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Tectono-climatic controls of the early rift alluvial succession : Plio-Pleistocene Corinth Rift (Greece).

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Abstract

Proximal alluvial sediments represent a precious sedimentary archive to reconstruct the tectono-climatic history of continental rift basins. However, poor dating of coarse fluvial successions usually prevents high-resolution distinction of tectonic and climatic processes and good determination of process rates. This paper presents a multi-method approach to the dating of Plio-Pleistocene sediments of the Kalavryta river system, during the development of the early Corinth Rift (northern Peloponnese, Greece). This river system developed across several active normal fault blocks that are now uplifted along the southern rift margin. The detailed sedimentary record constrains alluvial architectures from the proximal basin to the river outlet where small deltas built into a shallow lake. In four magnetostratigraphy sections the correlation to the reference scale relies on the identification of the Gauss/Matuyama magnetic reversal and biostratigraphic elements. The river system developed between about 3.6 to 1.8 Ma, with SARs ranging from 0.40 to 0.75 mm yr-1. SAR is lower in the alluvial fans than in the deltaic system, and higher at the centre of the normal fault depocentres than at the fault tip. By comparison with worldwide Cenozoic SARs based on magnetostratigraphy, our values are high but lie in the same range as those determined in coarse alluvial foreland basins. Moreover, in the context of overfilled intra-mountainous rift basins, these rates are minimum values and can be used as a proxy for accommodation rate. Therefore, early rift stratal wedges and growth synclines attest high sedimentation rates and also high rates of tectonic processes. Finally, in the distal river system, floral compositions and changes of vegetation deduced from palynological data are coherent with alternating fluvio-deltaic and shallow lacustrine deposits, which are linked to relative base level variations. Dry/cool climate is preferentially recorded in mouth bars and deltaic plains deposits during periods of low lake level, while the warm/moist climate is recorded in prodelta deposits during periods of high lake level. This correlation suggests that, despite the dominant control of active faulting, climate is a key control of syn-rift stratigraphic architectures.

Keywords: Early rifting, antecedent drainage, magnetostratigraphy, palynology, sediment accumulation rate, vegetation cycle.

Running title: Plio-Pleistocene early Corinth Rift alluvial succession.

1 Introduction

Alluvial successions are found in most foreland basins and continental rift basins. Due to their proximity to the uplifting relief and the hinterland source area, they represent a precious sediment archive to trace past tectonic and climatic changes. Indeed, many are constituted by conglomerates and sands that are rapidly transferred from the source area to the alluvial basins, and the original signals that they potentially carry are unlikely to be biased during transport (Allen et al., 2013; Romans et al., 2016). However, alluvial successions are difficult to date because of the rare biostratigraphic markers that they contain, and their important lateral facies variations over short distances.

The establishment of a precise syn-rift chronostratigraphy is particularly challenging in continental rift margins where sedimentation is distributed into different hangingwall depocenters limited to the size of the normal fault blocks (Cowie et al., 2006; Gawthorpe et Leeder, 2000; Gupta et al., 1998a). Hence, migration of fault activity along and across strike produces a discontinuous sediment record (Cowie et al., 2000; Goldsworthy et Jackson, 2001; Morley et Wonganan, 2000; Schlische et Anders, 1996). These limitations particularly inhibit our understanding of the early rift development, as well as the determination of rates of processes including sedimentation, tectonics and their controls. Only large antecedent or axial drainage systems have the power to deliver sediments basin-wide along continental rift margins and thus form larger depocentres (Hemelsdaël et al., 2017; Leeder et Mack, 2001; Santos et al., 2014; Tiercelin et al., 1992). This paper focuses on dating of the antecedent Kalavryta river system, which is characterised by continuous record from the proximal coarse alluvial fans to the distal deltas that built into a shallow lake (Hemelsdaël et al., 2017).

In the western part of the southern Corinth Rift margin, the gravel-dominated Kalavryta river system corresponds to the basal syn-rift succession also known as the Lower Group. This stratigraphic succession is well preserved and exposed in several inactive and uplifted narrow normal fault blocks (e.i. 4–7 km wide) to elevations up to 1500 m (Figure 1) (Rohais et al., 2007a; Ford et al., 2013). They represent a key archive to document tectonic, climatic and sedimentary processes during the early development of one of the most active rift of the world (Avallone et al., 2004; Briole et al., 2000; McClusky et al., 2000). The Late Pliocene and Early Pleistocene age assigned to the Lower Group is based on rare palynological dates and regional correlation arguments (Malartre et al., 2004; Rohais et al., 2007) but remains as yet poorly constrained.

We carried out magnetostratigraphic analyses on four logged sections located in different normal fault blocks. Correlation of the resulting magnetostratigraphic columns to the reference scale is completed by biostratigraphic data derived from mammal teeth, charophytes and pollen assemblages. The time lines across the different normal fault blocks provide an age model, which is used to estimate and discuss sediment accumulation rates, sediment preservation, and controls of the alluvial architecture in the context of basin overfill (A<S). The pollen record from sediments in the distal part of the Kalavryta river system documents different vegetation types reflecting Early Pleistocene climate variations in the Eastern Mediterranean. These original data are meaningful in a context where tectonics is unequivocally considered as the predominant control on coarse alluvial sedimentation, and where climate variations are rarely distinguished in resultant facies.

2 Geodynamic and structural setting of the Corinth Rift

The 110°E Gulf of Corinth (105 km long, 30 km wide) is located in an active rift system, which separates the Peloponnese Peninsula from mainland Greece (Figure 1). On a regional scale, the Corinth Rift is located between the southwest-propagating North Anatolian

Fault and the Cephalonia Fault to the west (Nyst et Thatcher, 2004; Papanikolaou et Royden, 2007; Sachpazi et al., 2007) and developed from back-arc extension through a slab roll-back (Jolivet et Brun, 2008; Le Pichon et al., 2002) of the African Plate under the European plate along the Hellenic trench (Figure 1). The Corinth Rift represents the most active rift in Europe according to GPS measurement over the last 30 years (Avallone et al., 2004; Billiris et al., 1991; Briole et al., 2000; McClusky et al., 2000; Reilinger et al., 2006, 1997). The present extension rates across the rift increases consistently westward from ca. 6–11 mm yr^{-1} to 15 mm yr^{-1} respectively (Bernard et al., 2006; Briole et al., 2000; Clarke et al., 1998). Most of the present-day extension is located in the offshore part of the rift. Based on the dating of ancient marine terraces, the uplift rate along the active southern rift margin is estimated between 0.9 and 1.1 mm yr^{-1} for the last 0.5 Myr (De Martini et al., 2004; McNeill et Collier, 2004) with a strong increase to 1.3–2.2 mm yr-1 during the Holocene (Pirazzoli et al., 2004; Stewart, 1996; Stewart et Vita-Finzi, 1996). Flexural rebound on the southern flank of the uplifted the syn-rift sediments to over 1000 m above sea level. Inland inactive fault blocks are on average 10 to 15 km long and 4 to 7 km wide. The strike of major faults is N086 to N110 and their average dip varies between 42°N and 64°N (Ford et al., 2013). Maximum throw on major faults varies between 400 and 1600 m. Pure dip-slip displacement is recorded on the majority of faults with stretching directions oriented N–S to SSW–NNE (Rohais *et al*., 2007a; Ford *et al*., 2013; Gawthorpe et al., 2018). Stratal wedging in tilted fault blocks and growth synclines are frequently observed (Figures 3 and 4).

The rift structures are superimposed at a high angle on the northwest-trending Hellenide external fold and thrust belt (Figure 1). These older thrust sheets were emplaced towards the west-southwest during the Eocene to Late Miocene associated with convergence between the European and African plates (Jolivet et Brun, 2008; Reilinger et al., 2006; VanHinsbergen et al., 2005; VanHinsbergen et Schmid, 2012). In the study area, exposed pre-rift lithologies belong principally to the Pindos thrust sheet, which consists of Upper Triassic to Jurassic cherty limestones with red radiolarites and Upper Cretaceous sandy turbidites (Aubouin, 1959; Degnan et Robertson, 1998; Dercourt et al., 1973; Fleury, 1980).

3 Syn-rift stratigraphy

In the western part of the southern Corinth Rift margin, the onshore syn-rift succession is divided into three informal lithostratigraphic groups named from bottom to top: the Lower, Middle and Upper groups (Figure 2) (Rohais et al., 2007a; Ford et al., 2013). This overall syn-rift stratigraphy located on the southern margin records the persistence of rivers systems and their reorganisation during the successive migrating phases of fault activity.

In the western margin, the inactive normal fault blocks are strongly incised by present day rivers, providing excellent exposures of early syn-rift deposits (Figure 2). In the Kalavryta region the Lower Group mainly consists of an alluvial succession that fines toward the east from coarse alluvial conglomerates to fine-grained lacustrine sediments. This succession was deposited by the antecedent Kalavryta river system that sourced from the SW and evolved toward the NE across a series of growing faults, burying the pre-existing relief (Ford et al., 2013; Hemelsdaël et al., 2017). It is interpreted as a distributive river system that was oblique to the north-dipping fault system in its proximal part, and became axial in the NE, building small deltas into a shallow lake margin. Based on detailed geological mapping, sedimentological analysis, magnetostratigraphy and correlations between the normal fault blocks, Hemelsdaël et al. (2017) built a coherent stratigraphy of the Lower Group. The presence of a major antecedent drainage is supported by: (i) significant palaeorelief inherited from the Hellenide fold and thrust belt; (ii) a single major sediment entry point; (iii) persistence of the main fluvial axis; (iv) downstream fining at a scale larger than the size of the normal fault block and ; (v) absence of significant topography generated by the faults.

The Middle Group that is also well exposed onshore in the southern rift margin (Backert et al., 2010; Gawthorpe et al., 2018; Rohais et al., 2008) is characterised by the giant Gilbert deltas (Figure 2) that were deposited after the northward migration of fault activity. It also records progressive basin deepening starting at about 1.8 Ma (Ford et al., 2007, 2013). A second northward migration of fault activity at about 0.7 Ma (Bell et al., 2008; Nixon et al., 2016), gave rise to the present-day morphology of the coastal margin. Deltas of the Upper Group form the coastal plains along the Corinth Gulf (Figure 2).

The Lower Group is absent in the westernmost part of the onshore rift (Ford et al., 2016) and its offshore continuation is uncertain. If present, it is likely to correspond to the base of seismic unit SU1 (Hemelsdaël et Ford, 2016; Nixon et al., 2016). The seismic unit SU2 corresponds to the Upper Group, which is mainly controlled by fault activity along the southern rift margin since the last 0.7–0.4 Myr (Bell et al., 2008; Nixon et al., 2016).

Age constraints for the Lower Group have been limited and a number of conflicting stratigraphic correlations at basin-scale have been proposed across the southern rift margin. The only absolute age at 2.55 Ma was obtained using $^{40}Ar/^{39}Ar$ dating of an ash layer (Xylocastro area; Figure 1) in the onshore central rift (Leeder et al., 2012). This dated ash layer found within basinal turbidites and hemipelagites — Rethi-Dendro Formation (Gawthorpe et al., 2018; Leeder et al., 2012) — was used to constrain a deepening event (referred as "rift climax"), which occurred at 3.2–3.0 Ma in the central rift. The correlation of both dated ash and deepening event with the Lower Group stratigraphy in the western margin remains uncertain. The basinal turbidites and hemipelagites have been correlated to the early rift deltaic system that sourced from the central part of the rift margin (Ford et al., 2016; Gawthorpe et al., 2018; Leeder et al., 2012). Building on this stratigraphic correlation, Rohais & Moretti (2017) propose that the upper part of the Lower Group in the Kalavryta area lies within the Middle Group. The authors place the base of the Lower Group at about 5.3 Ma and the limit between Lower and Middle groups at about 3.0 Ma, without any support by absolute dating. In this paper we present new magnetostratigraphic ages, allowing a more precise correlation of Lower Group stratigraphy. Our results and interpretations agree with the stratigraphic scheme provided by Gawthorpe et al. (2018).

4 Lithostratigraphy of the Kalavrita river system

The lithostratigraphic scheme of the Kalavryta river system is based on detailed mapping facies analysis previously established (Ford et al., 2013, 2007; Hemelsdaël et al., 2017).

4.1 Southern fault blocks – Coarsening upward succession

In the southern fault blocks (Doumena, Kerpini, Kalavryta, Demestika, Tsivlos; Figure 2), coarse alluvial conglomerates record a coarsening upward succession with local presence of palustrine deposits at the base.

The basal Drosato Formation (up to 100 m thick) is composed of silts and clays with variable proportions of terrestrial organic matter including true lignite beds (up to 1.5 m thick). It is interpreted to represent a palustrine environment. This formation is locally exposed in the Kalavryta fault block but its continuity across the block is uncertain (Figure 2).

The overlying Mega Spilaio Formation (300–1000 m thick) consists of coarse conglomerates to fine-grained fluvial deposits. In the central Doumena fault block, massive coarse alluvial conglomerates form distinctive cliffs up to 20 m high (Figure 3). This formation is dominant in the southern fault blocks. Laterally, at the fault tips, "fine-grained members" comprise conglomerates interbedded with variable amounts of silts (Figure 2; Figure 4).

The Kalavryta Formation is 100 to 500 m thick and consists of structureless to crudely stratified clast-supported conglomerates with abundant boulder clasts and presents no significant lateral facies change. This formation lies conformably above the Mega Spilaio Formation and forms the uppermost part of the southern syn-rift succession in the southern fault blocks (Figure 2). It also marks the coarsening up trend of the syn-rift succession.

4.2 Northern fault blocks – Fining upward succession

The syn-rift succession in the northern fault blocks (Valimi and Pirgaki-Mamoussia fault blocks; Figure 2) consists of a fining upward fluvial to deltaic succession that can be subdivided into 5 formations.

At the base of the syn-rift succession the Tsivlos Formation (100–300 m thick) consists of massive crudely stratified alluvial conglomerates (Figure 5), equivalent to the Exochi Formation of Rohais et al. *(*2007*a)* and the Basal Conglomerates unit of Ford *et al.,* 2013). These strata show onlap into a palaeorelief (up to 700 m high) and abrupt facies change at the top of the formation.

The overlying Lithopetra Formation is composed of coarse conglomerates, predominantly massive but interbedded with cross-bedded sandstones and siltstones in variable proportions. The thickness of this formation ranges from 200 to 700 meters (Figure 4; Figure 5A). It lies conformably above the Tsivlos Formation or directly on the basal syn-rift unconformity where it is laterally equivalent to the Mega Spilaio Formation (Doumena fault block; Figure 3).

The Ladopotamos Formation (200–500 m thick) consists of massive conglomerate bodies (up to 10 m thick) interbedded with red siltstone/sandstone intervals (Figure 6). The succession gradually fines upward and thins eastward to 200 m along the Krathis valley

(Figure 2) where fluvio-lacustrine deposits contain abundant oligohaline to freshwater fauna, recording the lateral transition of the Valimi Formation (see below).

The Valimi Formation is a 800 m thick succession lying above and laterally equivalent to the Ladopotamos Formation, in the Valimi fault block (Figure 5). It is interpreted as a deltaic and shallow lacustrine succession characterised by coarsening upward trends (20 to 80 m thick) of fine-grained lacustrine and prodelta deposits overlain by prograding packages of sandstones and conglomerates (up to 15 m thick) (Ambrosetti et al., 2017; Hemelsdaël et al., 2017; S. Rohais et al., 2007). Estimated water depth of the prograding deltas is 5 to 10 m with maximum values of 40 m (Rohais et al., 2007a). This formation corresponds to the most distal part of the Kalavryta river system (Hemelsdaël et al., 2017).

The Katafugion Formation (up to 30 m thick) is specifically located in the Pirgaki-Mamoussia fault block. It consists of lagoonal calcisiltites and upper shoreface conglomerates and sandstones (Malartre et al., 2004; Ford et al., 2007, 2013) lying conformably above the fluvial deposits of the Ladopotamos Formation (Figure 6). The Katafugion Formation record a transgression marking the end of the Lower Group just before the major deepening event (Ford et al., 2016, 2013).

5 Sampled and studied sections

Different logged sections are used for magnetostratigraphic and palaeontological analyses (Figure 2). Four of them were sampled for palaeomagnetic analyses: the Valimi, Voutsimos, Kerpini and Doumena sections.

The Doumena section (38.09°3–22.173°; 900 m thick) is located in the central Doumena fault block where syn-rift strata form a large hangingwall syncline (Figure 3). The basal part of the syn-rift succession is not exposed here. This section mainly consists of alluvial conglomerates (Mega Spilaio and Lithopetra formations) and displays a coarsening-upward trend. Sample sites correspond to rare preserved siltstone and sandstone intervals. The average orientation of the bedding is N290-22°.

The Kerpini section (38.082°–22.110°; 600 m thick) is located in the western Kerpini fault block where syn-rift strata onlap onto the pre-rift relief (Figure 4). The succession consists of coarse conglomerates (Mega Spilaio Formation) overlain by a fine-grained fluvial succession predominated by red sandstones and siltstones, which are particularly suitable for palaeomagnetic analysis. The average orientation of the bedding in this section is N060-24°.

The Valimi section (38.104°–22.283°; 1300 m thick) located in the Valimi fault block (Figure 5), displays a general fining upward trend. The base of the Lower Group comprises coarse alluvial conglomerates (Tsivlos Formation) and evolves vertically to fine-grained fluvial deposits (Lithopetra and Ladopotamos formations). The upper part of the section comprises the deltaic to lacustrine Valimi Formation. The average orientation of the bedding is N070-30°.

The Voutsimos section (38.144°–22.278°; 450 m thick) is located in the eastern Pirgaki-Mamoussia fault block (Figure 5D). In this area, the Lower Group succession is much thinner than the Valimi section and is characterised by a general fining-upward trend. It consists of coarse alluvial conglomerates at the base (Tsivlos Formation) overlain by fluvio-lacustrine deposits (Ladopotamos Formation; Figure 5D). The average orientation of the bedding in this section is N230-27°.

The Valimi section was also sampled for pollen assemblages. Other biostratigraphic markers were found in the Ladopotamos and Drosato sections (Sites 1 and 2; Figure 2).

6 Magnetostratigraphy

6.1 Sampling

The targeted facies for palaeomagnetic samples are red to brown silts, and fine to coarse sandstones. Samples were collected using a gasoline-powered drill and were oriented using magnetic and, when possible, sun compasses. The average magnetic declination anomaly is 3.4 ± 2.2° ($N = 347$). All cores are prepared into standard specimens of about 10 cm^3. When drilling was impossible in the poorly consolidated facies, oriented samples were housed in plastic boxes (8 cm^3). Samples were collected at 69, 62, 61 and 71 sites in the Kerpini, Doumena, Voutsimos and Valimi sections respectively. The average spacing between two sampled sites remains low and varies from 6 to 13 m. The mean spacing between Quality-1 samples ranges from 9 to 26 m. The intervals of low sample density are treated with caution. The magnetic analyses have been carried out at the 'Institut de Physique du Globe' of Paris (IPGP).

6.2 Magnetic mineralogy

The magnetic mineralogy was investigated using a combination of thermo-magnetic curves to determine the Curie points, isothermal remanent magnetisation (IRM) and hysteresis acquisitions (See details in Supplementary Data). The thermomagnetic curves were measured on 34 porphyrised sediments, using an AGICO KLY2 Kapabridge susceptibility meter coupled with a CS5 furnace and CSL cryostat under argon atmosphere to avoid oxidation of magnetic minerals during heating (Figure S1 in Supplementary Data). Isothermal remanent magnetisation (IRM) acquisition curves were obtained for 63 samples on a vibrating sampler magnetometer (VSM Micromag 3900) at the IPGP laboratory (Figure S2 in Supplementary Data). Hysteresis loops were also measured on the same 63 samples using the same VSM Micromag 3900 (Figure S3 in Supplementary Data). The results mainly point to a combination of magnetite and haematite, in most of the samples.

6.3 Demagnetisation and determination of magnetic directions

6.3.1 Demagnetisation techniques

A total of 398 specimens were submitted to progressive thermal (99 specimens) and alternating field (AF) stepwise demagnetisation (299 specimens) to clean the magnetic remanence. Thermal demagnetisation was applied using a furnace housed in a shielded room. AF demagnetisation was preferentially applied for poorly consolidated samples. Both demagnetisation methods were applied for samples of the Kerpini and Doumena sections. The samples were subjected to 10–12 steps of demagnetisation from 1 to 150 mT for AF and 100 to 700°C for thermal demagnetisation. The remanent magnetisation was then measured on a 2G Enterprises horizontal DC SQUID cryogenic magnetometer in the same laboratory. The intensity of the Natural Remanent Magnetization (NRM) is low and ranges from 7.00×10^{-5} to 5.58×10^{2} A m^{-1}, with an average value of $2.14 \pm 5.64 \times 10^{1}$ A m^{-1}.

6.3.2 Principal component analysis

Magnetic components were identified using stereographic projections and orthogonal vector diagrams (Zijderveld, 1967). The principal component and the mean directions were computed using Fisher statistics with the Paleomac software (Cogné, 2003; Fisher, 1953; Kirschvink, 1980). Both demagnetization techniques isolate two magnetic components (Figure 7): one at low temperature (<100°C) and low field (<15 mT) and another one at higher temperature (>200°C) and higher field (>15 mT). The second component usually passes through the origin and can be interpreted as the Characteristic Remanent Magnetisation (ChRM). The magnetic remanence is often unstable at temperatures above 400°C. The Doumena section, it was easier to isolate the ChRM with AF demagnetisation than thermally. Demagnetisation curves show a particular low resistance to alternative field as NRM drops after 4 mT in this section. Based on the overall quality of the demagnetization diagrams and the stability of the remanence, we defined three different quality groups named Quality-1, Quality-2 and Quality-3.

In Quality-1 samples, the low temperature and weak field component was successfully removed. Projected directions on the Zijderveld plot form a linear and stable demagnetisation path that decays through the origin (Figure 7A-D). The magnetic direction of the ChRM can be easily calculated and usually shows a maximum angular deviation (MAD) of the magnetic components of less than 20°.

Quality-2 samples are identified when the best-fit line does not pass through the origin, suggesting that the secondary magnetic component was only partially removed. The ChRM direction is determined with MAD>30°. This quality group also includes samples with their remanent direction trajectories following a great circle (Figure 7E, F).

Quality-3 samples are characterised by unstable magnetic behaviour. In several samples no clear demagnetisation path is identified, and the signal is too unstable to determine the ChRM (Figure 7G). Some Quality-3 samples are characterised by one single clear component that decays to the origin (Figure 7H) with intermediate E-W magnetic direction and very low inclination. These samples are systematically located at the top of sections and likely record secondary magnetisation acquired during lightening impact (Cox, 1961).

The polarity columns are established by using Quality-1 samples. Quality-2 samples are also used when demagnetisation paths of several successive samples follow a great circle on the stereographic projections and evolve toward a similar direction (Figure 8F). Each magnetozone was defined using a minimum of two successive Quality-1 samples possessing the same polarity. When polarity change is supported by only one sample, the magnetozone is interpreted as uncertain (Figure 8).

6.3.3 Magnetic directions results and statistical tests

Among the 398 samples, 168, 54 and 176 specimens were interpreted as Quality-1, Quality-2 and Quality-3, respectively. Quality-1 samples represent 45%, 57%, 43% and 29% of the samples in the Valimi, Voustsimos, Doumena and Kerpini sections, respectively (Figure 8). All palaeomagnetic directions are provided in Supplementary data (Tables A–D). The sections are subdivided into different thickness intervals with respect to the lithostratigraphic boundaries and magnetic polarities (Table 1). Most of the analysed samples present a normal polarity with few short reversed intervals. The mean directions in both geographic and stratigraphic coordinates and polarities are given in Table 1. The mean orientation for the normal polarities (D_S = +2.6°, I_S = +45.6°, a_{95} = 3.7°) is close to the present day field (Figure 9). The record of both normal and reversed polarities in two of the measured Valimi and Kerpini sections suggests that the original polarities of the samples were not altered. This is also supported by a positive reversal test at 95% performed on the Quality-1 samples on these two sections. The magnetic mineralogy and behaviour are similar in the different sections suggesting also that the original polarity was preserved.

The mean magnetic directions of each interval are used to perform a fold test despite the low dips of syn-rift stata (<30°) enhancing dispersion. Maximum clustering of these mean directions is at 23% unfolding (Figure 9D). Maximum clustering after partial unfolding suggests that magnetisation was acquired during tilting of the normal fault blocks. This interpretation is consistent with the observation of syn-rift growth strata across the different fault blocks. All together the statistical tests suggest that the magnetic polarities identified in the syn-rift sediments are reliable and can be used to establish polarity columns.

6.4 Polarity columns

In the Valimi section three magnetozones are identified. Most of the section (0–900 m) records a normal polarity (Figure 8). Then, one main polarity reversal is recorded (900–1200 m). Two small uncertain reversed magnetozones (29–40 m; 580–595 m) and one normal magnetozone (1220–1300 m) are tentatively identified. There is a gap interval of about 200 m in the lower part of the Valimi section.

In the Voutsimos section, normal polarity is mainly recorded (Figure 8). A small reversed polarity at 197 m is identified over a short spacing (2 m) within the Ladopotamos Formation. This reversed magnetozone is interpreted as uncertain.

The Doumena section is dominated by one normal magnetozone within which three uncertain reversed intervals are identified at 11–15 m, 444–461 m, 856–868 m (Figure 8)

Along the Kerpini section, four complete reversed magnetozones were identified (Figure 8). The main reversed magnetozone is recorded from 150 to 340 m. Two other reversed magnetozones are recorded over shorter intervals (110–120 m and 400–410 m). This is the best-constrained section.

7 Biostratigraphy

As previously mentioned, the lack of well-preserved fossils in coarse alluvial successions remains a major problem for stratigraphic correlations. Nevertheless, biological data are locally encountered within interbedded silts.

7.1 Mammal teeth

Teeth of voles (Arvicolidae, Rodentia) were found within a paleosol bed at the base of the Ladopotamos Formation (38.148747°N; 22.229661°E – Site 1, Figure 2). The fragmentary state of the specimens and the lack of characteristic elements do not allow a precise genus and species identification. Nevertheless, the geometry of molar teeth display a combination of characteristics indicating late Pliocene voles, such as *Mimomys* or Late Pliocene-Early Pleistocene voles like *Borsodia* (Popov, 2001; Sala et Masini, 2007). These fossils are therefore assigned to the Upper Pliocene.

7.2 Charophytes

Samples the Drosato Formation (38.072890°N; 22.016513°E – Site 2, Figure 2) show the presence of many gyrogonites of charophytes identified as *Nitellopsis megarensis*, *Nitellopsis group merianii*, *Chara sp.* and *Lychnothamnus sp.*. These charophytes indicate shallow freshwater environments, although they are not characteristic enough for a precise age determination (Riveline et al., 1996). However, the species *Nitellopsis megarensis* was initially described in the Megara basin in Greece (Soulié-Märsche, 1979) and is assigned to the Upper Pliocene. This is consistent with the overlying Pagea Ash dated to 2.82 Ma (Leeder et al., 2008) found in the topmost Megara basin sedimentary succession. The Drosato Formation is therefore also assigned to the Upper Pliocene.

7.3 Mollusks

Well-preserved mollusks are scarce in the sedimentary facies. However, fine-grained dominated formations locally show entire gastropod shells. The gastropod *Adelinella elegans* is locally abundant in the Ladopotamos Formation. The fine-grained lacustrine deposits (Valimi Formation) contain the gastropods *Melanopsis aff. mitzopoulosi*, *Adelinella elegans*, as wells as other undetermined bioclasts. Lagoonal deposits of the Katafugion Formation contain abundant broken bivalves and gastropod shells of *Theodoxus micans*. This fauna is relatively well known in Central Greece in the Atlanti basin (Koskeridou et Ioakin, 2009). All together, these species give a biostratigraphic age ranging from Upper Pliocene to Early Pleistocene in the Eastern Mediterranean (Bandel, 2001; Gillet, 1963; Keraudren, 1979, 1975; Koskeridou et Ioakin, 2009; Stevanovic, 1963).

7.4 Palynological analysis

7.4.1 <u>Sampling and treatment</u>

Palynological analyses were carried out on about 900 m thick sediments of the Ladopotamos and Valimi formations, along the Valimi section (Figure 5). 26 samples were collected depending on the accessibilty of the outcrops and the presence of the fine-grained layers. Standard methodology of pollen extraction of the Palynology Laboratory of the Institute of Ecology at the Leuphana University of Lüneburg was adopted (for samples preparation see Supplementary data).

7.4.2 Pollen diagram and vegetation units

Pollen percentages were calculated based on the sum of arboreal and non-arboreal pollen (AP and NAP respectively; Figure 10). Riparian taxa such as *Alnus, Liquidambar, Pterocarya, Salix* and *Ulmus/Zelkova* are found consistently in the section indicating wetland environments (like back swamps and fluvial sediment input into the basin) (Figure 11). There is no a marine marine indicators in the samples (absence of foraminifera test linings or dinoflagellate cysts). Most of the taxa have been grouped into paleoecological units: Steppe elements, High-altitude elements, Mid-altitude elements, Mesothermic elements and Mega-mesothermic elements (Figure 10). Based on the taxa predominances the diagram has been divided into 12 pollen zones and vegetation units (see details in the Supplementary data).

The pollen zones depict the different vegetation units following Bertini (2010) and Combourieu-Nebout (1993) (Figure 10). They can be described from (a) to (d) as:

- **(a)** Warm and relatively dry early interglacial deciduous vegetation (dominated by *Quercus*),
- **(b)** subtropical, humid interglacial vegetation (Taxodiaceae, *Carya, Liquidambar*),
- **(c)** transitional cool but still moist coniferous forest (*Tsuga, Cedrus, Picea, Abies*),
- **(d)** and finally a relatively open (cool, dry) herbaceous glacial vegetation dominated by Poaceae, *Artemisia, Ephedra* and Asteraceae a.o.

7.4.3 Identification of climatic cycles

The successice vegetation units in the Valimi section can be linked to glacial/interglacial cycles (Combourieu-Nebout, 1993). As shown for several localities in Italy and in other Mediterranean sites, the onset of the 41 ka obliquity-forced glacial/interglacial cycles can be traced back to about 2.6 Ma, around the time of the onset of the northern hemisphere glaciations (Suc and Zagwijn, 1983; Bertoldi et al., 1989; Combourieu-Nebout, 1993; Joannin et al., 2008; Bertini, 2010; Suc et al., 2010). The gradual vegetation changes around this time form a cyclicity with the vegetation units (a–d), which are well observed in the Valimi section. Moreover, the variations of Mesothermic/Steppe ratio throughout the Valimi section (Figure 10) is used as a proxy to identify warm/moist ("interglacial") and cool/dry ("glacial") phases (Joannin et al., 2008; Suc et al., 2010). The significance of this ratio in terms of climatic cycles will be discussed later when including sedimentological data and magnetostratigraphy of the Valimi section.

7.4.4 <u>Preliminary age estimations</u>

Based on their last appearance datum (LAD) of *Sciadopitys* (Figure 11B), sediments cannot be younger than MIS 46 at 1.4 Ma (Lisiecki et Raymo, 2005). However, it is likely that *Sciadopitys* had a longer survival period (Fusco, 2007). Therefore, the LAD of 1.07 Ma (Dubois, 2001; Rohais et al., 2007) is preferentially choosen for the Valimi section (Figure 11B). By recognising the group of taxa composed of *Carya*, *Tsuga*, *Cedrus*, *Pterocarya*, *Liquidambar* and *Zelkova,* Rohais et al. (2007b) dated the Lower Group sediment sequence between 1.78 Ma and 0.9 Ma (Figure 11).

The Valimi section shares numerous palynological similarities with the Citadel section of the Greek Zakynthos Island, which consists of 5 cycles of the vegetation units (a–d), well dated by magnetostratigraphy to 1.95–1.77 Ma (Olduvai subchron) (Subally et al., 1999). The Valimi section also shows a similar floral composition and cyclic behaviour compared to several sites in central and southern Italy (Bertini, 2010; Combourieu-Nebout, 1993; Joannin et al., 2008; Suc et al., 2010) dated to the Plio/Pleistocene transition at around 2.6 Ma. Taxa of the Taxodiaceae, Cupressaceae, and the genera *Cathaya*, *Tsuga*, *Sciadopitys, Carya*, *Pterocary*a, *Cedrus*, *Liquidambar* and *Ulmus*/*Zelkova* in the Valimi section (Figure 11) are indicative for the Late Pliocene-Early Pleistocene age in the Mediterranean area (Suc, 1986, 1984). Climatic cyclicity with summer drought and intercalating periods dominated by steppe elements developed from 3.2 Ma onwards and became more stable after 2.8 Ma (Suc, 1984).

At the bottom of the palynological section (Pollen Zone-1; Figure 10), cool arid steppe conditions dominated by Asteraceae and *Artemisia* occur, which then drastically changed into more humid conditions (Pollen Zone-2) suggested by the very few *Abies*, *Picea* and the steppe elements but relatively dominating *Quercus* and *Alnus*. This pollen zone might be correlated to the cooling event in 3.2 Ma (Suc, 1984). With respect to this correlation, the next glacial conditions characterised by the development of steppe vegetation (Pollen Zone-6) most likely represent climate at the end of the Pliocene. This interpretation is consistent with the palaeomagnetic dating.

Therefore we propose that the sediments of the Valimi section have been deposited during the Plio/Pleistocene transition around the Gauss/Matuyama magnetic boundary, although an accurrate age cannot be given. This age estimate is also supported by the relatively poor amounts of "Tertiary" floral elements such as *Sequoia, Taxodium*, *Symplocos* or *Nyssa* commonly found before 2.6 Ma (Arias et al., 1984; Bertoldi et al., 1989; Chorianopoulou et al., 1984).

8 Discussion

8.1 Age model for the Kalavryra fluvial system

Based on the new age constraints presented above we propose a correlation model for the Lower Group across the study area, following the trend of downstream facies changes of the Kalavryta river system (Figure 12). Both the Valimi and Kerpini sections provide the best magnetostratigraphic age constraints including several magnetic reversals. Mapping of the syn-rift succession across the fault blocks shows that the Kerpini section lies in the upper part of the Lower Group and is equivalent to the upper Doumena and Valimi sections (Figure 12). Thus, the normal polarity at the base of the Kerpini section cannot be older than the base of the Valimi section. We therefore propose that the main polarity change recorded in both the Valimi and Kerpini sections has the same age.

Palynological analyses of the Valimi section reveal a minimum age of 1.07 Ma (Figure 11B). The finding of charophytes and vole teeth in the Ladopotamos section (Figures 2 and 12) both older than 2.6 Ma suggest that the basal syn-rift succesion cannot be correlated to the Olduvai subchron (1.78–1.94 Ma). Therefore, the main polarity reversal recorded in both the Valimi and Kerpini sections most likely corresponds to the Gauss/Matuyama reversal at 2.58 Ma. The short reversed polarities within the large normal magnetozone show similarities with the Gauss polarity sequence (2.58–3.60 Ma) including two short reversed subchrons (Hilgen et al., 2012). Following this correlation, the uncertain reversed polarities in the uppermost Valimi section is likely to be dated at 2.15 Ma; and the complete section ranges from about 3.5 Ma to 2.1 Ma. By correlation, the Kerpini section is assigned to an age range from about 3.0 Ma to 1.9 Ma.

The large normal polarity interval recorded throughout the Voutsimos section is correlated with the Gauss polarity sequence (Figures 12). If true, the section age ranges between 2.6 and 3.6 Ma. Accordingly, the small polarity reversal recorded between 197 m and 199 m can be correlated with the reversed chron (3.12–3.03 Ma) and therefore would be equivalent to the uncertain reversed interval interpreted in the Valimi section. The base of the Valimi Formation in the Voutsimos section is laterally equivalent to the Ladopotamos Formation westward. This is consistent with the age given by Arvicollidae teeth found at the base of the Ladopotamos section (Site 2; Figure 2).

In the different palaeomagnetic sections, the Gilbert chron (4.2–3.6 Ma) predating the Gauss normal succession is not identified, and thus the lower limit of the syn-rift succession in this area should not be older than 3.6 Ma. However, the low density of the palaeomagnetic samples and the large gap reported at the base of the Valimi section suggest that some polarity reservals might have been missed. In addition, the Kerpini section lies in the upper part of the Lower Group succession in this fault block and its lower part remains unconstrained. Thus the syn-rift succession could be older than 3.6 Ma in some places. Regardless of these incertainties, our findings are consistent with existing literature, which has estimated the rifting initiation from Pliocene to Middle Pleistocene depending on the location along the rift axis (Collier et Dart, 1991; Doutsos et Piper, 1990; Ford et al., 2013; S. Rohais et al., 2007). The age for the top of the sections are also consistent with the previous age estimates of 1.8 Ma given for the top of the Lower Group succession in the western and central rift based on palynological data, foraminifera and other fossil remnants (Malartre et al., 2004; Rohais et al., 2007; Symeonidis et al., 1987).

8.2 Variations of sedimentation accumulation rate (SAR) and implications for sedimentary processes across the alluvial basin.

The palaeomagnetic columns are plotted against the polarity reference scale (Figure 13) and the slope of the correlation lines gives the SAR (non-decompacted).. Between 3.6 and 1.8 Ma, the Valimi, Kerpini, Doumena and Voutsimos sections are characterised by SARs of 0.75–0.40, 0.44, 0.75, 0.75 and 0.70 mm yr^{-1} respectively, with an average value of 0.6 mm yr^{-1}. As this simple approach does not correct for compaction especially in the intercalated silts within the Valimi Formation, these SARs are used as first order estimates.

In the present study, high SARs (0.75 and 0.70 mm yr^{-1}) are determined in the Valimi and Doumena sections, both located in the central part of the fault blocks where maximum sediment thickness is recorded, and where stratal wedge and growth syncline are well developed (Figure 3; Figure 5). In the opposite, a lower SAR (0.44 mm yr^{-1}) is calculated in the Kerpini section, in the western tip of the fault block, where sediment thickness is lessened (Figure 4), and where higher amount of interbedded silts is preserved. Magnetostratigraphic studies commonly record increasing SAR in alluvial fan conglomerates, within coarsening-upward successions of foreland basins (Barrier et al., 2010; Charreau et al., 2009; Echavarria et al., 2003; Fang et al., 2005, 2003; Jones et al., 2004; Sun et al., 2009). In these examples, high sedimentation rate is explained by tectonic uplift of the orogen, leading to transport of high volumes coarse-grained material in the basin, facies progradation and migration of the "gravel front". Moreover, SAR tends to be higher in growth strata than pre-growth strata, implying important control by tectonics (Charreau et al., 2008; Horton et al., 2004; Sun et al., 2009).

While the mean SAR value remains meangingful and robust, in the Doumena and Voutsimos sections, a higher time-resolution analysis of sedimentation rates is prohibited due to the low number of identified magnetozones. However, the temporal and spatial variations of SARs in the Valimi and Kerpini sections can be discussed.

The lower part of the Valimi section is characterised by a SAR of 0.7 mm yr^{-1}, while in the upper section the rate are lower (0.4 mm yr^{-1}). This change in SAR lies at 600 m (Figure 13) and corresponds to the base of the Valimi Formation, where facies change from alluvial conglomerates to deltaic to lacustrine sands and silts. The difference of >40% of the SAR between the sections is too large to be only explained by differential compaction thickness of the studied section (<2km),. Those SAR variations through time are instead more likely related to the spatio-temporal variations of the alluvial architectures. Our results in the Valimi section suggest lower SAR at the distal part of the river system but in the same order or magnitude than the proximal part.

[1]In the Kerpini section a break in slope in the SAR at 118–160 m (Figure 13) correlates with a major erosive surface within the stacked conglomerates. This interval of apparent low SAR is interpreted as a stratigraphic hiatus formed between 3.0 and 2.6 Ma. Although the context of limited accommodation space (low A/S) prevailed, this age interval is

not particularly associated with amplified progradation of the facies belts that could explain this hiatus as a result of long-term sediment bypass. Following the chronostratigraphic scheme of the Kalavryta fluvial system the age interval 3.0–2.6 Ma corresponds to the opening of the rift to the southwest and input of coarse-grained material in the alluvial basin (Hemelsdaël et al., 2017). Therefore we suggest that this hiatus formed as a result of one or several erosive events due to fault activity in the most upstream part of the basin. The presence of stratigraphic gaps implies that the calculated SARs must be taken as minimum, and thus rigorously represent sediment preservation rate during early rifting.

In conclusion, SARs in the Kalavrita river system are strongly controlled by the main architectures within the normal fault blocks. We demonstrated higher SAR in the proximal alluvial fans than in the deltaic system, and higher SAR at the centre of the normal fault depocentres than at the fault tip.

8.3 Compilation of worldwide SARs

In order to discuss the significance of SAR ranging from 0.40 to 0.75 mm yr^{-1} in the Kalavryta river system, we provide a non-exhaustive compilation of SARs calculated worldwide based on magnetostratigraphy in Cenozoic alluvial successions (Figure 14; see rates and selected references in Supplementaty Data; Table E). The SARs are determined in both proximal and distal parts of river systems, with marked variations. Marine and deep lacustrine sucessions have been excluded from this compilation. In order to avoid biases associated to the time scales over which sedimentological and stratigraphic processes occur (Miall, 2015; Sadler, 1981), we specifically focus on long-term deposition measured over several 10^5 to 10^6 years.

Most existing values of SAR are derived for ancient river systems in foreland basins (Figure 14). The rare existing values in syn-rift alluvial successions are established in the Teruel Basin (Spain) and Rio Grande Rift (New Mexico, USA) with average values of 0.07 mm yr^{-1} and 0.04 mm yr^{-1} respectively (Ezquerro et al., 2019; Mack et al., 2006). These rates are one order of magnitude lower than those calculated in the Kalavryta river system. Our range of 0.40–0.75 mm yr^{-1} is therefore particularly high for syn-rift basins. In contrast it is similar to rates calculated in coarse alluvial successions in foreland basins (Burbank et al., 1996; Horton et al., 2004; Medwedeff, 1989). Combining our results with published data widens the range of SAR estimates for rifts and suggests that the type of tectonic regime (extension or compression) has little impact on the resultant SAR. Our compilation of SARs (Figure 14) highlights the need to obtain accurate values in recent rifted alluvial basins developing over few Myr in order to document processes at a scale less than 10^6 years (Blum et Törnqvist, 2000).

8.4 Significance for tectonic growth during early rifting

The early rift phase is commonly characterised by a relatively low creation of accommodation space compared with sediment supply (low A/S) and thus overfilled conditions prevail where sedimentation largely keeps pace with subsidence (Bohacs et al., 2000; Carroll et Bohacs, 1999; Huerta et al., 2011; Muto et Steel, 1997). Low A/S is expressed by fluvial progradation from the rifted margin and large-scale coarsening upward cycles in the proximal basin (Blair et Bilodeau, 1988; Gawthorpe et Leeder, 2000; Prosser, 1993; Withjack et al., 2002). Thus, in such context of basin overfill, SARs were used as a proxy to estimate rate of created accommodation space (Burbank et al., 1988; Valero et al., 2015). The Kalavryta river system is characterised by strong aggradation and vertical stacking of conglomeratic bodies coupled with a constant progradational trend of the alluvial facies belts (Hemelsdaël et al., 2017). This suggests that overfilled conditions prevailed during early rifting in the Corinth Rift. The SAR range of 0.4–0.75 mm yr^{-1} gives minimum estimate of the accommodation space rate during the early rifting. [2]If our values of SARs are a proxy of created accommodation space, they cannot be used to estimate throw rates on individual normal faults due to the loading component generated by long-term sedimentation of the through-going antecedent river system (Hemelsdaël et al., 2017).

Based on the new age model of the early Corinth Rift phase between 3.6 and 1.8 Ma we revise the overall extension rates. Minimum extension rates for the early Corinth Rift have been estimated at 0.6–1.0 mm yr^{-1} considering 2.0 to 3.3 km of extension from 5 to 1.8 Ma (Ford et al., 2013). The maximum age of 3.6 Ma implies higher extension rates during the early rift phase, thus ranging from 1.1 to 2.0 mm yr^{-1}. These updated values for the early rift extension rate remain lower than those estimated for the following Middle and Upper groups — 2.0 to 2.5 mm yr^{-1} and 3.4 to 4.8 mm yr^{-1} respectively. In the western Corinth Rift, the transition from Lower to Middle Group is marked by northward migration of fault activity, fault linkage and the formation of 10–20 km long rift border faults (Ford et al., 2016). While this major tectonic event is marked by abrupt basin deepening and subsequent construction of giant Gilbert-type deltas during the Middle Group (Figure 2; Figure 6), our revised estimates imply that it was not associated with abrupt increase of extension rate as suggested by Ford et al. (2016). In other words, the localisation of deformation on fewer and larger faults after the early rift phase may not be associated with an abrupt increase of the average extension rate across the margin but is instead due to migration, growth and linkage of the normal fault network (Cowie et al., 2000; Gupta et al., 1998b).

8.5 Deciphering climatic signals in the distal part of the river system

The climatic signal along rifted margins is not easily identified, not simply owing to the coarseness of the facies, but also because of the overwhelming control of tectonics. We here discuss the role of climatic versus tectonic allocyclic controls. Using the pollen assemblages of the Valimi section in the distal part of the Kalavryta river system, where a shoal-water deltaic system developed, we decipher climate overprint on syn-rift sedimentation and stratigraphic architecture. Vegetation units are tentatively interpreted as climatic in origin and correlated to the sediment cycles of the Valimi Formation (Figure 15).

The main facies associations (Figure 15) recognized in the Valimi section include: conglomeratic channel deposits, deltaic plain deposits (overbank and floodplain deposits), mouth-bar to delta front deposits and prodelta to open-lake deposits (Ambrosetti et al., 2017; Hemelsdaël et al., 2017; S. Rohais et al., 2007). Based on these facies associations we identify 14 deltaic units (3rd order cycles comprising fine-grained lacustrine/prodelta facies overlain by prograding fluvio-deltaic packages although other higher-order cycles may be present (Figure 15). The successive sedimentary cycles range in thickness from 40 to 80 m. Their regressive parts (deltaic plain, floodplain and mouth bars deposits) are 30–70 m thick and their transgressive parts (lacustrine and prodelta deposits) are 5–15 m thick. On the same section, Ambrosetti et al. (2017) identify at least 25 cycles described as parasequences. These authors interpret the creation of accommodation space as due to both tectonics and climate-induced lake level variations but without providing absolute ages, quantification of processes or evidence of climatic signals.

Using the pollen data in the distal part of the river system we correlate the vegetation groups with the relative base level variations documented by the deltaic units. The different vegetation units (a–d; see description earlier in the text and Figure 10) mostly follow the relative base level variations derived from facies associations (Table 2). The relatively open herbaceous (cool/dry) glacial-like vegetation group almost systematically occurs within regressive parts of the parasequence. This suggests that dryer (glacial-like) conditions favoured the progradation of fluvio-deltaic packages, probably associated with higher sediment supply due to change of seasonality and periods of lowering of the lake level. In addition, the samples recording interglacial conditions (Mega-mesothermic and mesothermic vegetation units) lie almost exclusively within the transgressive part of parasequences (prodelta facies). This indicates that interglacial conditions prevailed during periods of relative lake level rise. In short, cool/dry conditions are preferentially recorded in mouth bar and deltaic plain deposits during periods of low lake level, while the warm/moist climate is recorded in prodelta deposits during periods of high lake level. Rare samples with glacial-like vegetation in prodelta/lacustrine deposits may be explained by reworking of pollens.

The variations of the Mesothermic/Steppe ratio throughout the Valimi section are tentatively used as a proxy to identify warm/moist ("interglacial") and cool/dry ("glacial") phases respectively (Joannin et al., 2008; Suc et al., 2010). However, the interpretation of glacial/interglacial cycles based on the identification of the different vegetation units and this ratio (Figure 15) is not straightforward due to periglacial conditions in the Eastern Mediterrean. Moreover, the large spacing between the samples (from 5 to 75 m in average) does not allow to accurately examine the vegetation changes within the deltaic units. Therefore, the derived Mesothermic/Steppe ratio here provides an incomplete record of climate cycles. Nevertheless, we suggest that the deposition of Valimi Formation was controlled by climate-induced lake level fluctuations. Thus we can assume that the deltaic units (about 800 m) represent climatic cycles. The Valimi Formation consists of 14 to 25 sedimentary cycles developing between 3.1 and 1.8 Ma, thus giving duration of 52 to 87 kyr for the indivual deltaic units. This approximate range is coherent with the 41 kyr cycles (obliquity orbital forcing) recorded by the Mediteranean Planktic oxygen isotope records ($\delta^{18}O$) during the Early Pleistocene (Lourens et al., 2004). The hypothesis that a glacial/interglacial signal can be observed in both the Valimi stratigraphy and palynology seems therefore robust. In the Eastern Mediterranean, other studies of fluvio-lacustrine successions document climatic cycles during Pliocene and Pleistocene with clear identification of astronomical forcing (Abdul Aziz et al., 2000; Ielpi, 2012; Sabato et al., 2005; Steenbrink et al., 1999; van Vugt et al., 2001, 1998). Among these studies, the Valimi section represents one of the rare deltaic to shallow lacustrine successions where the climate signal is recorded in continental rifts, in the context of high sediment supply and high subsidence rates.

9 Conclusions

1. Across the western Corinth Rift, the basal syn-rift succession (Lower Group) is a record of the antecedent Kalavryta river system evolving from proximal coarse conglomeratic alluvial fans to distal fluvio-deltaic and shallow lacustrine successions. Using magnetostratigraphy, palynology and other biostratigraphic age constaints, the Lower Group is dated between about 3.6 Ma and 1.8 Ma. The Gauss/Matuyama magnetic reversal corresponds to the most robust age constraint.

2. The age model enables to calculate average sediment accumulation rates ranging from 0.40 to 0.75 mm yr^{-1} with marked variations with respect to the main alluvial architectures. SAR tends to be lower in the distal part of the river system than in the proximal alluvial fans. Similarly, the SAR is lower at the fault block termination than at the centre where maximum subsidence is recorded. Moreover, we show evidences of an important stratigraphic hiatus that formed between 3.0 and 2.6 Ma. This age interval is synchronous to initiation of faults and input of coarse erosive material in the proximal basin. In the context of basin overfilling during early rifting, calculated SARs are minimum values and can be used as a proxy of created accommodation space.

3. This work represents a rare case study dedicated to the dating and quantification of processes in ancient river systems in rifts. The values of SARs are compared with rates obtained in worldwide alluvial systems of Cenozoic basins. The range 0.40–0.75 mm yr^{-1} is high for rift basins but of the same order of magnitude as most existing rates for coarse alluvial successions and growth strata of foreland basins. These high rates during the early rift phase are explained by high sediment supply from the antecedent drainage. The continuous high sediment supply superimposed on the growing normal fault system loaded the hangingwall depocentres and localised deformation. Such feedback during syn-tectonic growth emphasises the predominant role of drainage antecedence for the production of high rates of processes.

4. The pollen record in the distal part of the Kalavryta river system is interpreted as alternating warm/moist (“interglacial”) and cool/dry (“glacial”) periods. Although we cannot accurately identify the glacial/interglacial cycles, there is a good correlation

between vegetation groups and relative base level variations deduced from the successive deltaic units. Cool/dry climate is preferentially recorded in mouth bars and deltaic plains deposits during periods of low lake level, while the warm/moist climate is recorded in prodelta deposits during periods of high lake level. If we assume that the deltaic units are governed by climate, they may correspond to 52 to 87 kyr cycles, thus consistent with the 41 kyr obliquity forcing cycles. Such control and periodicity needs to be confirmed and investigated with further palynology analysis at the scale of the deltaic unit. Finally, the Valimi section accounts for one of the rare records of climate in syn-rift alluvial succession. Above all, these results are meaningful in a context where tectonics is unequivocally considered as the predominant control of alluvial sedimentation, and where climate variations are rarely distinguished in the resultant facies.

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References

Arias, C., Bigazzi, G., Bonadonna, F., Brunnacker, K., Urban, B., 1984. Correlation of Plio-Pleistocene deposits of the Lower Rhine Basin (north-west Germany) and the Valle Ricca Pits (Central Italy). Quat. Sci. Rev. 3, 73–89.

Berger, W.H., and Jansen, E., 1996. Climate, Mid-Pleistocene Connection, shift: the Nansen, in Johannessen, O.M., Muench, R.D., and Overlan, J.E. (Eds.), The Polar Oceans and their Role in Shaping the Global Environmen. AGU Geophysical Monograph, AGU, Washington D.C., pp. 295–311.

Abdul Aziz, H., Hilgen, F., Krijgsman, W., Sanz, E., Calvo, J.P., 2000. Astronomical forcing of sedimentary cycles in the middle to late Miocene continental Calatayud Basin (NE Spain). Earth and Planetary Science Letters 177, 9–22. https://doi.org/10.1016/S0012-821X(00)00035-2

Allen, P.A., Armitage, J.J., Carter, A., Duller, R.A., Michael, N.A., Sinclair, H.D., Whitchurch, A.L., Whittaker, A.C., 2013. The Qs problem: Sediment volumetric balance of proximal foreland basin systems. Sedimentology 60, 102−130. https://doi.org/10.1111/sed.12015

Ambrosetti, E., Martini, I., Sandrelli, F., 2017. Shoal-water deltas in high-accommodation settings: Insights from the lacustrine Valimi Formation (Gulf of Corinth, Greece). Sedimentology 64, 425−452. https://doi.org/10.1111/sed.12309

Arias, C., Bigazzi, G., Bonadonna, F., Brunnacker, K., Urban, B., 1984. Correlation of Plio-Pleistocene deposits of the Lower Rhine Basin (North-West Germany) and the Valle Ricca pits (Central Italy). Quaternary Science Reviews 3, 73−89.

Aubouin, J., 1959. Contribution à l'étude géologique de la Grèce septentrionale: les confins de l'Epire et de la Thessalie. Annales Géologiques des Pays Helléniques 10, 1−525.

Avallone, A., Briole, P., Agatza-Balodimou, A.M., Billiris, H., Charade, O., Mitsakaki, C., Nercessian, A., Papazissi, K., Paradissis, D., Veis, G., 2004. Analysis of eleven years of deformation measured by GPS in the Corinth Rift Laboratory area. Comptes Rendus Geoscience 336, 301−311. https://doi.org/10.1016/j.crte.2003.12.007

Backert, N., Ford, M., Malartre, F., 2010. Architecture and sedimentology of the Kerinitis Gilbert-type fan delta, Corinth Rift, Greece. Sedimentology 57, 543−586. https://doi.org/10.1111/j.1365-3091.2009.01105.x

Bandel, K., 2001. The history of Theodoxus and Neritina connected with description and systematic evaluation of related Neritimorpha (Gastropoda). Mitteilungen aus dem Geologisch-Paläontologischen Institut der Universität Hamburg 85, 65−164.

Barrier, L., Proust, J.-N., Nalpas, T., Robin, C., Guillocheau, F., 2010. Control of Alluvial Sedimentation at Foreland-Basin Active Margins: A Case Study from the Northeastern Ebro Basin (Southeastern Pyrenees, Spain). Journal of Sedimentary Research 80, 728−749. https://doi.org/10.2110/jsr.2010.069

Bell, R.E., McNeill, L.C., Bull, J.M., Henstock, T.J., 2008. Evolution of the offshore western Gulf of Corinth. Geological Society of America Bulletin 120, 156−178. https://doi.org/10.1130/B26212.1

Bernard, P., Lyon-caen, H., Briole, P., Deschamps, A., Boudin, F., 2006. Seismicity , deformation and seismic hazard in the western rift of Corinth: New insights from the Corinth Rift Laboratory (CRL). Tectonophysics 426, 7−30. https://doi.org/10.1016/j.tecto.2006.02.012

Bertini, A., 2010. Pliocene to Pleistocene palynoflora and vegetation in Italy: State of the art. Quaternary International 225, 5–24. https://doi.org/10.1016/j.quaint.2010.04.025

Bertoldi, R., Rio, D., Thunell, R., 1989. Pliocene-pleistocene vegetational and climatic evolution of the south-central mediterranean. Palaeogeography, Palaeoclimatology, Palaeoecology 72, 263–275. https://doi.org/10.1016/0031-0182(89)90146-6

Billiris, H., Paradissis, D., Veis, G., England, P., Featherstone, W., Parsons, B., Cross, P., Rands, P., Rayson, M., Sellers, P., Ashkenazi, V., Davison, M., Jackson, J., Ambraseys, N., 1991. Geodetic determination of tectonic deformation in central Greece from 1900 to 1988. Nature 350, 124–129.

Blair, T.C., Bilodeau, W.L., 1988. Development of tectonic cyclothems in rift, pull-apart, and foreland basins: Sedimentary response to episodic tectonism. Geology 16, 517–520. https://doi.org/10.1130/0091-7613(1988)016<0517:DOTCIR>2.3.CO;2

Blum, M.D., Törnqvist, T.E., 2000. Fluvial responses to climate and sea-level change: a review and look forward. Sedimentology 47, 2–48. https://doi.org/10.1046/j.1365-3091.2000.00008.x

Bohacs, K.M., Carroll, A.R., Neal, J.E., Mankiewicz, P.J., 2000. Lake-Basin Type, Source Potential, and Hydrocarbon Character: an Integrated Sequence-Stratigraphic–Geochemical Framework, in: Gierlowski-Kordesch, E.H., Kelts, K.R. (Éd.), Lake basins through space and time. American Association of Petroleum Geologists, Studies in Geology 46, p. 3–34.

Briole, P., Rigo, A., Lyon-Caen, H., Ruegg, J.C., Papazissi, K., Mitsakaki, C., Balodimou, A., Veis, G., Hatzfeld, D., Deschamps, A., 2000. Active deformation of the Corinth Rift Greece' Results from repeated Global Positioning System surveys between 1990 and 1995. Journal of Geophysical Research 105, 25 605-25 625.

Burbank, D.., Meigs, A., Brozovic, N., 1996. Interactions of growing folds and coeval depositional systems. Basin Research 8, 199–223. https://doi.org/10.1046/j.1365-2117.1996.00181.x

Burbank, D.W., Beck, R.A., Raynolds, R.G.H., Hobbs, R., Tahirkheli, R.A.K., 1988. Thrusting and gravel progradation in foreland basins: A test of post-thrusting gravel dispersal. Geology 16, 1143–1146. https://doi.org/10.1130/0091-7613(1988)016<1143:TAGPIF>2.3.CO;2

Carroll, A.R., Bohacs, K.M., 1999. Stratigraphic classification of ancient lakes: Balancing tectonic and climatic controls. Geology 27, 99–102. https://doi.org/10.1130/0091-7613(1999)027<0099:SCOALB>2.3.CO;2

Charreau, J., Avouac, J.-P., Chen, Y., Dominguez, S., Gilder, S., 2008. Miocene to present kinematics of fault-bend folding across the Huerguosi anticline, northern Tianshan (China), derived from structural, seismic, and magnetostratigraphic data. Geology 36, 871. https://doi.org/10.1130/G25073A.1

Charreau, J., Chen, Y., Gilder, S., Barrier, L., Dominguez, S., Augier, R., Sen, S., Avouac, J.-P., Gallaud, A., Graveleau, F., Wang, Q., 2009. Neogene uplift of the Tian Shan Mountains observed in the magnetic record of the Jingou River section (northwest China). Tectonics 28, n/a-n/a. https://doi.org/10.1029/2007TC002137

Chorianopoulou, P., Galeos, A., Ioakim, C., 1984. Pliocene lacustrine sediments in the volcanic succession of Almopias, Macedonia, Greece. Geological Society, London, Special Publications 17, 795–806.

Clarke, P.J., Davies, R.R., England, P.C., Parsons, B., Billiris, H., Paradissis, D., Veis, G., Cross, P.A., Denys, P.H., Ashkenazi, V., Bingley, R., Kahle, H.-G., Muller, M.-V., Briole, P., 1998. Crustal strain in central Greece from repeated GPS measurements in the interval 1989–1997. Geophysical Journal International 135, 195–214. https://doi.org/10.1046/j.1365-246X.1998.00633.x

Cogné, J.P., 2003. PaleoMac: A Macintosh™ application for treating paleomagnetic data and making plate reconstructions. Geochemistry, Geophysics, Geosystems 4, 509–520. https://doi.org/10.1029/2001GC000227

Collier, R.E.L., Dart, C.J., 1991. Neogene to Quarternary rifting, sedimentation and uplift in the Corinth Basin, Greece. Journal of the Geological Society, London 148, 1049–1065.

Combourieu-Nebout, N., 1993. Vegetation Response to Upper Pliocene Glacial/Interglacial Cyclicity in the Central Mediterranean. Quaternary Research 40, 228–236. https://doi.org/10.1006/qres.1993.1074

Cowie, P.A., Attal, M., Tucker, G.E., Whittaker, A.C., Naylor, M., Ganas, A., 2006. Investigating the surface process response to fault interaction and linkage using a numerical modelling approach. Basin Research 18, 231–266. https://doi.org/10.1111/j.1365-2117.2006.00298.x

Cowie, P.A., Gupta, S., Dawers, N.H., 2000. Implications of fault array evolution for synrift depocentre development: insights from a numerical fault growth model. Basin Research

12, 241−261. https://doi.org/10.1111/j.1365-2117.2000.00126.x

Cox, A., 1961. Anomalous remanent magnetization of basalt. U.S. Geological Survey Bulletin 1083E, 131−160.

De Martini, P.M., Pantosti, D., Palyvos, N., Lemeille, F., McNeill, L.C., Collier, R.E.L., 2004. Slip rates of the Aigion and Eliki Faults from uplifted marine terraces, Corinth Gulf, Greece. Comptes Rendus Geoscience 336, 325−334. https://doi.org/10.1016/j.crte.2003.12.006

Degnan, P.J., Robertson, A.H.F., 1998. Mesozoic-early Tertiary passive margin evolution of the Pindos ocean (NW Peloponnese, Greece). Sedimentary Geology 117, 33−70. https://doi.org/http://dx.doi.org/10.1016/S0037-0738(97)00113-9

Dercourt, J., Flament, J.M., Fleury, J.J., Meilliez, F., 1973. Stratigraphie des couches situées sous les radiolarites de la zone du Pinde-Olonos (Grèce): le Trias supérieur et le Jurassique inférieur. Annales Géologiques des Pays Helléniques 25, 397−406.

Doutsos, T., Piper, D.J.W., 1990. Listric faulting, sedimentation, and morphological evolution of the Quaternary eastern Corinth Rift, Greece: First stages of continental rifting. Geological Society of America Bulletin 102, 812−829.

Dubois, J.M., 2001. Cycles climatiques et paramètres orbitaux vers 1 Ma. Etude de la coupe de Monte San Giorgio (Caltagirone, Sicile): palynologie, isotopes stables, calcimétrie. Unpublished Master Thesis, University of Lyon 52p.

Echavarria, L., Hernández, R., Allmendinger, R., Reynolds, J., 2003. Subandean thrust and fold belt of northwestern Argentina: Geometry and timing of the Andean evolution. American Association of Petroleum Geologists Bulletin 87, 965−985. https://doi.org/10.1306/01200300196

Ezquerro, L., Luzón, A., Simón, J.L., Liesa, C.L., 2019. Alluvial sedimentation and tectono-stratigraphic evolution in a narrow extensional zigzag basin margin (northern Teruel Basin, Spain). Journal of Palaeogeography 8, 1−25. https://doi.org/10.1186/s42501-019-0044-4

Fang, X., Garzione, C., Van der Voo, R., Li, J., Fan, M., 2003. Flexural subsidence by 29 Ma on the NE edge of Tibet from the magnetostratigraphy of Linxia Basin, China. Earth and Planetary Science Letters 210, 545−560. https://doi.org/10.1016/S0012-821X(03)00142-0

Fang, X., Yan, M., Van der Voo, R., Rea, D.K., Song, C., Parés, J.M., Gao, J., Nie, J., Dai, S.,

2005. Late Cenozoic deformation and uplift of the NE Tibetan Plateau: Evidence from high-resolution magnetostratigraphy of the Guide Basin, Qinghai Province, China. Geological Society of America Bulletin 117, 1208–1225. https://doi.org/10.1130/B25727.1

Fisher, R., 1953. Dispersion on a Sphere. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 217, 295–305. https://doi.org/10.1098/rspa.1953.0064

Fleury, J.J., 1980. Evolution d'une plateforme et d'un bassin dans leur cadre alpin: les zones de Gavrovo-Tripolitze et du Pinde-Olonos, in: Société Géologique du Nord, Spécial Publication 4. p. 473p.

Ford, M., Hemelsdaël, R., Mancini, M., Palyvos, N., 2016. Rift migration and lateral propagation: evolution of normal faults and sediment-routing systems of the western Corinth Rift (Greece), in: Childs, C., Holdsworth, R.E., Jackson, C.A.-L. (Éd.), The Geometry and Growth of Normal Faults. Geological Society, London, Special Publications 439, p. 131–168.

Ford, M., Rohais, S., Williams, E., Bourlange, S., Jousselin, D., Backert, N., Malartre, F., 2013. Tectono-sedimentary evolution of the western Corinth Rift (Central Greece). Basin Research 25, 3–25. https://doi.org/10.1111/j.1365-2117.2012.00550.x

Ford, M., Williams, E.A., Malartre, F., Popescu, S., 2007. Stratigraphic architecture, sedimentology and structure of the Vouraikos Gilbert-type fan delta, Gulf of Corinth, Greece, in: Williams, E.A., Nichols, G.J., Paola, C. (Éd.), Sedimentary processes, environments and basins: A tribute to Peter Friend. International Association of Sedimentologists, Special Publication 38, p. 49–90.

Fusco, F., 2007. Vegetation response to early Pleistocene climatic cycles in the Lamone valley (Northern Apennines, Italy). Review of Palaeobotany and Palynology 145, 1–23. https://doi.org/10.1016/j.revpalbo.2006.08.005

Gawthorpe, R.L., Leeder, M.R., 2000. Tectono-sedimentary evolution of active extensional basins. Basin Research 12, 195–218. https://doi.org/10.1046/j.1365-2117.2000.00121.x

Gawthorpe, R.L., Leeder, M.R., Kranis, H., Skourtsos, E., Andrews, J.E., Henstra, G.A., Mack, G.H., Muravchik, M., Turner, J.A., Stamatakis, M., 2018. Tectono-sedimentary evolution of the Plio-Pleistocene Corinth Rift, Greece. Basin Research 30, 448–479.

Gillet, S., 1963. Nouvelles données sur le gisement villafranchien de Néa-Corinthos. Praktika

Akadimias Athinion 40, 400–419.

Goldsworthy, M., Jackson, J., 2001. Migration of activity within normal fault systems: examples from the Quaternary of mainland Greece. Journal of Structural Geology 23, 489–506. https://doi.org/10.1016/S0191-8141(00)00121-8

Gupta, S., Cowie, P.A., Dawers, N.H., Underhill, J.R., 1998a. A mechanism to explain rift-basin subsidence and stratigraphic patterns through fault-array evolution. Geology 26, 505–598.

Gupta, S., Cowie, P.A., Dawers, N.H., Underhill, J.R., 1998b. A mechanism to explain rift-basin subsidence and stratigraphic patterns through fault-array evolution. Geology 26, 595–598. https://doi.org/10.1130/0091-7613(1998)026<0595:AMTERB>2.3.CO;2

Hemelsdaël, R., Ford, M., 2016. Relay zone evolution: a history of repeated fault propagation and linkage, central Corinth Rift, Greece. Basin Research 28, 34–56. https://doi.org/10.1111/bre.12101

Hemelsdaël, R., Ford, M., Malartre, F., Gawthorpe, R., 2017. Interaction of an antecedent fluvial system with early normal fault growth: Implications for syn-rift stratigraphy, western Corinth Rift (Greece). Sedimentology 64. https://doi.org/10.1111/sed.12381

Hilgen, F.J., Lourens, L.J., Van Dam, J.A., Beu, A.G., Boyes, A.F., Cooper, R.A., Krijgsman, W., Ogg, J.G., Piller, W.E., Wilson, D.S., 2012. The Neogene Period, in: The Geologic Time Scale. Elsevier, p. 923–978. https://doi.org/10.1016/B978-0-444-59425-9.00029-9

Horton, B.K., Constenius, K.N., DeCelles, P.G., 2004. Tectonic control on coarse-grained foreland-basin sequences: An example from the Cordilleran foreland basin, Utah. Geology 32, 637. https://doi.org/10.1130/G20407.1

Huerta, P., Armenteros, I., Silva, P.G., 2011. Large-scale architecture in non-marine basins: The response to the interplay between accommodation space and sediment supply. Sedimentology 58, 1716–1736. https://doi.org/10.1111/j.1365-3091.2011.01231.x

Ielpi, A., 2012. Orbitally-driven climate forcing in late Pliocene lacustrine siderite-rich clastic rhythms (Upper Valdarno Basin, Northern Apennines, Italy). Palaeogeography, Palaeoclimatology, Palaeoecology 331–332, 119–135. https://doi.org/10.1016/j.palaeo.2012.03.004

Joannin, S., 2003. Forçage climatique des séquences emboîtées du Pléistocène inférieur et moyen de Tsampika (île de Rhodes, Grèce). Unpublished Master Thesis, University of Lyon 52p.

Joannin, S., Ciaranfi, N., Stefanelli, S., 2008. Vegetation changes during the late Early Pleistocene at Montalbano Jonico (Province of Matera, southern Italy) based on pollen analysis. Palaeogeography, Palaeoclimatology, Palaeoecology 270, 92–101. https://doi.org/10.1016/j.palaeo.2008.08.017

Joannin, S., Cornée, J.-J., Moissette, P., Suc, J.-P., Koskeridou, E., Lécuyer, C., Buisine, C., Kouli, K., Ferry, S., 2007. Changes in vegetation and marine environments in the eastern Mediterranean (Rhodes, Greece) during the Early and Middle Pleistocene. Journal of the Geological Society, London 164, 1119–1131.

Jolivet, L., Brun, J.-P., 2008. Cenozoic geodynamic evolution of the Aegean. International Journal of Earth Sciences 99, 109–138. https://doi.org/10.1007/s00531-008-0366-4

Jones, M.A., Heller, P.L., Roca, E., Garcés, M., Cabrera, L., 2004. Time lag of syntectonic sedimentation across an alluvial basin: theory and example from the Ebro Basin, Spain. Basin Research 16, 489–506. https://doi.org/10.1111/j.1365-2117.2004.00244.x

Keraudren, B., 1979. Le Plio-Pléistocène marin et oligohalin en Grèce: stratigraphie et paléogéographie. Revue de Géologie Dynamique et de Géographie Physique 21, 17–28.

Keraudren, B., 1975. Essai de stratigraphie et de paléogéographie du Plio-Pléistocène égéen. Bulletin de la Société Géologique de France S7-XVII, 1110–1120. https://doi.org/10.2113/gssgfbull.S7-XVII.6.1110

Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data. Geophysical Journal International 62, 699–718. https://doi.org/10.1111/j.1365-246X.1980.tb02601.x

Koskeridou, E., Ioakin, C., 2009. An early Pleistocene mollusc fauna with Pono-Caspian elements in intra-Hellenic Basin of Atlanti, Arkitsa region (Central Greece), in: 9th Symposium on Oceanography and Fisheries. p. 96–101.

Le Pichon, X., Lallemant, S.J., Chamot-Rooke, N., Lemeur, D., Pascal, G., 2002. The Mediterranean Ridge backstop and the Hellenic nappes. Marine Geology 186, 111–125.

Leeder, M.R., Mack, G.H., 2001. Lateral erosion (‘toe-cutting’) of alluvial fans by axial rivers: implications for basin analysis and architecture. Journal of the Geological Society 158, 885–893. https://doi.org/10.1144/0016-760000-198

Leeder, M.R., Mack, G.H., Brasier, A.T., Parrish, R.R., McIntosh, W.C., Andrews, J.E., Duermeijer, C.E., 2008. Late-Pliocene timing of Corinth (Greece) rift-margin fault migration. Earth and Planetary Science Letters 274, 132–141.

https://doi.org/10.1016/j.epsl.2008.07.006
Leeder, M.R., Mark, D.F., Gawthorpe, R.L., Kranis, H., Loveless, S., Pedentchouk, N., Skourtsos, E., Turner, J., Andrews, J.E., Stamatakis, M., 2012. A « Great Deepening »: Chronology of rift climax, Corinth Rift, Greece. Geology 40, 999‑1002. https://doi.org/10.1130/G33360.1
Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ 18 O records. Paleoceanography 20, n/a-n/a. https://doi.org/10.1029/2004PA001071
Lourens, L., Hilgen, F., Shackleton, N.J., Laskar, J., Wilson, D., 2004. The Neogene Period, in: Gradstein, F.M., Ogg, J.G., Smith, A.G. (Éd.), A Geological Time Scale. Cambridge University Press, p. 409‑440.
Mack, G.H., Seager, W.R., Leeder, M.R., Perez-Arlucea, M., Salyards, S.L., 2006. Pliocene and Quaternary history of the Rio Grande, the axial river of the southern Rio Grande rift, New Mexico, USA. Earth-Science Reviews 79, 141‑162. https://doi.org/10.1016/j.earscirev.2006.07.002
Malartre, F., Ford, M., Williams, E.A., 2004. Preliminary biostratigraphy and 3D geometry of the Vouraikos Gilbert-type fan delta, Gulf of Corinth, Greece. Comptes Rendus Geoscience 336, 269‑280. https://doi.org/10.1016/j.crte.2003.11.016
McClusky, S., Balassanian, S., Barka, A., Demir, C., Ergintav, S., Georgiev, I., Gurkan, O., Hamburger, M., Hurst, K., Kahle, H., Kastens, K., Kekelidze, G., King, R., Kotzev, V., Lenk, O., Mahmoud, S., Mishin, A., Nadariya, M., Ouzounis, A., Paradissis, D., Peter, Y., Prilepin, M., Reilinger, R., Sanli, I., Seeger, H., Tealeb, A., Toksöz, M.N., Veis, G., 2000. Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. Journal of Geophysical Research: Solid Earth 105, 5695‑5719. https://doi.org/10.1029/1999JB900351
McNeill, L.C., Collier, R.E.L., 2004. Uplift and slip rates of the eastern Eliki fault segment, Gulf of Corinth, Greece, inferred from Holocene and Pleistocene terraces. Journal of the Geological Society 161, 81‑92.
Medwedeff, D.A., 1989. Growth fault-bend folding at Southeast Lost Hills, San Joaquin Valley, California. American Association of Petroleum Geologists Bulletin 73, 54‑67.
Miall, A.D., 2015. Updating uniformitarianism: stratigraphy as just a set of ‘frozen accidents’. Geological Society of London Special Publication 404, 11‑36.

https://doi.org/10.1144/SP404.4

Morley, C.K., Wonganan, N., 2000. Normal fault displacement characteristics, with particular reference to synthetic transfer zones, Mae Moh mine, northern Thailand. Basin Research 12, 307–327. https://doi.org/10.1111/j.1365-2117.2000.00127.x

Muto, T., Steel, R.J., 1997. Principles of regression and transgression; the nature of the interplay between accommodation and sediment supply. Journal of Sedimentary Research 67, 994–1000. https://doi.org/10.1306/D42686A8-2B26-11D7-8648000102C1865D

Nixon, C.W., McNeill, L.C., Bull, J.M., Bell, R.E., Gawthorpe, R.L., Henstock, T.J., Christodoulou, D., Ford, M., Taylor, B., Sakellariou, D., Ferentinos, G., Papatheodorou, G., Leeder, M.R., Collier, R.E.L., Goodliffe, A.M., Sachpazi, M., Kranis, H., 2016. Rapid spatio-temporal variations in rift structure during development of the Corinth Rift, central Greece. Tectonics 35, 1225–1248. https://doi.org/10.1002/2015TC004026

Nyst, M., Thatcher, W., 2004. New constraints on the active tectonic deformation of the Aegean. Journal of Geophysical Research 109, B11406. https://doi.org/10.1029/2003JB002830

Okuda, M., Van Vugt, N., Nakagawa, T., Ikeya, M., Hayashida, A., Yasuda, Y., Setoguchi, T., 2002. Palynological evidence for the astronomical origin of lignite-detritus sequence in the Middle Pleistocene Marathousa Member, Megalopolis, SW Greece. Earth and Planetary Science Letters 201, 143–157. https://doi.org/10.1016/S0012-821X(02)00706-9

Papanikolaou, D.J., Royden, L.H., 2007. Disruption of the Hellenic arc: Late Miocene extensional detachment faults and steep Pliocene-Quaternary normal faults-Or what happened at Corinth? Tectonics 26, TC5003. https://doi.org/10.1029/2006TC002007

Pirazzoli, P.A., Stiros, S.C., Fontugne, M., Arnold, M., 2004. Holocene and Quaternary uplift in the central part of the southern coast of the Corinth Gulf (Greece). Marine Geology 212, 35–44. https://doi.org/10.1016/j.margeo.2004.09.006

Popov, V. V, 2001. Late Pliocene voles (Mammalia: Arvicolidae) from Varshets (North Bulgaria). Acta zoologica cracoviensia 44, 143–172.

Prosser, S., 1993. Rift-related linked depositional systems and their seismic expression, in: Williams, G.D., Dobb, A. (Éd.), Tectonics and Seismic Sequence Stratigraphy. Geological Society, London, Special Publications 71, p. 35–66. https://doi.org/10.1144/GSL.SP.1993.071.01.03

Reilinger, R., McClusky, S., Vernant, P., Lawrence, S., Ergintav, S., Cakmak, R., Ozener, H., Kadirov, F., Guliev, I., Stepanyan, R., Nadariya, M., Hahubia, G., Mahmoud, S., K., S., ArRajehi, A., Demitris, P., Al-Aydrus, A., Prilepin, M., Tamara, G., Evren, E., Dmitrotsa, A., Filikov, S.V., Gomez, G., Al-Ghazzi, R., Karam, G., 2006. GPS constraints on continental deformation in the Africa-Arabia-Eurasia continental collision zone and implications for the dynamics of plate interactions. Journal of Geophysical Research 111, B05411. https://doi.org/doi:10.1029/2005JB004051

Reilinger, R., McClusky, S.C., Oral, M.B., King, R.W., Toksoz, M.N., Barka, A.A., Kinik, I., Lenk, O., Sanli, I., 1997. Global Positioning System measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone. Journal of Geophysical Research: Solid Earth 102, 9983–9999. https://doi.org/10.1029/96JB03736

Riveline, J., Berger, J.-P., Feist, M., Martin-Closas, C., Schudack, M., Soulie-Maersche, I., 1996. European Mesozoic-Cenozoic charophyte biozonation. Bulletin de la Société géologique de France 167, 453–468.

Rohais, Eschard, R., Guillocheau, F., 2008. Depositional model and stratigraphic architecture of rift climax Gilbert-type fan deltas (Gulf of Corinth, Greece). Sedimentary Geology 210, 132–145. https://doi.org/10.1016/j.sedgeo.2008.08.001

Rohais, Joannin, S., Colin, J.-P., Suc, J.-P., Guillocheau, F., Eschard, R., 2007. Age and environmental evolution of the syn-rift fill of the southern coast of the gulf of Corinth (Akrata-Derveni region, Greece). Bulletin de la Société Géologique de France 178, 231–243. https://doi.org/10.2113/gssgfbull.178.3.231

Rohais, S., Eschard, R., Ford, M., Guillocheau, F., Moretti, I., 2007. Stratigraphic architecture of the Plio-Pleistocene infill of the Corinth Rift: Implications for its structural evolution. Tectonophysics 440, 5–28. https://doi.org/10.1016/j.tecto.2006.11.006

Romans, B.W., Castelltort, S., Covault, J.A., Fildani, A., Walsh, J.P., 2016. Environmental signal propagation in sedimentary systems across timescales. Earth-Science Reviews. https://doi.org/10.1016/j.earscirev.2015.07.012

Sabato, L., Bertini, A., Masini, F., Albianelli, A., Napoleone, G., Pieri, P., 2005. The lower and middle Pleistocene geological record of the San Lorenzo lacustrine succession in the Sant'Arcangelo Basin (Southern Apennines, Italy). Quaternary International 131, 59–69. https://doi.org/10.1016/j.quaint.2004.07.001

Sachpazi, M., Galvé, a., Laigle, M., Hirn, a., Sokos, E., Serpetsidaki, a., Marthelot, J.-M., Pi Alperin, J.M., Zelt, B., Taylor, B., 2007. Moho topography under central Greece and its compensation by Pn time-terms for the accurate location of hypocenters: The example of the Gulf of Corinth 1995 Aigion earthquake. Tectonophysics 440, 53–65. https://doi.org/10.1016/j.tecto.2007.01.009

Sadler, P.M., 1981. Sediment accumulation rates and the completeness of stratigraphic sections. The Journal of Geology 89, 569–584.

Sala, B., Masini, F., 2007. Late Pliocene and Pleistocene small mammal chronology in the Italian peninsula. Quaternary International 160, 4–16. https://doi.org/http://dx.doi.org/10.1016/j.quaint.2006.10.002

Santos, M.G.M., Almeida, R.P., Godinho, L.P.S., Marconato, A., Mountney, N.P., 2014. Distinct styles of fluvial deposition in a Cambrian rift basin. Sedimentology 61, 881–914. https://doi.org/10.1111/sed.12074

Schlische, R.W., Anders, M.H., 1996. Stratigraphic effects and tectonic implications of the growth of normal faults and extensional basins, in: Beratan, K.K. (Éd.), Reconstructing the History of Basin and Range Extension Using Sedimentology and Stratigraphy. Geological Society of America Special Publication 303, p. 183–203.

Soulié-Märsche, I., 1979. Charophytes fossiles des formations pliocènes de l'Isthme de Megara (Grèce). Annales Géologiques des Pays Helléniques Tome hors série fasc. 4, 1127–1136.

Steenbrink, J., van Vugt, N., Hilgen, F.J., Wijbrans, J.R., Meulenkamp, J.E., 1999. Sedimentary cycles and volcanic ash beds in the Lower Pliocene lacustrine succession of Ptolemais (NW Greece): discrepancy between 40Ar/39Ar and astronomical ages. Palaeogeography, Palaeoclimatology, Palaeoecology 152, 283–303. https://doi.org/https://doi.org/10.1016/S0031-0182(99)00044-9

Stevanovic, P.M., 1963. Beitrag zur Kenntnis der pontischen Molluskenfauna aus Griechenland und ihre stratigraphische Bedeuting. Académie Serbe des Sciences et des Arts 32, 73–93.

Stewart, I.S., 1996. Holocene uplift and paleoseismicity on the Eliki fault, western Gulf of Corinth, Greece. Annals of Geophysics 39, 575–588.

Stewart, I.S., Vita-Finzi, C., 1996. Coastal uplift on active normal faults: The Eliki Fault, Greece. Geophysical Research Letters 23, 1853–1856. https://doi.org/10.1029/96GL01595

Subally, D., Bilodeau, G., Tamrat, E., Ferry, S., Debard, E., Hillaire-Marcel, C., 1999. Cyclic climatic records during the Olduvai Subchron (uppermost Pliocene) on Zakynthos Island (Ionian Sea). Geobios 32, 793–803.

Suc, J.-P., 1986. Flores néogènes de Méditerranée occidentale. Climat et paléogéographie. Bulletin des Centres de Recherche et d'Exploration-Production d'Elf-Aquitaine 10, 477–488.

Suc, J.-P., 1984. Origin and evolution of the Mediterranean vegetation and climatr in Europe. Nature 307, 429–432.

Suc, J.-P., Comboireu-Nebout, N., Seret, G., Popescu, S.-M., Klotz, S., Gautier, F., Clauzon, G., Westgate, J., Insinga, D., Sandhu, A.S., 2010. The Crotone series: A synthesis and new data. Quaternary International 219, 121–133. https://doi.org/10.1016/j.quaint.2010.01.008

Suc, J.-P., Popescu, S.-M., 2005. Pollen records and climatic cycles in the North Mediterranean region, in: Head, M.J., Gibbard, P.L. (Éd.), Early– Middle Pleistocene Transitions: The Land–Ocean Evidence. Geological Society of London, p. 147–158. https://doi.org/10.1144/GSL.SP.2005.247.01.08

Suc, J.-P., Zagwijn, W.H., 1983. Plio–Pleistocene correlations between the northwestern Mediterranean region and northwestern Europe according to recent biostratigraphic and palaeoclimatic data. Boreas 12, 153–166.

Sun, J., Li, Y., Zhang, Z., Fu, B., 2009. Magnetostratigraphic data on Neogene growth folding in the foreland basin of the southern Tianshan Mountains. Geology 37, 1051–1054. https://doi.org/10.1130/G30278A.1

Symeonidis, N., Theothorou, G., Schutt, H., Velitzelos, E., 1987. Paleontological and stratigraphic observations in the area of Achaia and Etoloakarnania W-Greece. Annales Géologiques des Pays Helléniques 38, 317–353.

Tiercelin, J.-J., Soreghan, M., Cohen, A.S., Lezzar, K.-E., Bouroullec, J.-L., 1992. Sedimentation in large rift lakes: example from the Middle Pleistocene—Modern deposits of the Tanganyika Trough, East African Rift System. Bulletin des centres de Recherche Exploration et Production d'Elf Aquitaine 16, 83–111.

Tzedakis, P.C., Andrieu, V., de Beaulieu, J.-L., Crowhurst, S., Follieri, M., Hooghiemstra, H., Magri, D., Reille, M., Sadori, L., Shackleton, N.J., Wijmstra, T.A., 1997. Comparison of terrestrial and marine records of changing climate of the last 500,000 years. Earth and Planetary Science Letters 150, 171–176.

Tzedakis, P.C., Andrieu, V., De Beaulieu, J.L., Birks, H.J.B., Crowhurst, S., Follieri, M., Hooghiemstra, H., Magri, D., Reille, M., Sadori, L., Shackleton, N.J., Wijmstra, T.A., 2001. Establishing a terrestrial chronological framework as a basis for biostratigraphical comparisons. Quaternary Science Reviews 20, 1583–1592. https://doi.org/10.1016/S0277-3791(01)00025-7

Tzedakis, P.C., Hooghiemstra, H., Pälike, H., 2006. The last 1.35 million years at Tenaghi Philippon: revised chronostratigraphy and long-term vegetation trends. Quaternary Science Reviews 25, 3416–3430. https://doi.org/10.1016/j.quascirev.2006.09.002

Valero, L., Huerta, P., Garcés, M., Armenteros, I., Beamud, E., Gómez-Paccard, M., 2015. Linking sedimentation rates and large-scale architecture for facies prediction in nonmarine basins (Paleogene, Almazán Basin, Spain). Basin Research 29, 213–232. https://doi.org/10.1111/bre.12145

van Vugt, N., Langereis, C.G., Hilgen, F.J., 2001. Orbital forcing in Pliocene–Pleistocene Mediterranean lacustrine deposits: dominant expression of eccentricity versus precession. Palaeogeography, Palaeoclimatology, Palaeoecology 172, 193–205. https://doi.org/10.1016/S0031-0182(01)00270-X

van Vugt, N., Steenbrink, J., Langereis, C.G., Hilgen, F.J., Meulenkamp, J.E., 1998. Magnetostratigraphy-based astronomical tuning of the early Pliocene lacustrine sediments of Ptolemais (NW Greece) and bed-to-bed correlation with the marine record. Earth and Planetary Science Letters 164, 535–551. https://doi.org/10.1016/S0012-821X(98)00236-2

VanHinsbergen, D., Hafkenscheid, E., Spakman, W., Meulenkamp, J.E., Wortel, R., 2005. Nappe stacking resulting from subduction of oceanic and continental lithosphere below Greece. Geological Society of America 33, 325–328. https://doi.org/10.1130/G20878.1

VanHinsbergen, D., Schmid, S.M., 2012. Map view restoration of Aegean-West Anatolian accretion and extension since the Eocene. Tectonics 31, TC5005. https://doi.org/10.1029/2012TC003132

Withjack, M.O., Schlische, R.W., Olsen, P.E., 2002. Rift-basin structure and its influence on sedimentary systems, in: Renaut, S., Ashley, G. (Éd.), Sedimentation in Continental rifts. Society of Economic Paleontologists and Mineralogists, Special Publication 73, p. 57–81.

Zijderveld, J.D.A., 1967. AC demagnetization of rocks: analysis of results, in: Collinson, D.W., Creer, K.M., Runcorn, S.K. (Éd.), Methods in paleomagnetism. Elsevier, Amsterdam, Netherlands, p. 254–286.

Figure captions

Figure 1: (A) Geological map of the Corinth Rift. The black box corresponds to the study area shown in the Figure 2. (B) Regional context of the Corinth Rift in the back-arc of the active Hellenic subduction zone, and lying between the Kephalonia Fault (KF) and the North Anatolian Fault (NAF). Subduction of the African plate generated the Aegean Volcanic Arc (AVA). The rift separates mainland Greece from the Peloponnese peninsula (Pel.).

Figure 2: Geological map of the study area. The onshore syn-rift stratigraphy is defined for the southern and northeastern fault blocks. The studied logged sections and main biostratigraphic sites are also indicated.

Figure 3: Interpretation of the syn-rift succession in the central Doumena fault block. The yellow line corresponds to the trace of the Doumena section sampled for palaeomagnetic analysis.

Figure 4: Interpretation of the syn-rift succession in the western part of the Kerpini fault block where the Kerpini section was sampled for palaeomagnetic analysis.

Figure 5: (A): Interpretation of the syn-rift succession in the Valimi fault block along the Krathis River valley. The yellow line corresponds to the trace of the lower Valimi section for palaeomagnetic analysis. (B): N-S oriented cross section of the Valimi fault block. The low dip of the fault and rotation of the early fault blocks is due to later activation of the Valimi Fault to the south. (C): Upper part of the Valimi section sampled for palaeomagnetic analysis. (D): Upper part of the Voutsimos.

Figure 6: Interpretation of the syn-rift succession in the Pirgaki-Mamoussia fault block exposed along the Lapodotamos River valley. Both the Ladopotamos and Katafugion formations are preserved below the Vouraikos Gilbert-type delta (Middle Group). Note the presence of a transgressive surface within the Katafugion Formation, with the shoreface deposits onlapping onto the lagoon deposits.

Figure 7: Representative demagnetization diagrams and stereographic projections (tilt cor- rected). (A-B): Quality-1 samples showing normal polarity. (C-D): Quality-1 samples

showing reversed polarity. (E): Quality-2 sample. (F): Stereographic projection showing a typical great circle. (G-H): Quality-3 samples excluded from the palaeomagnetic analysis. Full symbol are projected on the horizontal plane. Open symbols are projected on the vertical plane.

Figure 8: Polarity columns in the 4 studied sections. The declination and inclination curves are traced using Quality-1 samples (blacks dotes). Quality-2 samples are also represented (open symbols). The polarity columns show normal, reversed, uncertain magnetozones and large intervals without good quality data available.

Figure 9: (A) Equal-area projections of the principal component directions (Quality-1 samples) for the Valimi, Voutsimos, Doumena and Kerpini sections. *In situ* non-corrected (IS) and tilt-corrected (TC) coordinates are plotted separately. (B) Equal-area projections of the principal component directions from all sections (IS). (C) Means of normal and reversed polarities in all sections to perform the fold test. Directions before bedding correction is D_g = 1.4°; I_g = 43.9°; a_{95} = 15.8° and change to D_s = 11.0°; I_s = 50.9°; a_{95} = 20.1° after bedding correction. Blue diamond represents the present-day earth's magnetic field and red star is the geomagnetic axial dipole direction. (D) Fold test result using 6 direction means (McElhinny, 1964). *k* parameter represents the clustering of direction.

Figure 10: Pollen diagram of the Valimi section (between 400 m and 1350 m thickness) showing percentages of taxa and vegetation units. The ratio of Mesothermic-Steppe elements is presented in a semi-logarithmic plot. The palynological section is subdivided into 12 pollen zones and at least 3 vegetation units. Open circles correspond to the palynological samples in Rohais et al. (2007b).

Figure 11: Relative age determination based on palynological analyses. (A) Last Appearance Datum in Ma (LAD) for arboreal pollen taxa in different Mediterranean sites [A-I] with A: Tenaghi Philippon (Tzedakis et al., 2006), B: Caltagirone-Sicily (Dubois, 2001; Suc & Popescu, 2005 in Rohais et al., 2007b), C: Zakynthos Island (Subally et al., 1999 in Rohais et al., 2007), D: Rhodes (Joannin, 2003; Joannin et al., 2007), E: Vouraikos Gilbert Delta (Ford et al., 2007), F: Caltagirone-Sicily (Dubois, 2001 in Rohais et al., 2007), G: Megalopolis (Okuda et al., 2002), H: Ioannina 249 (Tzedakis et al., 1997), I: Tenaghi Philippon, Valle di Castiglione (Tzedakis et al., 2001). (B) Pollen distribution based on

relative age determination between 400 m and 1350 m showing that this section is older than 1.07 Ma.

Figure 12: Correlation model across the Kalavryta river system across several normal fault blocks combining magnetostratigraphic and biostratigraphic ages. The best time constraint is the Gauss/Matuyama magnetic reversal at 2.58 Ma.

Figure 13: Thickness vs polarity reference scale for the different palaeomagnetic sections (Lourens et al., 2004). The best-fit line is tentatively traced for each section. The grey dashed line indicates a SAR of 0.4 mm yr-1.

Figure 14: Non-exhaustive compilation of SARs based on magnetostratigraphy of Cenozoic continental successions deposited in foreland, rift and strike-slip tectonic setting. The values for the Kalavryta river system are relatively high compared to most of the existing studies. The selected references and values are provided in Supplementary Data (Table E).

Figure 15: Subdivision of the Valimi section into deltaic units based on the facies associations and identification of the main coarsening upward trends. The Mesothermic/Steppe plot is colored with respect to the facies associations. The deltaic units are tentatively correlated with the interpreted vegetation groups (a) deciduous warm loving elements, (b) mesothermic elements, (c) high- and mid-altitude elements, (d) Steppe elements.

Table captions

Table 1: Summary of palaeomagnetic directions for all sections, which are separated in different thickness intervals.

Table 2: Sampling depth, lithosttratigraphy, facies assocation and deltaic units combined with the vegetation units of the Valimi section. The deltaic units are tentatively correlated to the vegetation units (a-d; see details in the text). The shaded zones correspond to the intervals of glacial-like (dominated by steppe vegetation).

1260