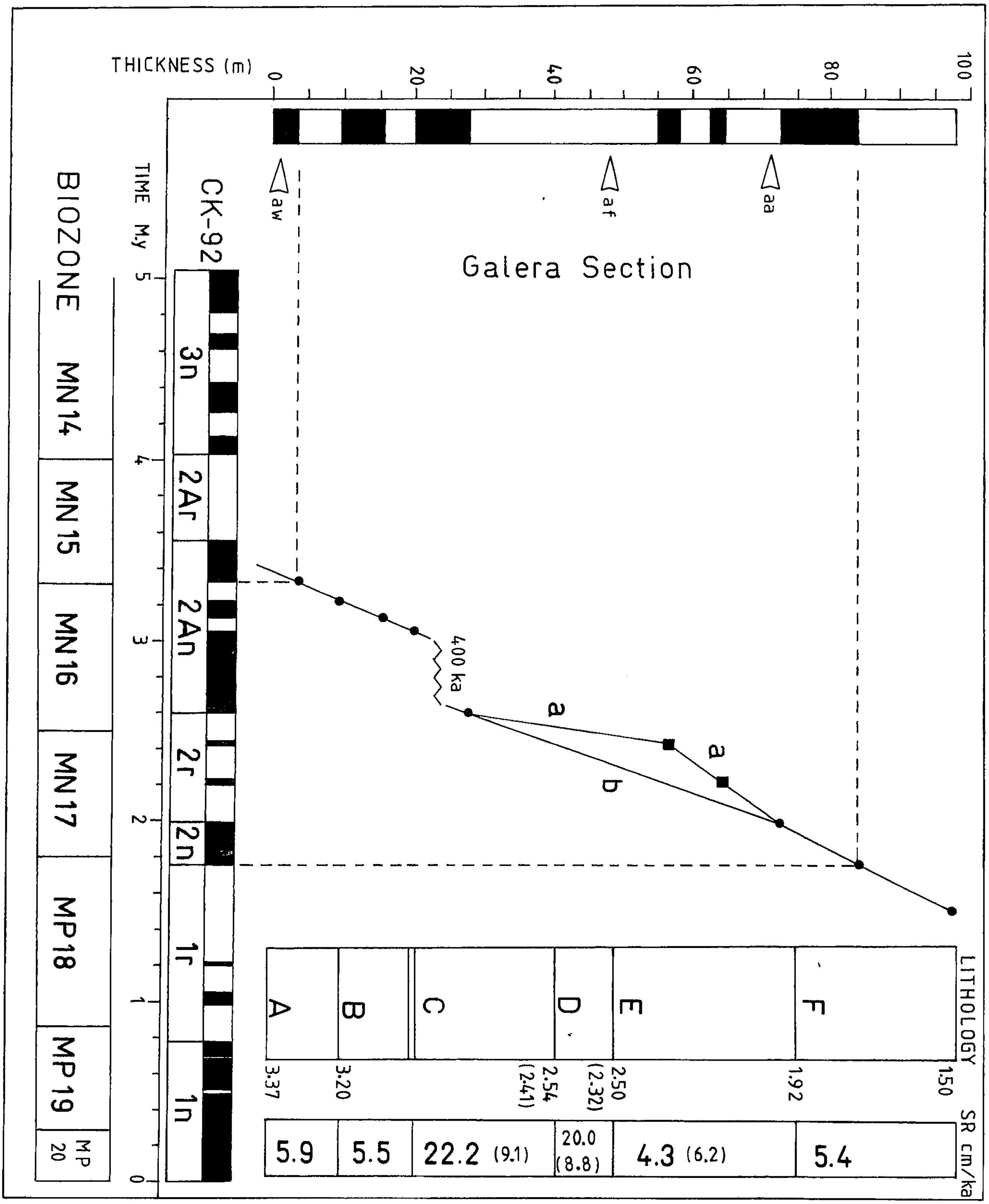


Figure 4.- Correlation between the magnetostratigraphic and lithostratigraphic sequences of the Galera section (modified from Garcés, 1993). Lithostratigraphic sequence (main lithologies): A: marls. B: limestones and marls. C: marls. D: sandstones, marls and gypsum. E: marly limestones and marls. F: conglomerates. Sedimentation rates (SR) are given in cm/ka. A hiatus of approximately 400 ka is recognized at the base of interval C, due to the absence of Chron 2An.3N (Garcés, 1993). Note how, from intervals C to E, a more precise correlation (García Aguilar, 1997) (a) than that originally presented by Garcés (1993) (b), can be established using magnetoevents C2R.1N and C2R.2N. Values in parentheses correspond to those given by Garcés (1993). Biostratigraphic data (Martín Suárez, 1988; Martín Suárez, pers. comm., 1999) are from palaeontological sites aa, af, and aw, the position of which is indicated to the right of the magnetostratigraphic sequence. Geomagnetic polarity time scale after Cande and Kent (1992). Intervals A and B correspond to Unit II (this paper) (Alfambrian-lower Villanian). Intervals C, D, E and F belong to Unit III (Villanian-lower Pleistocene). The hiatus detected by the partial absence of Chron 2An.3N is thus placed between Units II and III.

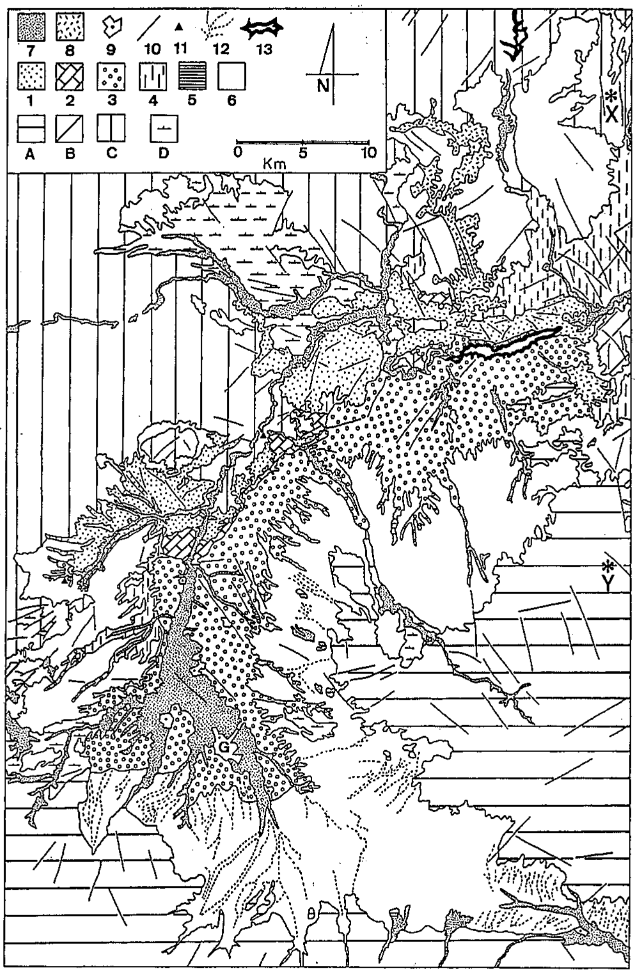
tion and an automatic slit. 150 thin sections of lacustrine carbonates were also studied under the polarizing microscope.

Seismic profiles have been used in order to complete the information referring to the different stages of infilling of the basin and to back the proposed scheme of tectonic evolution. Nevertheless, the information obtained is far from complete as the very few seismic profiles available are located at marginal positions within the basin.

Stratigraphy of the continental record of the basin

Five areas, considered to be the most representative of the basin, have been selected to draw up a synthethic stratigraphic scheme. Five time-modified stratigraphic sections, made from a total of 90 detailed stratigraphic profiles (García Aguilar, 1997) summarizing the most significant stratigraphic features of each area, are here presented and correlated (Fig. 6). The synthetic stratigraphic scheme (Fig. 7) has been prepared using all this information and is discussed in detail below.

Five units are distinguished, separated by hiatuses (Fig. 7). Their absolute-age calibration, and subsequent estimates of average sedimentation rates and hiatus durations, have been determined from a series of



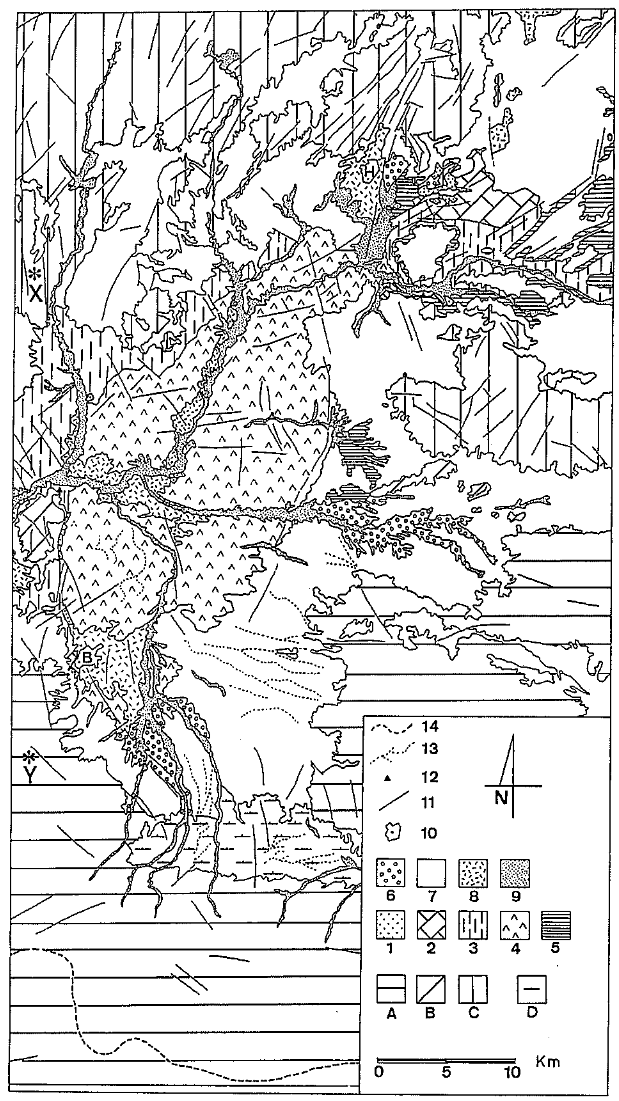


Figure 5.- Detailed geological map of the Guadix-Baza basin (from García Aguilar, 1997). A: Nevado-Filábride and Alpujárride Complexes (Internal Zone). B: "Dorsal Bética" (Internal Zone). C: External Zone. D: Undifferentiated Miocene marine sediments.

Part A: Guadix subbasin. 1: Upper Turolian unit. 2: Alfambrian-lower Villanian unit. 3: Villanian-lower Pleistocene unit (alluvial deposits). 4: Villanian-lower Pleistocene unit (lacustrine, non-evaporitic deposits). 5: Middle-upper Pleistocene unit (lacustrine deposits). 6: Middle-upper Pleistocene unit (alluvial deposits) and Sub-Recent, Holocene glacis-surface outcrops. 7: Present-day alluvial sediments. 8: Agricultural fields, landslides and fluvial terraces. 9: Town (G-Guadix). 10: Faults. 11: Sub-Recent, Holocene travertine deposits. 12: Sub-Recent, river drainage systems detected by satellite images under the glacis surface. 13: Water reservoir.

Part B: Baza subbasin. 1: Upper Turolian unit. 2: Alfambrian-lower Villanian unit. 3: Villanian-lower Pleistocene unit (lacustrine, non-evaporitic deposits). 4: Villanian-lower Pleistocene unit (lacustrine, evaporitic deposits). 5: Middle Pleistocene unit (lacustrine deposits). 6: Middle-upper Pleistocene unit (alluvial deposits). 7: Sub-Recent, Holocene glacis surface. 8: Agricultural fields, landslides and fluvial terraces. 9: Present-day alluvial sediments. 10: Towns (B-Baza; H-Huescar). 11: Faults. 12: Sub-Recent, Holocene travertine deposits. 13: Sub-Recent, river drainage systems detected by satellite images under the glacis surface. 14: Water-shed divide.

Corresponding anchor points (X, Y) are marked on both maps.

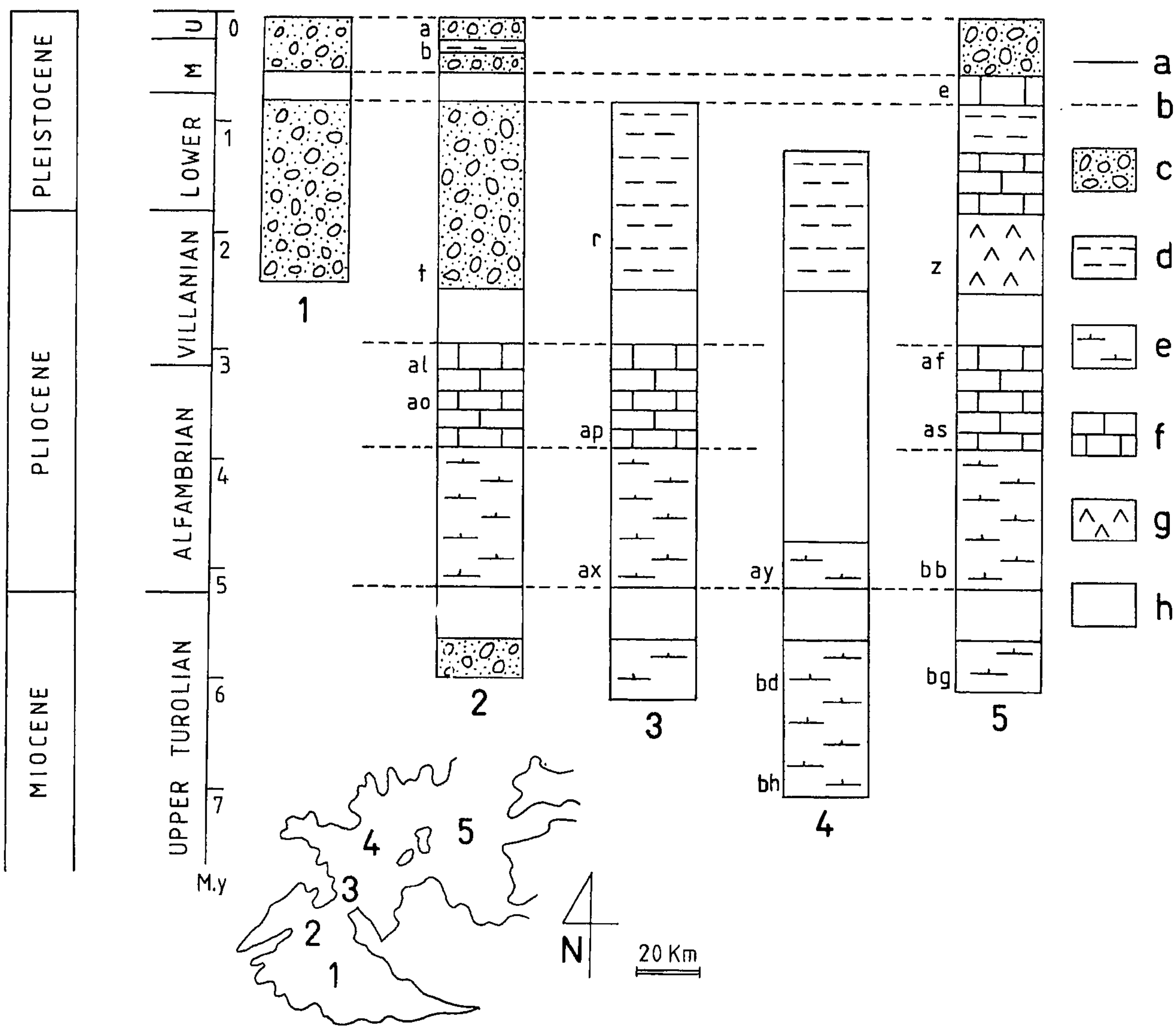


Figure 6.- Selected stratigraphic sections of the Guadix-Baza basin and their correlation. These are time-modified logs in which the thickness of the different deposits is represented in accordance with their temporal range distribution. Key to symbols: a: boundaries between units; b: correlation lines; c: alluvial, coarse-grained detrital deposits; d: undifferentiated fine-grained detrital, distal-fluviatile and lacustrine deposits; e: lacustrine marls; f: lacustrine carbonates; g: lacustrine evaporites; h: hiatus. The positions of the corresponding, most significant palaeontological sites are indicated to the left of each section (lowercase lettering code as in Fig. 3). Geochronology time-scale after Berggren et al., 1995.

well-dated palaeontological sites (Fig. 3) in the 90 detailed stratigraphic sections logged in the basin (see García Aguilar, 1997), used in combination with the palaeomagnetic data for the Galera section (Garcés, 1993) (Fig. 4). (The work of Garcés, 1993, is here considered to be the most significant, as nothing new has been added to the palaeomagnetic interpretation of the Galera section in the most recent publications of Garcés *et al.*, 1997, Parés and Dinarès Turell, 1997, and Oms *et al.*, 1999). As the method is not entirely precise, a possible error of ±20% must be considered for the different values given below.

The first unit is upper Turolian in age (MN12 and MN13 biozones). The outcrops of this unit, at present slightly tilted to the south (some 15°), are aligned NE-SW. Most of them are located along the northern margin of the basin, occupying an area of around 200 km^2 (Fig. 5). Rocks in this unit consist mostly of detrital material, with a maximum thickness of 170 m and an average sedimentation rate of 11 cm/ka. At the top of the unit there is a hiatus of approximately 600 ka, as deduced from biostratigraphic data.

The second unit, covering some 150 km^2 along the margins of the basin (the smallest value of all these units), has mostly dispersed outcrops, although also aligned NE-SW (Fig. 5). The lower part of the unit is formed exclusively of marls whereas the upper part consists of marl-limestone interbeds. The hiatus at the top comprises an interval of approximately 400 ka (Fig. 4), as deduced by palaeomagnetic and biostratigraphic markers. An Alfambrian-lower Villanian age (MN14, MN15 and MN16 biozones) is assigned to the unit, which has a maximum thickness of 75 m and an average sedimentation rate of 4 cm/ka.

The third unit has an age ranging from Villanian to lower Pleistocene (upper part of MN16, MN 17 and MP 18 biozones). It crops out extensively, mainly in the central parts of the basin, over about 1000 km^2 (Fig. 5).

Coarse-detrital sediments (conglomerates and sands), together with evaporites, limestones, marls, and lutites, characterise this unit. The maximum thickness is 250 m and an average sedimentation rate of 15 cm/ka has been deduced.

The fourth unit is present exclusively in the Baza subbasin and consists of thin (up to 8 m) deposits formed of marl-limestone interbeds of middle Pleistocene age (lower MP 19 biozone). In the Guadix subbasin this period corresponds to a hiatus of approximately 200 ka.

The fifth unit is middle-upper Pleistocene in age (MP 19 and MP 20 biozones), with an average thickness of around 15 m and extensive outcrops occupying about 900 km^2. Sediments are mainly coarse-detrital (conglomerate and sand) deposits. Silts, marls, limestones and marly limestones are also present very locally. On top of this unit there is a glacis (piedmont slope) approximately 10 ka old (Viseras, 1991).

Major breaks (hiatuses) separate the different units. The discontinuity on top of Unit I is a true unconformity. The rest of the units are separated by paraconformities (locally appearing as disconformities at the basin's margins). These units can therefore be considered as tectonosedimentary units in the sense of Megías (1982). Vera's (1970) formations are related with the above-differentiated units in the following way: Unit II would correspond to the *Gorafe-Húelago Formation*. The coarse-grained deposits (conglomerates and sands) of Units III and V would make up the bulk of the *Guadix Formation*. The fine-grained siliciclastics, marls and carbonates of Units III, IV and V would mainly belong to the *Baza Formation*. The stratigraphy here presented is different from that of Vera (1970) and Viseras (1991). Both authors considered the *Gorafe-Húelago Formation* to be the lateral equivalent of the *Guadix Formation*. Field relationships, however, show that the siliciclastic sediments of the *Guadix Formation* always appear on top of the carbonates of the *Gorafe-Húelago Formation* (Fig. 6), and palaeomagnetic data combined with biostratigraphic datings demonstrate that a major break exists between the two formations (Fig. 5). Moreover, Viseras (1991) interpreted all the materials forming Units III, IV and V as a single tectonosedimentary unit.

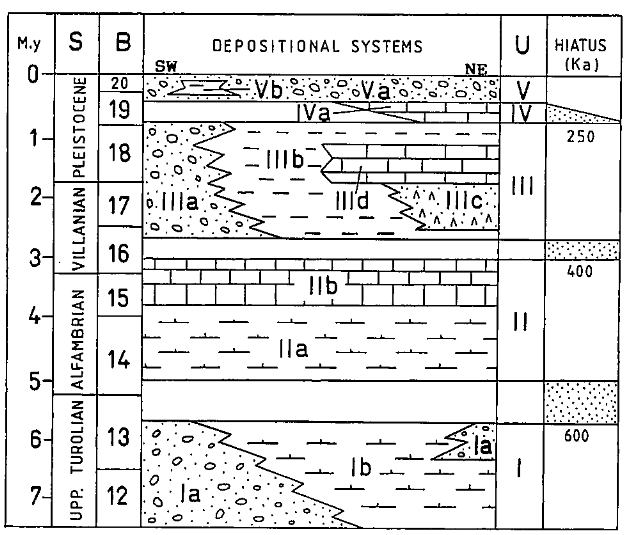


Figure 7.- Stratigraphic model for the Guadix-Baza basin in a NE-SW section (as deduced from Fig. 6), showing main units and depositional systems, and their temporal distribution. Lithological symbols as in Fig. 6. Thickness of deposits not to scale. S: Series. B: Biozone. U: Unit. Depositional systems: Ia: alluvial fans and fan deltas. Ib: lakes with predominantly marly sedimentation. IIa: lakes with mainly marly sedimentation. IIb: lakes with predominantly carbonate sedimentation. IIIa: undifferentiated alluvial environments (alluvial fans and meandering rivers). IIIb: undifferentiated distal fluviatile environments and lakes with primarily lutite sedimentation. IIIc: lakes with predominantly evaporitic sedimentation. IIId: lakes with mainly carbonate sedimentation. IVa: lakes with predominantly carbonate sedimentation. Va: undifferentiated alluvial environments (alluvial fans and braided rivers). Vb: lakes with primarily marly/carbonate sedimentation. Geochronology time-scale after Berggren et al., 1995.

Major sedimentological features of the units and depositional environments

Unit I (Turolian) comprises alluvial and lacustrine deposits (depositional systems Ia and Ib respectively in Fig. 7) that interfinger laterally. The alluvial sediments are conglomerates and sands deposited in alluvial fans and fan deltas, whereas the lacustrine sediments are mainly marls. The main source area for the terrigenous material was to the north (External Zone of the Betic Cordillera) (Viseras, 1991; García Aguilar, 1997; Soria *et al.*, 1998).

In Unit II (Alfambrian-lower Villanian), alluvial sediments are almost absent, occurring only in its lowermost part as decimetre-thick sand layers. The source area in this case was located to the south (Internal Zone). Most of the sediment is lacustrine (García Aguilar, 1997), consisting of marls (the lower half of the unit) (depositional system IIa in Fig. 7) and marl/limestone interbeds (the upper half) (depositional system IIb in Fig. 7).

Coarse-detrital, alluvial sediments are particularly abundant in Unit 3 (Villanian-lower Pleistocene). They derive from the erosion of the Sierra Nevada and the Sierra de Baza, located to the S and E of the basin respectively (Fig. 1), and both belonging to the Internal Zone of the Betic Cordillera. Most of the alluvial sediment was deposited proximally within the Guadix subbasin (depositional system IIIa in Fig. 7), close to the source areas. A rim of alluvial fans developed around the above-mentioned uplands, and a major, meandering trunk river flowed NNE towards the Baza subbasin (Viseras, 1991; Calvache and Viseras, 1997). This subbasin was occupied by a lake for most of its history, with deposition either of lutites (marls) (depositional system IIIb in Fig. 7), evaporites (depositional system IIIc in Fig. 7), or limestones (depositional system IIId in Fig. 7) at different times (Vera, 1970; García Aguilar, 1997). The alluvial-lacustrine evolution consists of retrogradation followed by progradation of the alluvial system on top of the lacustrine deposits.

The fourth unit (middle Pleistocene) is exclusively lacustrine (depositional system IVa in Fig. 7). The most

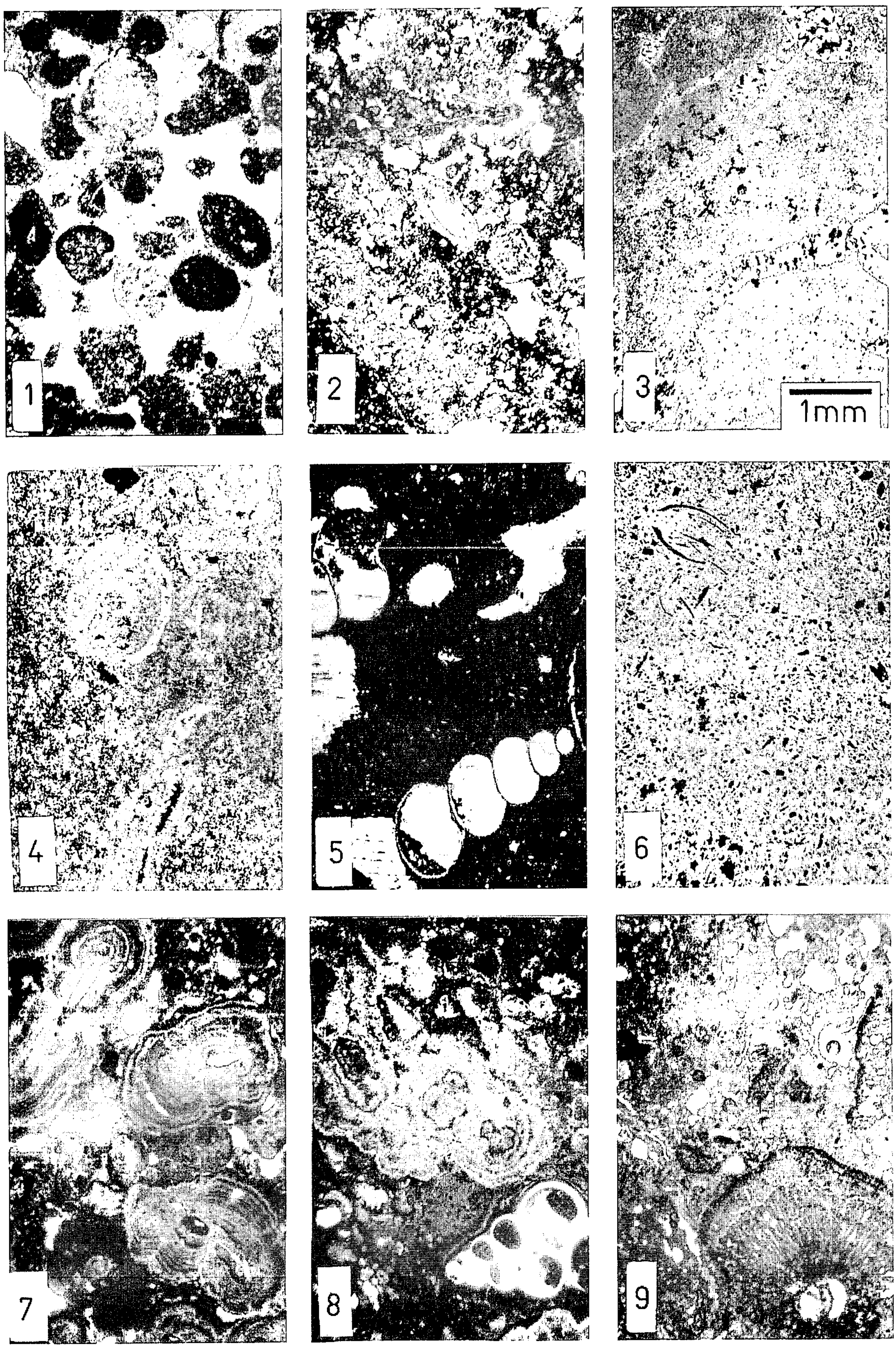


Figure 8.- Examples of the most representative lacustrine-limestone microfacies. All pictures have the same scale (shown in 3). 1: Intramicrite. Unit II (Fonelas). 2: Peloidal, clotted limestone with fenestrae. Unit IV (Huélago). 3: Micrite with root and ostracode moulds filled by sparry calcite. Unit III (Orce). 4: Biomicrite with charophyte remains (some of them as crushed moulds) and fine-grained, sandy siliciclasts. Unit III (Castillejar). 5: Biomicrite with gastropods. Unit III (Castillejar). 6: Micrite with very fine-grained, silty siliciclasts and bivalve moulds. Unit III (Cortes de Baza). 7: Biomicrite with oncolites. Unit II (Gorafe). 8: Biomicrite with oncolites and gastropods. Unit II (Gorafe). 9: Biomicrite with oncolites and fenestrae. Unit II (Fonelas).

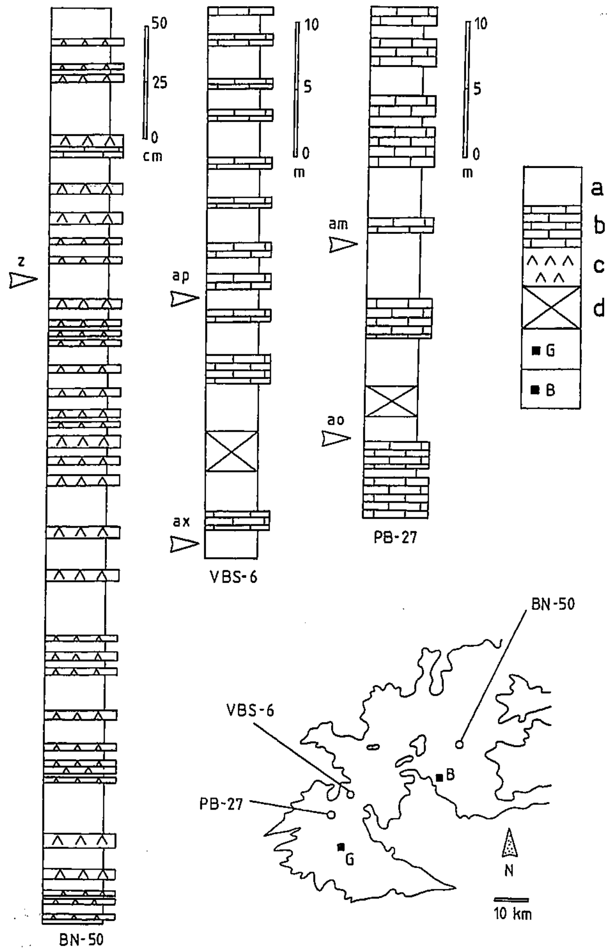


Figure 9.- Selected sections on which cyclicity studies have been carried out. Sections PB-27 and VBS-6 are from Unit II, depositional system IIb (upper Alfambrian) and Unit III, depositional system IIId (lower Pleistocene), respectively. They exemplify the limestone-marl interbeds. Section BN-50 is from Unit III, depositional system IIIc (upper Villanian), and is representative of the gypsum-lutite/marl interbeds. The position of the palaeontological sites in each section is also marked (see Fig. 3 for code). In the case of the evaporite section, this information comes from laterally correlatable, nearby non-evaporitic sections (García Aguilar, 1997) containing palaeontological sites of biochronological interest. Small inset map shows the geographical location of these sections. Key to lithological symbols: a: marls and lutites; b: limestones; c: gypsum; d: not visible (covered). G: Guadix; B: Baza.

significant feature is the existence of marl-limestone interbeds (García Aguilar, 1997).

The last unit (middle-upper Pleistocene) consists predominantly of coarse detrital, braided-river deposits (Viseras, 1991) (depositional system Va in Fig. 7). These rivers drained the Internal Zone (mostly Sierra Nevada) and were particularly active during Pleistocene glacial episodes (García Aguilar, 1997). Small lakes and swamps temporarily developed marginal to these rivers in the western part of the basin (depositional system Vb in Fig. 7). Limestones (marly limestones), marls, silts and clays formed in these lacustrine and palustrine environments.

Cyclicity of the lacustrine deposits

One of the most significant features of the lacustrine deposits is the existence of marl-limestone interbeds. This is the case in the upper part (depositional system IIb) of Unit II (Alfambrian-lower Villanian) and in Unit III (depositional system IIId). A similar pattern can be found in Units IV (depositional system IVa) and V (depositional system Vb).

Limestones in Unit II are mainly micrites and biomicrites with gastropods, bivalves and oncolites (Fig. 8: 7 and 8) and, locally, intraclasts and fenestrae (Fig. 8: 1 and 9), indicating very shallow-water conditions and even occasional emergence. In Unit III, micrites and biomicrites are common and, in some cases, contain siliciclastic material (Fig. 8: 4, 5 and 6). Ostracodes are omnipresent in some of the biomicrites (Anadón *et al.*, 1986). Root structures appear as well (Fig. 8: 3). Abundant macromammal remains are also locally found in the limestones (Agustí *et al.*, 1987; Martín Suárez, 1988; Alberdi and Bonadonna, 1989; Arribas and Palmqvist, 1998, 1999a and b), accompanied by a possible lithic industry (stone artifacts) and, according to some authors (Gibert *et al.*, 1983; Gibert et al., 1993), human bones. Microfacies studies in the Unit IV limestones also show them to be very shallow-water deposits (Fig. 8: 2). In Unit V, fenestral micrites and micrites with intraclasts are the dominant limestone microfacies. These Unit V limestones also have scattered, sand-sized, siliciclastic grains and frequently exhibit pedogenic textures such as pseudointraclasts, circumgranular cracks, etc., indicative of prolonged episodes of subaerial exposure with local soil development.

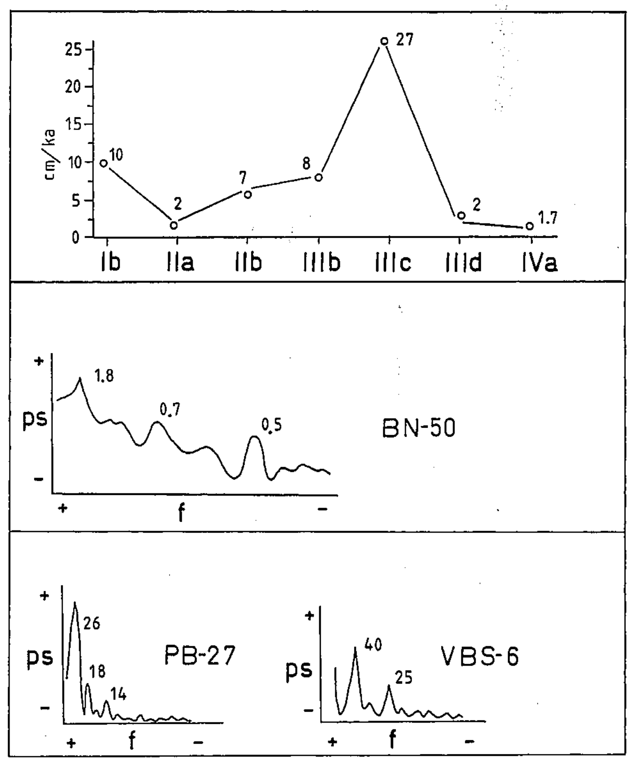


Figure 10.- Sedimentation rate and cyclicity (CYSTRATI curves) of the lacustrine deposits within different units. Lacustrine depositional systems as in Fig. 7. Main peak values (given in ka) relate the marl-limestone interbeds to obliquity and precession cycles. The gypsum-lutite/marl alternations correspond to short-term, climatic fluctuations (from 500 to 1800 years). Key to the symbols: ps: power spectrum; f: frequencies.

The average marl-limestone sequence thickness is around 3 m (Fig. 9). As seen above, the limestones correspond to shallow-water deposits. The marls, in contrast, are thought to have formed in deeper water and to represent periods of more significant inundation with fine-grained, siliciclastic input. Illite, smectites, palygorskite, chlorite and kaolinite are the main clay-minerals found in the marls. Palygorskite most likely formed directly in the lacustrine environment, while illite, chlorite, and kaolinite are considered to be detrital. The smectites are partly detrital and partly neomorphic (Sebastián Pardo, 1979).

Cyclicity studies carried out with the "CYSTRATI" program (Pardo Igúzquiza *et al.*, 1994), taking into account the thicknesses of the units and their sedimentation rates, relate the marl-limestone interbeds to obliquity and precession cycles (main peaks at around 40 and 25 ka, see Fig. 10).

Evaporite deposits in Unit III (depositional system IIIc) consist of microcrystalline, thinly laminated ("balatino-type") gypsum layers alternating with fine-grained terrigenous materials (silts and clays) and/or marls (Fig. 9, section BN-50). Early-diagenetic gypsum rosettes are also commonly found within the fine-grained siliciclastics and marls. The elementary sequence of gypsum-lutite/marl interbedding ranges from centimetre- to decimetre-thick, with some repetitive patterns that reflect, as revealed by the "CYSTRATI" program, very high-frequency cyclicities (from 500 to 1800 years) (Fig. 10). Lacustrine sedimentation was in this case strongly influenced by the dominant climatic conditions. During more humid, temperate periods, marls were deposited. During arid conditions evaporite precipitated. These inferred climatic variations, which occurred with a periodicity of several hundred years, are, however, not easy to relate to any particular cause (see Einsele *et al.*, 1991, and Glenn and Kelts, 1991).

Dynamic evolution and palaeogeography of the basin

The sedimentary record shows that the Guadix-Baza basin evolved from a marine environment to a continental one. Continental, alluvial-lacustrine sedimentation started in the late Turolian, and continued during the Alfambrian-lower Villanian after a break of approximately 600 ka. In these initial continental stages, the basin was relatively limited in extent (around some 300 km2, as can be deduced from the outcrop map in Figure 5 and interpreted seismic profiles in Figure 11), forming a NE-SW elongated depression.

Continental sedimentation resumed in the Villanian after a break of approximately 400 ka, and continued up to the late Pleistocene. During the Villanian, the morphology of the basin changed significantly with the appearance of two depocentres, the Guadix and Baza subbasins. Villanian-Pleistocene continental deposits crop out in an area of around 1000 km^2 (Fig. 5), extending far beyond the underlying deposits (Fig. 11). They are especially well represented in the central parts of the Guadix

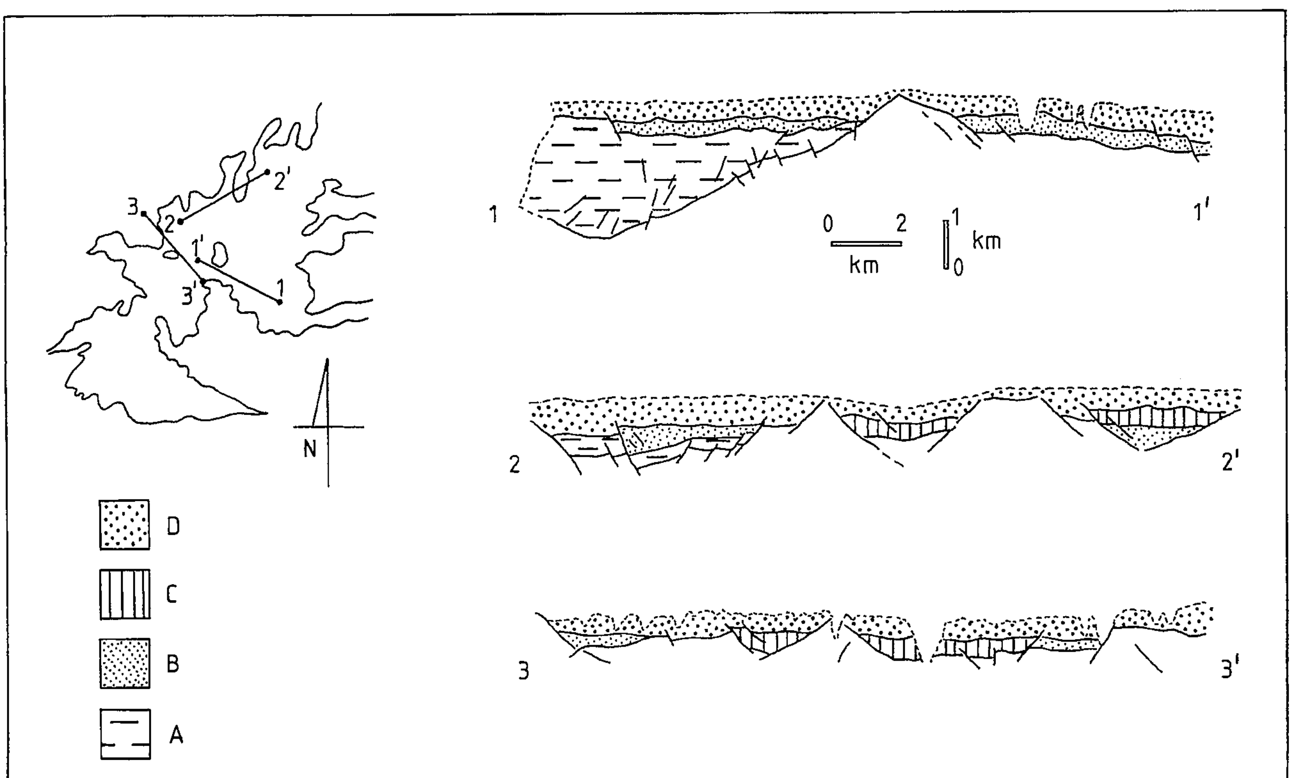


Figure 11.- Interpretation of some of the most representative, available seismic profiles for the Guadix-Baza basin. A: Uppermost Oligocene-Miocene marine deposits. B: Upper Turolian continental deposits. C: Alfambrian continental deposits. D: Villanian-Pleistocene continental deposits. Note the marginal position of the underlying marine units and of some of the oldest continental units.

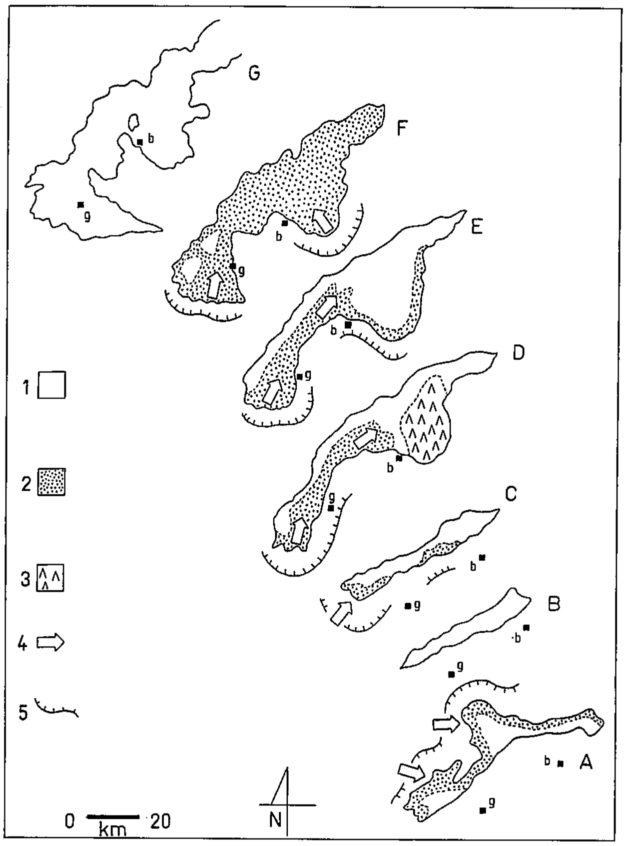


Figure 12.- Palaeogeographic evolution of the basin since the Turolian. Configuration of the basin during the Turolian (A), early Alfambrian (B), late Alfambrian (C), late Villanian (D), early Pleistocene (E), late Pleistocene (F), and at present (G). During the late Turolian and Alfambrian the Guadix-Baza basin, stretching NE-SW, was relatively limited in extent. In the Villanian it experienced considerable NW-SE extension at two different points, the Guadix and Baza subbasins. 1: Lacustrine, non-evaporitic deposits and distal, fluviatile deposits; 2: Alluvial deposits; 3: Lacustrine evaporitic deposits; 4: Major, sediment-transport directions; 5: Source areas; g: Guadix; b: Baza.

and Baza subbasins (Fig. 5). The connection between these two subbasins was established north of the Guadix subbasin (Fig. 12). Significant uplift of the southern and eastern marginal massifs (Sierra Nevada and Sierra de Baza) took place. Alluvial sedimentation concentrated mainly in the Guadix subbasin and lacustrine sedimentation mostly in the Baza subbasin. During the Pleistocene, the configuration of the basin remained more or less the same. In the early middle Pleistocene, sedimentation was not very significant in terms of vertical accumulation and was restricted to the Baza subbasin, where a broad, shallow lake developed. In the middle to late Pleistocene, alluvial sedimentation predominated, becoming especially significant during the glacial periods. Small lakes and swamps temporarily formed, very locally, in the western part of the basin.

Tectonic model

There is no doubt that tectonics played a major role in the development and evolution of the Guadix-Baza basin. During the late Turolian and Alfambrian, the basin was aligned NE-SW, indicating significant extensional movements in that direction. During the Villanian, the basin experienced considerable NW-SE extension at two different points, NE and SW of the former NE-SW elongated depression. As a result, the basin increased considerably in extent (to more than three times its size during the Alfambrian), and the Guadix and Baza subbasins as such opened and differentiated. As a consequence as well of these latter movements, some of the deposits, especially those of the underlying marine units and of the older continental units, were separated and displaced to the margins of the newly-opened areas (Fig. 11).

The evolution of the Guadix-Baza basin is similar to that exhibited by pull-apart basins controlled by two-parallel, *en echelon*, right-stepping, right-lateral strike-slip master faults. According to Rodgers (1980), in these tectonic systems as the offset across the master faults increases, the overlap increases concomitantly, keeping the separation between the two master faults more or less constant. As a result, the basin configuration changes from that of a single elongated basin, with its axis joining the ends of the master faults, to that of a two-depocentre basin. These depocentres develop near the ends of the two faults. At the beginning of this tectonic evolution, the zone of normal faulting is located in the central part of the basin. As the overlap increases, however, the zones of normal faulting are displaced to the ends of the basin and the faulting in the centre of the basin is strike-slip.

In the case of the Guadix-Baza basin, the master faults controlling its tectonic evolution can no doubt be related to the Negratín dextral strike-slip fault system. This fault system, aligned N50-70E, has presumably worked as two parallel but separate master faults from the late Miocene onwards. In relation to this fault zone, a small NE-SW orientated lacustrine pull-apart basin formed during the late Turolian (Fig 12). This basin was completely filled in, and its sediments were uplifted and slightly tilted southwards before the Pliocene. After an interval of approximately 600 ka, the activity of the master faults renewed during the early Alfambrian. The basin was then occupied by a lake, also orientated NE-SW (Fig. 12). During the Villanian-early Pleistocene, secondary strike-slip faults aligned more or less perpendicular (N150-170E) to the main master faults and with the same relative movement appeared in the centre of the basin. Considerable extension then took place in the inter-fault areas near the basin margins, resulting in the Guadix and Baza depocentres (Fig. 12).

Conclusions

The uppermost Miocene-Pleistocene continental sedimentary record of the Guadix-Baza basin is around 500 m thick and comprises five units, separated by hiatuses. Their ages are upper Turolian, Alfambrian-lower Villanian, Villanian-lower Pleistocene, middle Pleistocene, and middle-upper Pleistocene respectively.

Lacustrine sedimentation is present in all of these units and consists predominantly of marls (lutites) and limestones. Evaporite (balatino gypsum) deposition was also very significant at one specific period (during the late Villanian). The thickest lacustrine deposits are from the upper Turolian (up to 170 m) and the Villanian-lower Pleistocene (up to 250 m).

Repetitive sedimentary sequences are common in the lacustrine deposits of the Guadix-Baza basin. Sequences of marls intercalated with evaporites and carbonates are characteristic in the Villanian, and sequences of marls intercalated with limestones are commonly found in the Alfambrian and in the lower Pleistocene lacustrine deposits. Cyclicity studies carried out with the CYSTRATI program relate the marl-limestone interbeds to obliquity and precession cycles. The gypsum-lutite/marl alternations reflect very high-frequency cyclicities (from 500 to 1800 years).

During the initial continental stages (late Turolian and Alfambrian), the Guadix-Baza basin was relatively limited in extent (some 300 km^2), elongated NE-SW, and mainly occupied by a lake. During the Villanian, there was a significant increase (more than three-fold) in the basin area, with considerable NW-SE extension along major faults. This resulted in a pronounced change in basin morphology, with the appearance of two depocentres, those of the Guadix and Baza subbasins. This configuration has remained more or less unchanged from the Villanian to the present time. Lacustrine sedimentation concentrated mostly in the Baza subbasin, whilst alluvial sedimentation dominated in the Guadix subbasin. The tectonic history and evolution of the Guadix-Baza basin seems to be closely related to the activity of the N50-70 trending Negratín dextral strike-slip fault system.

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