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Age and environmental evolution of the syn-rift fill of the southern coast of the gulf of Corinth (Akrata-Derveni region, Greece)

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Key words. – Sedimentology, Palynology, Ostracod, Pleistocene, Corinth Rift, Greece

Abstract. – The southern coast of the gulf of Corinth exhibits syn-rift deposits, giving insights into the first stages of continental extension as well as the geodynamic evolution of the surrounding Aegean region. The stratigraphy (relative position, 3D geometry, dating) of these deposits is still subject to controversies. The syn-rift evolution of the central part of the southern coast of the Corinth rift is revisited, based on new sedimentological and paleontological data. While ostracods analysis provides precise information about the paleoenvironments, recent advances in palynology supply a more accurate chronology.

For the first time, we document marine evidences and Pleistocene evidences below the well-known giant Gilbert-type fan deltas of the Corinth rift. The syn-rift fill records a three-phase history: (1) the Lower Group corresponds to continental to lacustrine environments passing up progressively to brackish environments with occasionally marine incursions from before 1.8 Ma to some time after 1.5 Ma, (2) the Middle Group corresponds to giant alluvial fans and to Gilbert-type fan deltas prograding in an alternating marine and lacustrine environment from around 1.5 Ma to some time after 0.7 Ma, and (3) the Upper Group corresponds to slope deposits, Gilbert-type fan deltas and marine terraces indicating the emergence of syn-rift sediments along the southern coast from at least 0.4 Ma to the present day, with alternating marine and lacustrine deposition controlled by the position of the Mediterranean sea level relative to the Rion Strait sill.

Age et évolution paléoenvironnementale du remplissage syn-rift de la marge sud du golfe de Corinthe (Grèce)

Mots clés. – Sédimentologie, Palynologie, Ostracode, Pléistocène, Rift de Corinthe, Grèce

Résumé. – Le remplissage sédimentaire qui affleure sur la marge sud du golfe de Corinthe a enregistré les premiers stades d'une extension continentale mais aussi des éléments de l'évolution géodynamique de la région égéenne. La stratigraphie (position relative, géométrie 3D, datation) de ces dépôts est toujours sujette à controverse. Une nouvelle étude sédimentologique et paléontologique permet de proposer un modèle d'âge plus précis à l'aide d'une étude palynologique et une reconstitution paléoenvironnementale des dépôts basées sur les faciès sédimentaires et les assemblages d'ostracodes.

Ce travail présente pour la première fois des indices marins et des évidences d'âges pléistocènes sous les fameux Gilbert-type fan deltas du golfe de Corinthe. Le remplissage syn-rift enregistre trois grandes phases : (1) le Groupe inférieur (Lower Group) correspond à des environnements continentaux à lacustres qui évoluent progressivement vers des environnements saumâtres avec des incursions marines ponctuelles à partir d'au moins 1,8 Ma jusqu'à 1,5 Ma, (2) le Groupe intermédiaire (Middle Group) correspond à des cônes alluviaux géants et des Gilbert-type fan deltas progradants dans une étendue d'eau alternativement marine et lacustre de 1,5 Ma jusqu'à au moins 0,7 Ma, et (3) le Groupe supérieur (Upper Group) correspond à des dépôts de pente et des terrasses marines témoignant de la surrection progressive et toujours active de la marge sud du golfe de Corinthe depuis au moins 0,4 Ma, mais aussi de l'alternance de conditions marines et lacustres contrôlée par la position du seuil de Rion par rapport au niveau relatif de la mer Méditerranée.

INTRODUCTION

Active extensional basins are important to understand because their well preserved sedimentary fill and tectonic structures record (1) controlling factors of sedimentation such as climate, sediment supply or accommodation space, (2) information on the relative chronology of fault activity and (3) information about the timing and evolution of the surrounding area geodynamics [e.g. Leeder and Gawthorpe, 1987; Gawthorpe *et al.*, 1994]. The gulf of Corinth is a classical example of an active extensional basin, recording the first stages of a rift evolution [e.g. Doutsos *et al.*, 1988;

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Gawthorpe *et al.*, 1994; Roberts and Jackson, 2002; Moretti *et al.*, 2003]. It has been extensively studied for more than a century and has been the subject of many controversies, dealing with dating and stratigraphic correlation since the first interpretation of a late Pliocene age [Fucus, 1876; Philippson, 1892; Deperet, 1913].

Seismic profiles and cores collected offshore indicate an alternating marine and lacustrine water body in the present rift since at least 0.13 Ma [Perissoratis *et al.*, 2000; Moretti *et al.*, 2004]. While the first syn-rift deposits preserved onshore correspond to continental, lacustrine and brackish environments, the timing and mode of transition between the oldest and youngest periods of time are still undetermined. It is a critical issue for rift evolution from closed to open conditions, which may be related to fault growth and linkage, lake expansion or changes in sediment supply or climate [Gawthorpe and Leeder, 2000]. When was the gulf connected for the first time to the Mediterranean Sea ? Is this connection perennial ? These are the questions addressed in the present paper based on a coupled approach of sedimentology, paleoecology and palynology.

The syn-rift succession is preserved and uplifted in spectacular outcrops on the southern coast of the gulf of Corinth. Biostratigraphical and paleoenvironmental studies on the central part of the southern coast of the gulf are scarce [e.g. Strauch, 1994], and have never been placed within a clear stratigraphical scheme for the whole syn-rift series. Most of the syn-rift series do not contain clear biostratigraphic and paleoenvironmental markers in this area. We used ostracods as paleoenvironment indicators, and pollens as biostratigraphical indicators, to complement recent lithostratigraphical work in the Akrata to Derveni region [Rohais *et al.*, 2007].

REGIONAL SETTING OF THE CORINTH RIFT

The Corinth rift corresponds to one of the most recent extensional features in the Aegean area (fig. 1). Extension in the Aegean Sea started in Miocene times [Le Pichon and Angelier, 1979; Jolivet *et al.*, 1994; Armijo *et al.*, 1996] but the relationships between Aegean extension and the evolution of the gulf of Corinth are still unclear [Doutsos and Kokkalas, 2001; Nyst and Tatcher, 2004].

The gulf of Corinth is a 105 km long and less than 30 km wide graben, bounded on each side by systems of recent normal faults (fig. 1) [e.g. Jackson *et al.*, 1982; Roberts *et al.*, 1993; Roberts and Koukouvelas, 1996; Moretti *et al.*, 2003; McNeill *et al.*, 2005]. It obliquely crosses the underlying stack of Mesozoic tectonic units made of phyllites, schists, quartzite and carbonates. The present day gulf has a maximum depth of about 900 m and is separated from the Mediterranean Sea by a sill at the Rion strait (62 m).

The Corinth rift extension is assumed to have started in Pliocene times and is still ongoing [Billiris *et al.*, 1991; Roberts, 1996; Davies *et al.*, 1997; Doutsos and Kokkalas, 2001]. It is the most seismically active zone in Europe with up to 15 mm/y of N-S extension as measured with

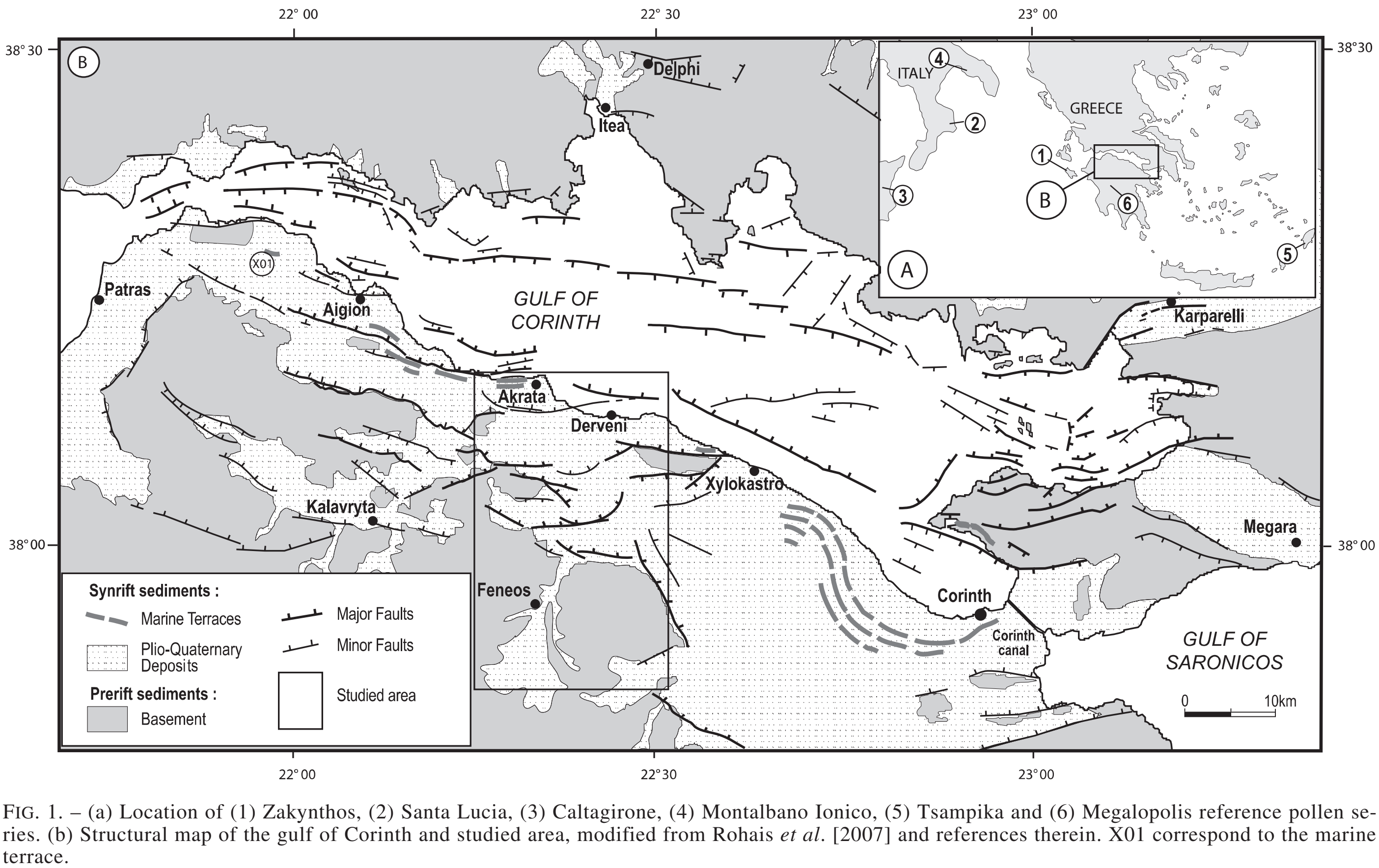

FIG. 1. – (a) Location of (1) Zakynthos, (2) Santa Lucia, (3) Caltagirone, (4) Montalbano Ionico, (5) Tsampika and (6) Megalopolis reference pollen series. (b) Structural map of the gulf of Corinth and studied area, modified from Rohais *et al.* [2007] and references therein. X01 correspond to the marine terrace.

FIG. 1. – (a) *Localisation des coupes de références en palynologie. (b) Schéma structural du golfe de Corinthe et localisation de la zone d'étude, modifié d'après Rohais* et al. *[2007] et références citées. X01 indique la localisation de la nouvelle terrasse marine.*

instantaneous GPS data [Briole *et al.*, 2000] and more than 1 mm/y of uplift of the southern margin with a higher value to the west decreasing to the east [e.g. Tselentis and Makropoulos, 1986; Billiris *et al.*, 1991; Collier *et al.* 1992; Armijo *et al.*, 1996; Davies *et al.*, 1997; De Martini *et al.*, 2004; Leeder *et al.*, 2003; Mc Neill and Collier, 2004]. Subsidence rates in the central part of the present gulf are estimated at between 2.5 to 3.6 mm/y [Perissoratis *et al.*, 2000; Moretti *et al.*, 2004] based on dating of Holocene deposits.

STRATIGRAPHICAL SETTING OF THE CORINTH RIFT

Rohais *et al.* [2007] propose a revised simple lithostratigraphic scheme for the central part of the rift that is representative for the entire southern coast of the gulf [Ghisetti and Vezzani, 2005]. Syn-rift deposits of the southern coast of the gulf of Corinth can be subdivided in three main lithostratigraphic units, which are in stratigraphic order: (1) a Lower Group mostly made of fluvio-lacustrine deposits, (2) a Middle Group comprising thick Gilbert-type fan delta conglomerates and (3) an Upper Group of slope deposits, Gilbert-type fan delta and uplifted recent terraces forming steps along the coastline.

The Lower Group exhibits facies ranging from alluvial fan to shallow-water lacustrine environments [Ori, 1989; Doutsos and Piper, 1990]. The oldest age given in literature for the lowermost deposits of the Lower Group is Miocene based on palynological analysis [Muntzos, 1992] and ostracods studies [Danatsas, 1989, 1994]. Upper Pliocene to Lower Pleistocene ages are reported for the Lower Group sediments in the central part of the southern coast of the gulf of Corinth based on palynological analysis [Sauvage, 1975, 1977, Sauvage and Dufaure, 1976; Papavassiliou *et al.*, 1989; Muntzos, 1992; Katagas *et al.*, 1993] and ostracods studies [Danatsas, 1989, 1994]. Age attribution of these sediments has been also proposed by correlating them with the basal syn-rift series outcropping in the gulf of Patras (west) and with the sediments in Corinth canal region to the east (fig. 1). There, the oldest syn-rift fill has been dated at Middle to Late Pliocene using the faunal and floral assemblages [Freyberg, 1973; Kontopoulos and Doutsos, 1985; Frydas, 1987, 1989]. The paleontological dating is also consistent with the radiometric age given by interbedded dacites, dated at 3.62 +/– 0.18 and 4.00 +/– 0.4 Ma near the Corinth canal [Collier and Dart, 1991].

Fluvio-lacustrine deposits of the Lower Group are overlain either conformably or unconformably by conglomeratic facies of the Middle Group which were deposited in large and thick alluvial fans in the south, distally passing to large Gilbert-type fan deltas, then to fine-grained turbidites to the north [e.g. Doutsos *et al.*, 1988; Doutsos and Piper, 1990; Poulimenos, 1993; Zelilidis and Kontopoulos, 1996]. The basal part of these conglomerates have been dated as Calabrian (~ 1.8 to 0.8 Ma) using mammalian fossils [Dercourt, 1964; Symeonidis *et al.*, 1987], an age that is also in agreement with the Lower Pleistocene age provided by palynological analysis of the same interval in the Vouraikos fan delta to the west [Malartre *et al.*, 2004] and in the Akrata and Evrostini fan delta [Muntzos, 1992]. Assuming a constant uplift rate of 1 to 1.5 mm/y, Lower Pleistocene ages (0.9 to 0.78 Ma) are reported for the Mavro fan delta and the Evrostini fan delta [e.g. Westaway, 1996]. Recently, palynological analysis have bracketed the age of the Vouraikos fan delta from before 1.1 Ma to sometime after 0.7 Ma [Ford *et al.*, 2007].

The Upper Group overlies either conformably or unconformably the previous groups. Fluvial or marine sediments of this unit were deposited on perched terraces or form carbonate reefs encrusting fault block crests [e.g. Schröder, 1975; Keraudren and Sorel, 1987; Pirazzoli *et al.*, 2004; Kershaw *et al.*, 2005]. The oldest marine or fluvial terraces are dated about 0.312-0.307 Ma from radiometric data in the Akrata area [Collier *et al.,* 1992; McNeill and Collier, 2004], and the youngest about 1806-305 years B.P. [Stiros and Pirazzoli, 1998]. The terrace system is locally associated to Gilbert-type fan deltas perched along the coast recording high sediment supply [McMurray and Gawthorpe, 2000]. They have been dated 0.386 Ma using radiometric U-series method on corals in the Akrata region [Vita-Finzi, 1993]. This age is consistent with the nannofossil NN20 zone, which begins about 0.46-0.45 Ma ago, determined in samples collected in the distal fan delta facies in the Xylokastro region [Keraudren and Sorel, 1987].

PALEOENVIRONMENT: FACIES SEDIMENTOLOGY AND PALEOECOLOGY

The studied area has already been surveyed [Doutsos *et al.*, 1988; Ori, 1989; Doutsos and Poulimenos, 1992; Zelilidis, 2000]. Nevertheless none of these studies provide a combined approach based on mapping, sedimentological studies and paleontological analysis. A detailed geological map was compiled showing the main structural elements and the main lithostratigraphic units on a 25 x 30 km area at a scale of 1:25 000 (fig. 2). Key sections were logged at different scales ranging from 1:100 to 1:5000 and were simplified into synthetic sections (fig. 3). Samples have been analysed to characterise the paleoenvironmental evolution through time and space by two of the author (J.P. Colin and S. Rohais) (fig. 4). Those determinations and paleoenvironnement interpretations are consistent with previous published works in surrounding areas [e.g. Danatsas, 1989, 1994; Fernandez-Gonzalez *et al.*, 1994; Mostafawi, 1994; Guernet *et al.*, 2003].

The syn-rift sediment thickness of the southern coast of the rift of Corinth can reach more than 2800 m in the Mavro Oros region (fig. 3). In the Derveni area, the maximum thickness of the sediment reaches 2100 m. This value is close to the maximum sediment thickness of the present day gulf, which ranges from 1700 to 2200 m [Clément *et al.*, 2004; Zelt *et al.*, 2004]. The composite section logged in the Derveni area (fig. 3g) is representative of the syn-rift infill within a tilted block in the central part of the southern margin. Here, the fluvio-lacustrine Lower Group, the Gilbert-type fan delta Middle Group and the perched systems of the Upper Group previously mentioned can be recognised. The Lower Group can be subdivided into three main formations [Rohais *et al.*, 2007] in the Derveni area, which are in stratigraphic order: the Exochi Formation, the Valimi Formation and the Aiges Formation. These formations are laterally equivalent as suggested by mapping and general correlation (fig. 3), the Exochi Formation corresponding to the most proximal facies association (more developed toward the West) and the Aiges Formation (more developed toward the east) to the most distal facies association. While the foreset height of Gilbert-type fan deltas indicates the water depth at time of deposition, ostracod assemblages help to decipher whether the basin was marine, brackish or lacustrine.

Lower Group

Exochi Formation

The Exochi Formation (50 to more than 600 m thick) is made of alluvial depositional systems unconformably overlying the folded basement (fig. 2). Proximal alluvial fan facies are recognised, consisting of poorly sorted pebble to boulder conglomerates and breccias organised in massive tabular beds-sets (h = 1 to 20 m) interbedded with lenticular beds of pebbly sandstones and siltstones. Distal settings are also recorded, comprising coarse-grained fluvial channel-fill deposits passing laterally to overbank, floodplain and lacustrine fine-grained sediments with local soil horizons. Lacustrine environments are documented by the *Candona* sp. monospecific assemblage (ostracods) (fig. 4). Paleocurrent measurements show a northward and eastward trend, indicating longitudinal and lateral sources of sediment supply into the basin (fig. 3).

Vertically stacked alluvial fans are organised in a globally thinning and upward fining trend progressively passing upward into fluvio-lacustrine sediments. This suggests a global transgressive evolution toward the Valimi Formation.

Valimi Formation

The Valimi Formation (50 to more than 800 m thick) corresponds to fluvio-lacustrine sediments, globally finer than those of the Exochi Formation. The proximal part of the depositional system is made up of granule to pebble conglomerates organised in channelised lenticular beds of wide lateral extent (h = 0.5 to 10 m, l = 100 to 1000 m), interbedded with mudstones and siltstones showing pedogenetic

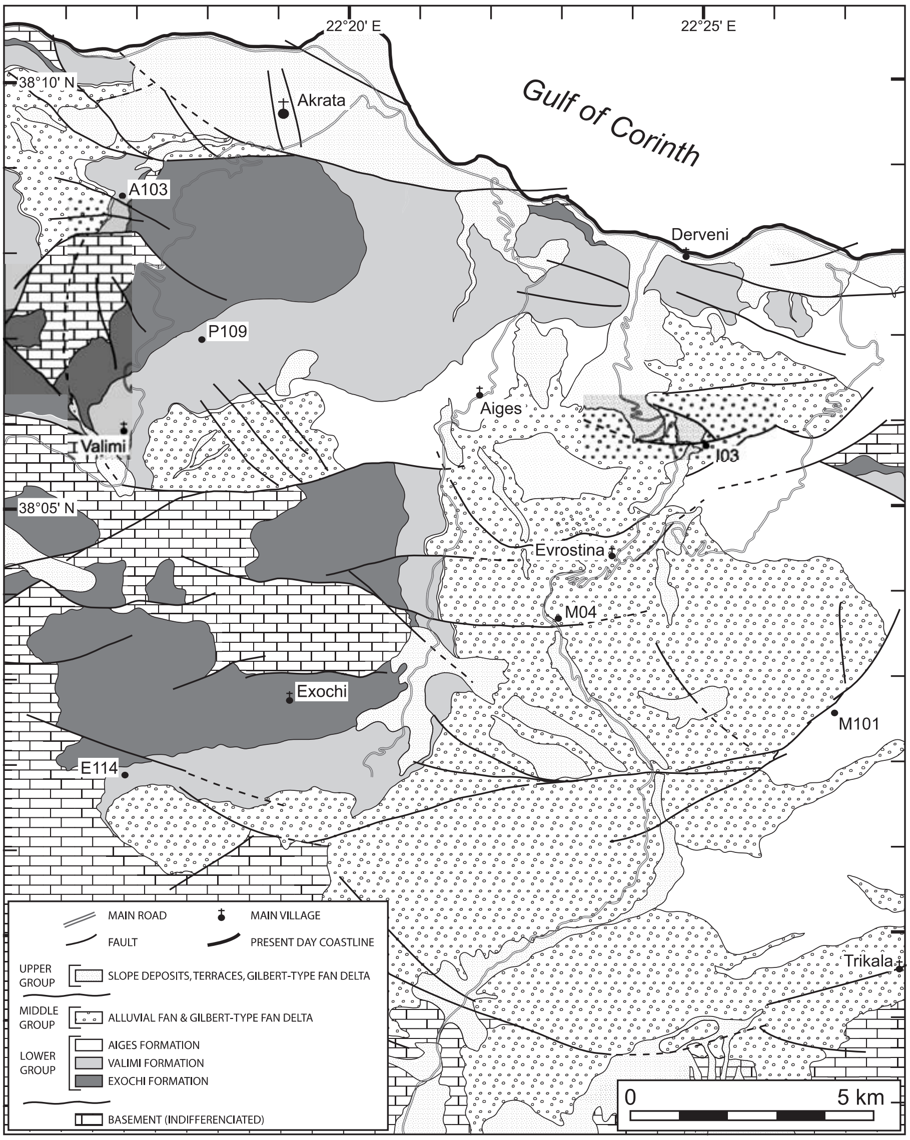

FIG. 2. – Geological map of the central part of the gulf of Corinth and sample location for palynological analysis [modified from Rohais *et al.*, 2007]. Sample M203 is located 2 km west of sample M101 in the Valimi Formation.

FIG. – *Carte géologique de la partie centrale de la marge sud du golfe de Corinthe [modifié de Rohais* et al., *2007]. L'échantillon M203 est localisé à 2 km à l'ouest de l'échantillon M101, en dehors de la carte présentée.*

weathering or containing freshwater to brackish gastropods and bivalves (*Theodoxus* sp., *Adelina elegans*, *Planorbis* sp., *Melanopsis* sp., *Neritina* sp., *Limnocardium* sp.). These facies have been interpreted as braided plain channels interbedded with floodplain deposits. More distally along the depositional profile, very-coarse grained to granular sandstones formed steeply inclined sets (h = 0.1 to 1 m, amplitude = 5 to 30 m, dip = 10 to 30°). These sediments were deposited in prograding sandy Gilbert-type fan deltas to shallow lakes as documented by the ostracod association (fig. 4). The height of the Gilbert-type fan delta foreset indicates a water depth of around five to ten meters. Paleocurrent measurements and foreset orientations indicate that the dominant delta progradation were from south to north and

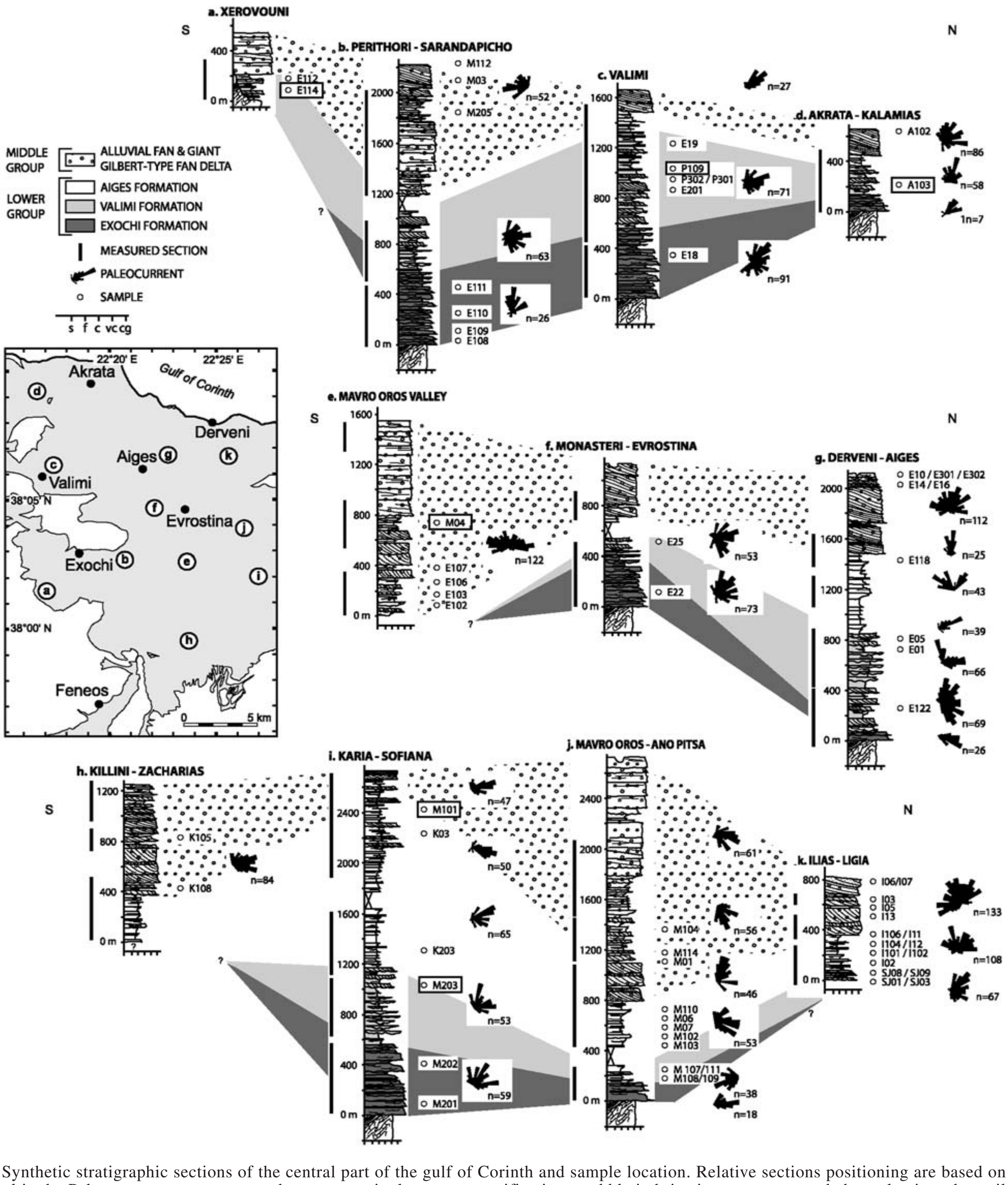

FIG. 3 – Synthetic stratigraphic sections of the central part of the gulf of Corinth and sample location. Relative sections positioning are based on the present day altitude. Paleocurrents were measured on current ripples, cross-stratifications, pebble imbrications, grooves, and channel axis and are tilt corrected. Grain size scale: shale (s), fine sandstones (f), coarse sandstones (c), very coarse sandstones (vc) and conglomerates (cg).

FIG. 3 – *Colonnes lithologiques synthétiques de la partie centrale du golfe de Corinthe et localisation des échantillons. Les mesures de paléocourant ont été effectuées sur des rides de courant, des stratifications obliques, des imbrications, des figures de base de bancs et des axes de chenaux et sont débasculées. Granulométrie : argiles (s), grès fins (f), grès grossiers (c), grès très grossiers (vc) et conglomérats (cg).*

from west to east, with local evidences of southward progradation (fig. 3).

The relative percentage of lacustrine versus fluvial sediments increases upward. This suggests a transgressive evolution from braided-plain to Gilbert-type fan delta and subaqueous environments. Limestones outcropping on the tilted block crest of Xylokastro (section J, fig. 3) have a marine content (fig. 4) and correspond to local coastal facies, isolated in the rift basin.

Aiges Formation

The Aiges Formation (10 m to more than 1000 m thick) mainly corresponds to fine-grained deposits from lacustrine, distal fan delta and turbiditic depositional systems.

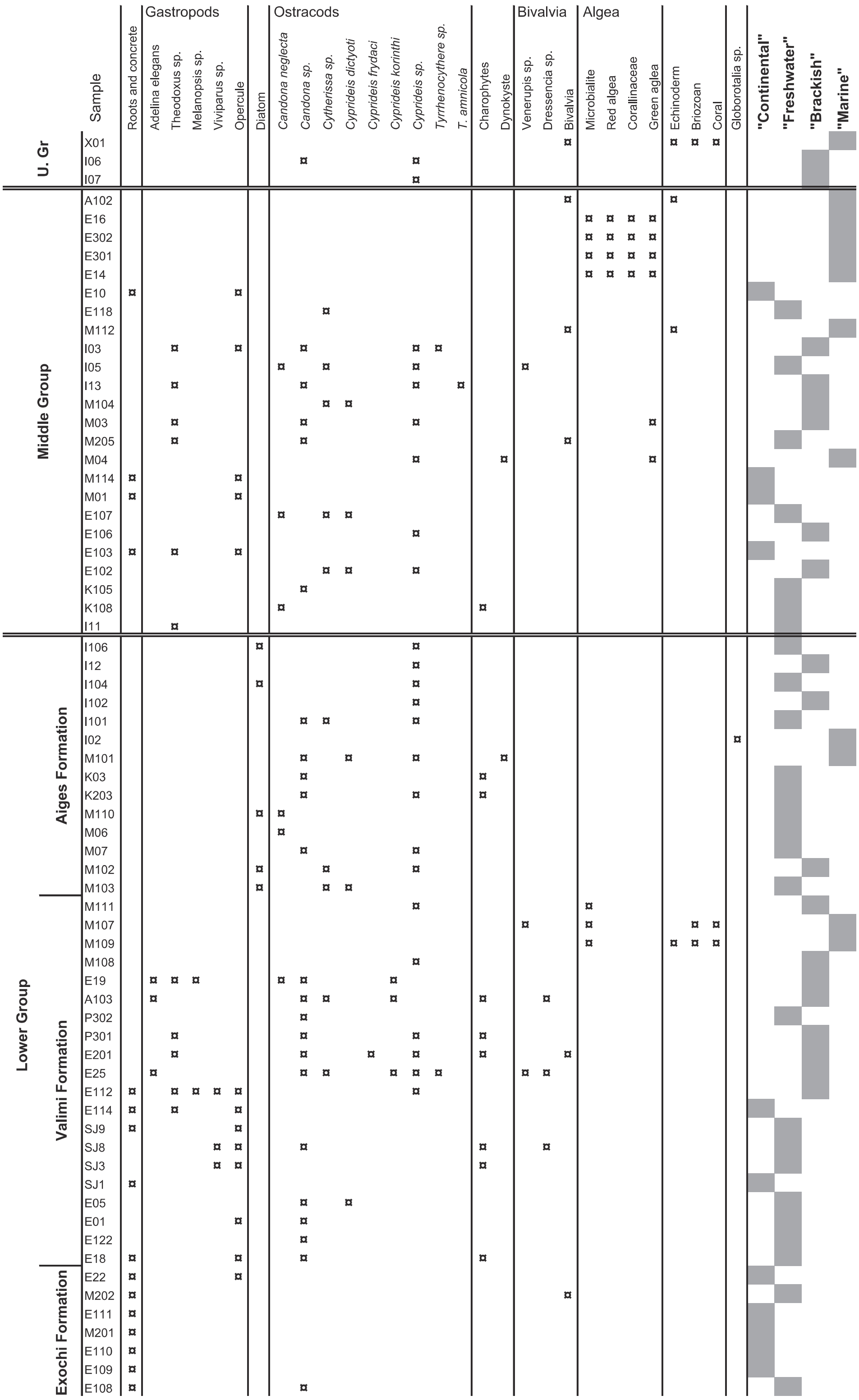

FIG. 4. – Fauna-floral assemblages from sample analysis and paleoenvironmental implications. Samples are classified based on a relative stratigraphic position for each group and formation.
FIG. 4. – *Analyses des associations faunistiques et implications paléoenvironnementales. Les échantillons sont reportés en fonction de leur position relative dans chacun des groupes et formation.*

The dominant facies consists of shaly siltstones and marls, often bioturbated, deposited in lacustrine environments. These fine-grained sediments are interbedded with thin-bedded laminated fine- to coarse-grained sandstones (h = 0.5 to 5 cm). The beds are erosionally based and generally inverse graded, passing upward to current ripples bedding. They are interpreted as high density (proximal) to low density turbidity currents and fallout deposits (distal). The water body was alternatively under lacustrine or marine influences. Freshwater conditions are documented with the *Candona* sp. monospecific assemblage (ostracods) and diatoms, brackish to freshwater conditions by *Cyprideis* sp., *Candona* sp., *Tyrrhenocythere* sp. (ostracods), and marine conditions by Globorotalidea juvenile forms (foraminifers) and dynokysts marine species from *Spiniferites/Achomosphaera* complex [Head, *com. pers.*] (fig. 4). The turbiditic systems of the Aiges Formation may correspond to the distal equivalent of the fluvio-lacustrine systems observed below but also to the distal part of the giant Gilbert deltas above (Middle Group). For mapping purposes, we choose to group these two indistinguishable heterolithic fine-grained facies into one lithostratigraphic unit: the Aiges Formation. Paleocurrents of the Aiges Formation show a northward and westward polarity (fig. 3).

Middle Group

Proximal topset facies correspond to poorly sorted granule-boulder conglomerates organised in tabular bed-sets with high lateral continuity. These massive beds are locally interbedded with finer-grained erosive beds, and occasionally show pebble imbrication or cross-bedding. The foresets of the Gilbert deltas can reach more than 500 m in height in the Evrostini Gilbert delta with a dip around 35° (h = 0.2 to 5 m, l = 50 to 900 m, dip = 25 to 35°). The foresets are made of granule-cobble conglomerates organised in moderately sorted and graded tabular to lenticular dipping beds, interbedded with fine-grained deposits. The bottomsets and the distal facies correspond to granule to pebble conglomerates organised in tabular to lenticular horizontal beds (h = 0.2 to 5 m, dip 10°). Conglomerate beds are massive or graded and are interbedded with laminated and graded pebbly sandstones or siltstone beds with floating pebbles.

Red algae, blue algae and green algae with marine affinity have been identified within fine-grained topset deposits. Some dinokysts, which belong to the *Spiniferites/Achomosphaera* complex, as *Spiniferites bentorii,* have been identified within fine-grained distal deposits [Head, *com. pers.*]. All of them are marine species [Head *et al.*, 2005]. Nevertheless, the distal basin environments are devoid of planktic and benthic foraminifera species suggesting restricted marine condition. Freshwater ostracods (*Candona* sp.) and gastropods (*Theodoxus* sp., *Adelina elegans*, Planorbides) have also been identified within very fine-grained topset deposits, different from the previous marine one. Water depths can be estimated using foreset package geometry, which indicate 50 m for the smallest Gilbert-type fan delta developed to the south up to 500 m for those developed along the present day coastline (Evrostini fan delta).

The Middle Group (500 to more than 1000 m thick, mean thickness ca. 800 m) corresponds to a northward prograding sedimentary system, ranging from a proximal alluvial fan in the south to a Gilbert-type fan delta and a distal turbiditic system in the north. Fauna-floral associations suggest that the fan delta prograded into an alternating marine and lacustrine water body.

Upper Group

The Upper Group was generally deposited unconformably above the previous groups and drapes an incised paleomorphology (incision from 1 m to more than 80 m). Red soil (thickness = 1 to 5 m) and consolidated red slope breccias made of reworked Middle Group sediments, are developed in the south and merge northward with perched Gilbert-type fan delta topsets (alt. ~ 200 m). Locally, the Upper Group also corresponds to small terraces with bored pebbles, perched along the present day coastline. Brackish conditions are documented during this period of time by ostracods assemblages (fig. 4). Marine influences are also documented with the highest marine terrace of the gulf (alt. ~ 730 m), which has been located for the first time to the west of Aigion (fig. 1). It corresponds to an encrusted notch and contains marine bivalves and gastropods such as *Pecten maximus*, *Chlamys* sp., *Spondylus* sp., *Arca* sp., *Patella* sp. and many foraminifera, corals, bryozoans and algae (fig. 4).

The Upper Group corresponds to a by-pass and/or incision period in the southern part of the study area and to poorly consolidated Gilbert-type fan deltas and terraces perched along the present day coastline (fig. 2). These deposits recorded marine and lacustrine alternating conditions.

BIOSTRATIGRAPHY: AN AGE MODEL BASED ON PALYNOLOGY

Dataset and methodology

Samples collected for pollen analysis were prepared using a standard chemical technique adapted from Cour [1974]. Only 7 samples – out of the 29 samples prepared – provided enough pollen grains for quantitative analysis (fig. 5). More than 1800 pollen grains were counted, which corresponds to at least 150 per sample (excluding *Pinus* grains). The pollen floras (fig. 5) were documented with an average of 23 taxa per sample.

The building of an Eastern Mediterranean regional palynostratigraphic chart requires the knowledge of the chronological range of taxa in this area. In Europe and Mediterranean areas, Pliocene taxa inherited from tropical-subtropical vegetation [Thompson and Flemming, 1996] did not survive to long-term global cooling and establishment of Pleistocene climatic cycles (i.e. interglacial/glacial periods) [Ruddiman, 2003]. Each climatic cooling cycle forced land plants to shift southward [Combourieu-Nebout, 1993]. This phenomenon, combined with the Mediterranean southern barrier and the E-W oriented massifs, is responsible for progressive extinction of taxa [Svenning, 2003]. However, estimation of timing of extinction is difficult because of the beginning of interglacial/glacial transitions since the Pleistocene. Indeed, the beginning of a glacial period corresponds to a typical cortege of vegetation (i.e. *Artemisia*, *Ephedra*). During interglacial periods, mesothermic vegetation dominated (Deciduous *Quercus*, *Liquidambar*…), and then altitude elements (*Picea*, *Cedrus*, *Tsuga*..)

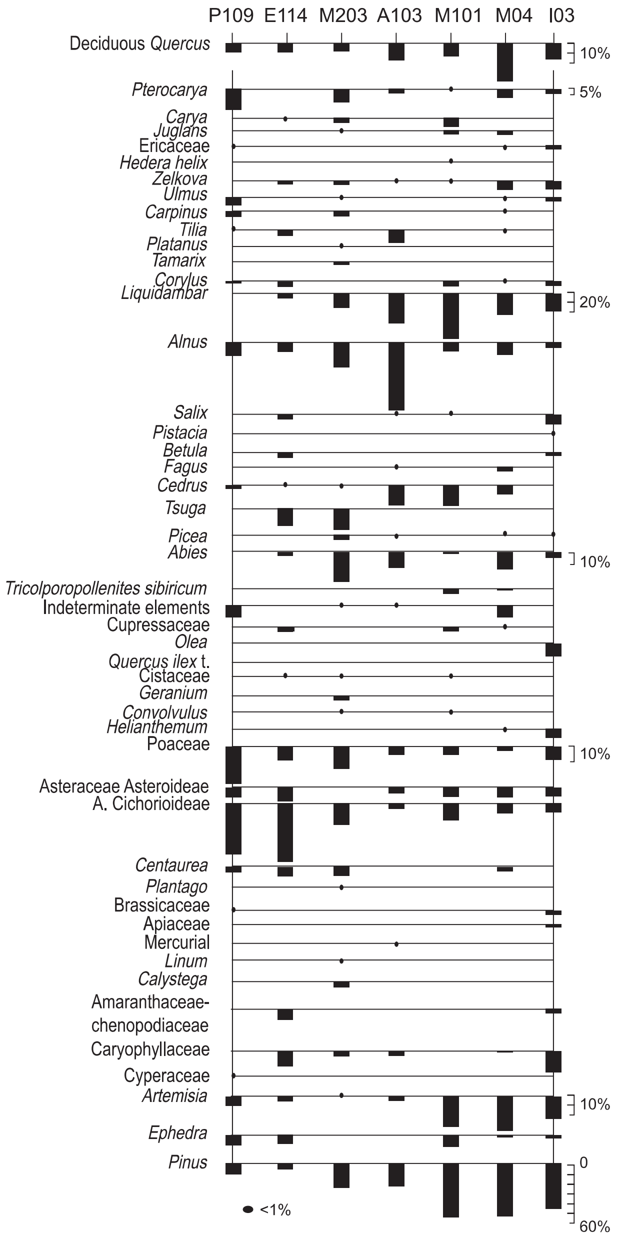

FIG. 5. – Detailed pollen diagram. All taxa (except *Pinus*) are represented in relative percentages, which are calculated according to the total of counted pollen grains minus *Pinus*. Only *Pinus* has a relative percentage based on the total of counted pollen grains.
FIG. 5. – *Diagramme pollinique détaillé. Tous les taxons (sauf les* Pinus*) sont représentés en pourcentage relatif qui est calculé par rapport au nombre total de pollen minoré des* Pinus*. Seul le pourcentage de* Pinus *est relatif à l'ensemble des pollens comptés.*

grew. Pleistocene samples may fall into either interglacial or glacial periods. Moreover, existence of microclimates located, for example in a mountain range, lead to mixed vegetation. Lastly, warm conditions induced by the southerly location of Greece and humidity from the Mediterranean Sea on minima precession time, can create a vegetation refuge [Mommersteeg *et al.*, 1995]. As a consequence, in the Mediterranean islands, the South Italy peninsula and Greece, taxa are generally the last to disappear from the entire European region [Svenning, 2003]. To attribute ages of presence (variations in abundance) and extinction of taxa, we use pollen sites from Greece (Zakynthos) [Subally *et al.*, 1999]; (Tsampika in Rhodes) [Joannin, 2003; Cornée *et al.*, 2006]; (Megalopolis) [Okuda *et al.*, 2002] and southern Italy (Santa Lucia) [Joannin *et al.*, 2007]; (Caltagirone) [Dubois, 2001; Suc and Popescu, 2005] (Montalbano Ionico). These sites span from the Pliocene to the Upper Pleistocene and are the reference for our age model (fig. 6).

Proposal age model from palynomorphs

The pollen analyses are first grouped on the basis of presence/absence of some key-taxa (fig. 6). Cluster samples E114, P109, M203, A103 and M101 (Lower Group) can be associated due to the presence of *Carya*, *Tsuga*, *Cedrus*, *Pterocarya*, *Liquidambar* and *Zelkova*. Those taxa were still present at 0.9 Ma in South Italy (Montalbano Ionico). Taxodiaceae and *Cathaya*, which were characteristic from pollen content in Zakynthos before 1.78 Ma [Subally *et al.*, 1999], occurred sporadically after 1.78 Ma in the Santa Lucia Section until about 1.32 Ma [Joannin, 2003; Joannin *et al.*, 2007] and in the Caltagirone Section until about 1.07 Ma [Dubois, 2001] in Sicily. We do not identify those two characteristic pollen markers in cluster samples E114, P109, M203, A103

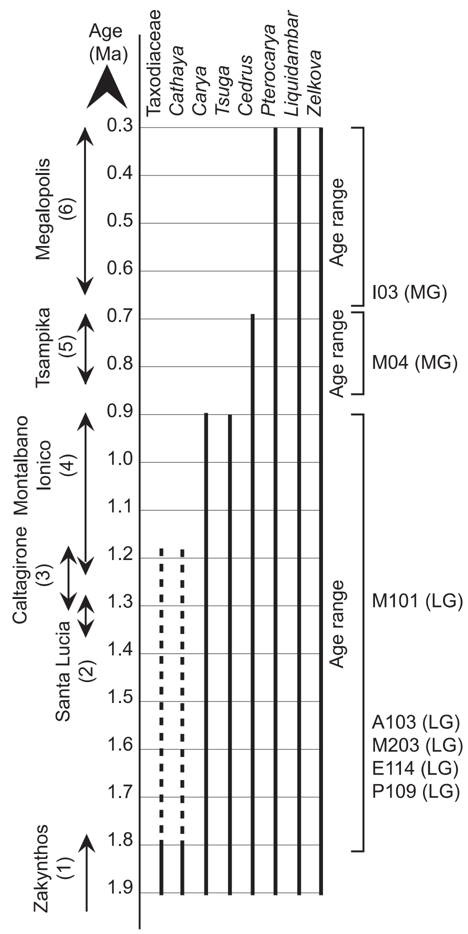

FIG. 6. – Pollen assemblage and proposed correlation with dated series from the Mediterranean region. LG: Lower Group. MG: Middle Group (location on fig. 1).
FIG. 6. – *Association pollinique et corrélation possible avec les séries datées du pourtour Méditerranéen.* LG : *Groupe inférieur. MG : Groupe moyen (localisation sur la figure 1).*

and M101. Thus, we choose to group all those samples in a period of time ranging from 1.78 up to 0.9 Ma.

Sample M04 (Middle Group) did not record the presence of *Carya* and *Tsuga*, which were also absent in Tsampika from 0.82 to 0.7 Ma. M04 could thus belong to this time interval. Sample I03 (Middle Group) recorded *Pterocarya*, *Liquidambar* and *Zelkova*. As *Cedrus* was absent from 0.65 to 0.3 Ma in a place very close to the Corinthian Gulf (at Megalopolis), this sample could belong to this time interval.

Environmental implications from palynomorphs

Corinthian pollen analyses are also grouped on the basis of their similar environmental taphonomy, which is observed in the percentages of *Pinus* grains [Cornée *et al.*, 2006]. Indeed, E114 and P109 are grouped because of low *Pinus* percentages. M203 and A103 are grouped because of moderate *Pinus* percentages (~ 25%). M101, M04 and I03 are grouped because of high *Pinus* percentages (50%). Because of its high buoyancy, *Pinus* pollen concentration increases with distance to river mouth [Heusser, 1988; Beaudouin, 2003]. Evolution of those three type percentages (low, ~ 25% and 50% of *Pinus* percentages) suggests a landward shift and a relative sea level rise from the Lower Group to the basal part of the Middle Group.

DISCUSSION

Age model

The most detailed biostratigraphical studies on the central part of the southern coast of the gulf correspond to those of Danatsas [1994]. While this work is very detailed on ostracod associations and their environmental implications, its conclusions for the structural and sedimentological evolution of the rift is not in agreement with the recent proposed model [Doutsos and Piper, 1990; Rohais *et al*, 2007]. Danatsas [1994] proposes that the first terrestrial and lacustrine deposits of the Lower Group (Exochi Formation) are Middle to Late Miocene, but he does not clearly indicate the biostratigraphic markers. Danatsas [1994] ages are apparently based on (1) non to poorly diagnostic Parathetyan species and genera of non-marine ostracods of the Candonidae family (*Candona, Typhlocyprella, Lineocypris*), (2) the highly morphologicaly variable genus *Cyprideis* and (3) a few endemic species. Muntzos [1992] also suggests that the basal series in the Derveni area is Miocene in age (Tortonian / Messinian) based on the occurrence of *Tricolpopollenites henrici*. However, Sauvage [1977] indicates the same pollen species is representative of the Upper Pliocene.

Most of our samples from the Exochi Formation (Lower Group) are devoid of reliable biostratigraphic markers. We are thus not able to better constrain the ages of the first deposits. Nevertheless, the Miocene ages proposed by Munztos [1992] and Danatsas [1994] have to be rejected because they are based on non to poorly diagnostic species and taxa. Based on our analysis, the Valimi Formation (P109, E114, M203, A103) is Lower Pleistocene. Proposed age model from palynomorphs suggests a period of time ranging from around 1.8 up to 0.9 Ma. Those two boundary ages are not fixed because of incertitude error bars due to this approach. Those ages are consistent with recent published work for the western part of the Corinth rift [Ford *et al.*, 2007].

The transition from the Lower Group to the Middle Group is recorded by the upper part of the Aiges Formation (M101). The last shoreline evidence of the Gilbert-type fan deltas of the Middle Group corresponds to the Evrostini fan delta topsets perched at ca. 1200 m in altitude. Assuming a constant uplift rate close to the present day uplift rate (1 to more than 1.5 mm/y), it suggests that the final stage of the Middle Group has an age ranging from 1.2 up to some time after 0.8 Ma. Our analysis of the samples from Middle Group indicate a period of time ranging from 0.9 to 0.7 Ma (M04), up to 0.7 to 0.3 Ma (I03). Thus, the Middle Group probably ended after 0.7 Ma. The timing of the transition from the Lower Group to the Middle Group is poorly constrained. This transition had to occur during the Pleistocene, because clear evidences of Pleistocene palynomorphs have been found in the Lower Group. Assuming a constant subsidence rate similar to the present day subsidence rate of the gulf (1 to 3.6 mm/y), it suggests that the Middle Group (mean thickness of 800 m), corresponds to a period of time ranging from 0.2 up to 0.8 Ma. Thus, the Middle Group progradation probably started some time after 1.5 Ma. This is in agreement, and more accurate, than the previous works [Dercourt, 1964; Symeonidis *et al.*, 1987; Muntzos, 1992; Malartre *et al.*, 2004]. Those ages are also consistent with recent published works for the western part of the Corinth rift [Ford *et al.*, 2007].

Finally, the Upper Group probably begins after 0.7 Ma and is correlated with the well constrained marine terraces dated from 0.4 Ma to recent [e.g. Collier *et al.*, 1992; Vita-Finzy, 1993; McNeill and Collier, 2004].

Paleoenvironmental evolution of the central part of the Corinth rift

During the initial phase of rifting recorded by the Exochi Formation (Upper Pliocene to Lower Pleistocene), sedimentation was mostly continental and sediments were mainly transported from SW to NE (fig. 3). Alluvial fans laterally passed to braided plain depositional environments toward the centre of the studied area. Shallow lakes were locally developed in the distal part of the system as documented by the ostracod associations. Depositional systems were mainly vertically aggrading, which means that the sediment supply (S) balanced the creation of accommodation space (A) (fig. 7).

During deposition of the Valimi Formation (Lower Pleistocene), a major transgressive trend was marked by the backstepping (landward migration) of the alluvial systems (fig. 3). The deposition of brackish sediments within the dominant lacustrine sediments illustrates the progressive increase of marine influences. Rare fine-grained marine sediments and carbonate facies (Xylokastro tilted block crest) also recorded a gradual connection to open marine conditions. Water depth remained shallow and did not exceed 40 m with an average depth of 5 to 10 m. Again, the sediment supply approximately balanced the creation of accommodation space (A/S ~ 1) (fig. 7). During the Aiges Formation deposition, the sediment source to the West was progressively abandoned while a dominant S-N polarity was established (fig. 3). Alluvial fans passed laterally into small Gilbert-type deltas, themselves passing into fine-grained sediments. This distal sedimentation (turbiditic systems) remained dominantly lacustrine to brackish, but marine incursions were more pronounced than in the previous stage. During deposition of the lower Aiges Formation the sediment supply did not balance the creation of accommodation space (A/S > 1) and therefore, water depth increased (fig. 7).

During deposition of the Middle Group, the Gilbert-type fan deltas prograded northward from the southernmost part of the study area. This progradation corresponds to a basinward shift of the shoreline of about 15 km. Water depths, as measured by the maximum foreset height, progressively increased to up to 500 m. Marine conditions were more common than in the previous stages, but still not perennial. Sediment supply outpaced creation of accommodation space and the system prograded (0 < A/S < 1), while the distal basin remained starved of sediment.

During deposition of the Upper Group, the former Gilbert-type fan deltas were incised, as recorded by perched valleys, slope breccias and stepped terraces. The shoreline shifted northward by more than 5 km between the Middle Group and the Upper Group with a relative sea-level fall of more than 1000 m [Rohais *et al*., 2007]. Such an event was associated with the uplift of the margin and the northward migration of the graben axis since at least 0.4 Ma (oldest dated terraces).

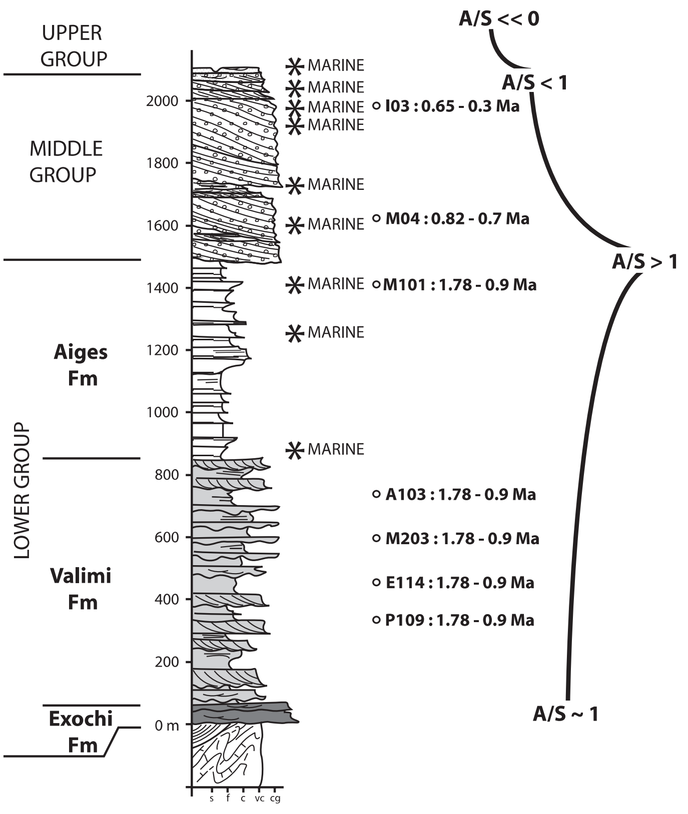

FIG. 7. – Age and paleoenvironmental evolution placed along the composite stratigraphic section for the Derveni-Evrostini area. Samples are projected based on relative stratigraphic correlation. A: accommodation, S: sediment supply. *Marine correspond to marine evidences.

FIG. 7 – *Ages et évolution paléoenvironnementale replacés selon la colonne synthétique de la région de Derveni-Evrostini. Les échantillons sont projetés sur la colonne à partir de corrélation stratigraphique.* A : *accommodation,* S : *flux sédimentaire. *Marine indique les évidences marines.*

Mediterranean connection path

Paleoenvironmental reconstructions suggest that the Gulf recorded alternating marine and lacustrine conditions from at least the Aiges Formation (Lower Group). There are three possible pathways to connect the gulf to the Mediterranean Sea, two eastwards which correspond to the Corinth Isthmus and the Megara basin, and one westwards which corresponds to the Rion Strait (fig. 1).

To the east, the Corinth Isthmus basin and the Megara basin recorded almost the same relative stratigraphic succession as for the central part of the Corinth rift [Bentham *et al*., 1991; Collier and Dart, 1991]. They also recorded an uplift that had probably started during the Middle to Late Pleistocene for the Megara basin [Leeder *et al*., 1991; Bentham *et al*., 1991] and around 0.3 Ma for the Corinth isthmus basin [Collier, 1990]. These basins were probably Mediterranean connection pathways, providing episodic marine incursions within the central part of the Corinth rift.

The western end of the Corinth rift exposes an alluvial to lacustrine succession that is poorly dated [Doutsos *et al*., 1985]. The only marine evidence corresponds to the undated terraces (730 m) mentioned in this paper (fig.1 & 3) and to fine-grained sediments of the Aigion borehole, Upper Pleistocene to Holocene in age [Guernet *et al*., 2003]. The Rion strait sill corresponds to the present day connection between the gulf of Patras and the gulf of Corinth. Onshore and offshore data are too scarce to really discuss the influence of this sill throughout the Pleistocene. After a possible marine incursion during the rift initiation, this Mediterranean connection path seems to have been active during the Middle to Upper Pleistocene [Piper *et al*., 1990; Perissoratis *et al*., 2000; Zelilidis, 2003; Moretti *et al*., 2004].

Stratigraphical analysis [e.g. Doutsos *et al*., 1988; Ori, 1989; Collier and Dart, 1991; Poulimenos *et al*., 1993; Rohais *et al*., 2007] suggest a distal setting to the east and proximal setting to the west during deposition of the Lower Group and a marine incursion from the east (Corinth Isthmus basin and the Megara basin). After the beginning of the southern coast uplift (around 0.7 Ma), those connection paths were probably closed and the Rion strait provided the only connection path to the Mediterranean Sea until recent time.

CONCLUSION

In this paper we document a syn-rift stratigraphy up to 2800 m thick in the central part area of the Corinth rift (fig. 7). The syn-rift succession is divided into three lithostratigraphic groups, in which facies and thickness changes have been studied across an area of ~ 700 km^2 in the Akrata-Derveni region. Based on palynomorph analysis and fauna-floral assemblages, we propose for the first time a clear age model and environmental evolution respecting a simple lithostratigraphic scheme. Marine evidences have been found for the first time in this area below and within the well-known giant Gilbert-type fan delta (Middle Group). Pleistocene evidences have also been found for the first time below the Middle Group. A three phase rift history can thus be proposed in the light of these new results.

1. The Lower Group records the initial stages of rifting corresponding to the Exochi Formation, and the progressive

flooding during a transgressive stage (Valimi Formation). Continental to lacustrine environments pass up progressively to brackish environments with occasionally marine incursions from before 1.8 Ma up to some time after 1.5 Ma. The gulf of Corinth was temporally connected to the Mediterranean Sea though the Corinth Isthmus and the Megara basin.

2. The transition from the Lower Group to the Middle Group (some time after 1.5 Ma) is characterised by an increase in bathymetry. While the rapid increase in accommodation space is here proposed to be mainly tectonic in origin, a significant increase in sediment supply during a highstand stage of relative sea-level (Middle Group) may be related to a climatic changes such as the Mid-Pleistocene revolution. During the northward progradation of the Middle Group, the gulf is characterised by alternating marine and lacustrine conditions with a probable connection to the Mediterranean Sea eastward. The final stage of this progradation occurs before the beginning of the regional uplift some time after 0.7 Ma.

3. Lastly, the emergence of syn-rift sediments along the southern coast of the gulf of Corinth resulted in a narrowing of the basin from some time after 0.7 Ma to the present day. The Corinth Isthmus basin and the Megara basin were also uplifted and the only connection to the Mediterranean Sea corresponds to the Rion strait sill. Water salinity is thus controlled by the Mediterranean sea level relative to the Rion strait sill.

The relative role of controlling factors on stratigraphic architecture may thus be quantified using numerical modelisation based on these data. It will be performed in a next step of the project in order to validate and refine the age model proposed here.

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