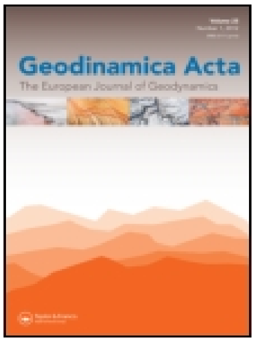

Geodinamica Acta

ISSN: 0985-3111 (Print) 1778-3593 (Online) Journal homepage: https://www.tandfonline.com/loi/tgda20

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To cite this article: Riccardo Caputo, Jean-Paul Bravard & Bruno Helly (1994) The Pliocene-Quaternary tecto-sedimentary evolution of the Larissa Plain (Eastern Thessaly, Greece), Geodinamica Acta, 7:4, 219-231, DOI: 10.1080/09853111.1994.11105267

To link to this article: https://doi.org/10.1080/09853111.1994.11105267

Geodinamica Acta (Paris) 1994, 7, 4, 219-231

The Pliocene-Quaternary tecto-sedimentary evolution of the Larissa Plain (Eastern Thessaly, Greece)

Evolution tecto-sédimentaire du Pliocène-Quaternaire de la plaine de Larissa (Thessalie orientale, Grèce)

by Riccardo Caputo*, Jean-Paul Bravard** and Bruno Helly***

ABSTRACT – In order to understand the present-day morphological, geographical and environmental patterns of the Larissa Plain, a large amount of historical, archaeological, sedimentological, stratigraphic, tectonic and seismic data have been collected and analysed. The collaboration of different specialists was essential for these aims. The Larissa Plain is an inter-mountain basin formed during the Pliocene as a result of the post-orogenic collapse of the Hellenides. From the Middle Pleistocene, the region has been affected by a new tectonic phase which caused an important palaeogeographic change and fragmented the study area into three distinct geographical domains characterised by different sedimentary conditions : the Pinios alluvial plain to the North, the Karla Lake to the South, and the Chasambali Bulge in between. The first sector corresponds to the active Tyrnavos Basin, and the second to the southern part of the inherited Pliocene Larissa Basin. The Chasambali Bulge has been differentiated by a system of northward down-stepping normal faults thus creating a temporary hydrographic divide between the two major domains. Recent dikes have disconnected the present physiography of the plain from the hazards of the recurrent floods of the Pinios River over the alluvial plain and discharged the Asmaki River of its past function of an overflow convector from the northern drainage system (Tyrnavos Basin) towards the southern one (Karla Lake). A four-step model of the tecto-sedimentary evolution of the Tyrnavos Basin is proposed. a) The profile of the Pinios River is in equilibrium. b) The area is affected by a tectonic paroxysm that produces a partition of the plain. c) Local erosion as well as a distributed fluvio-lacustrine sedimentation occures until the gap is filled up. d) Once widespread sedimentation halts, the abandoned alluvial plain suffers a diffuse pedogenesis. Several secondary factors (prolonged morphogenic activity, compaction-induced subsidence, differential sedimentary compaction, erosional phenomena outside the basin, climate variations and anthropic activity) that may have disturbed and changed this simple cyclic evolution, locally or temporarily, have been considered and analysed in detail. The paradox of the Larissa Plain, where the Pinios River flows 20 to 40 m higher than the Karla Lake and exits the area crossing the Palaeozoic bedrock along the Rodia Narrow, has been satisfactorily explained. Probably during the last few thousand years, this palaeogeographic pattern being characterised by an alluvial plain in the Tyrnavos Basin and an independent large lake in the southern Larissa Plain, since Middle Pleistocene, became unstable due to one or more concomitant and possibly inter-dependent causes which are discussed here in detail. The build up of an artificial embankment along the Pinios River North of Larissa, definitely fossilised the present-day geography.

Key-words : palaegeographic evolution, morphology, tectonics, Quaternary, Larissa Plain.

RÉSUMÉ – Dans le but de comprendre le fonctionnement géomorphologique et environnemental actuel de la plaine de Larissa, une équipe interdisciplinaire a collecté et analysé un grand nombre de données historiques, archéologiques, sédimentologiques, stratigraphiques, tectoniques et sismiques. La plaine de Larissa est un bassin intra-montagnard formé au Pliocène à la suite de l'effondrement post-orogénique des Hellénides. Depuis le milieu du Pléistocène, la région est affectée par une nouvelle phase tectonique qui a causé d'importants changements paléogéographiques et l'a morcelée en trois secteurs géographiques distincts définis par les conditions de la sédimentation : il s'agit de la plaine alluviale du

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Pinios au nord, du lac Karla au sud et, entre les deux, du seuil de Kasambali. Le premier secteur correspond au bassin actif de Tyrnavos, le second à la partie méridionale de l'ancien bassin pliocène de Larissa. Le seuil de Kasambali a été individualisé par un système de failles normales plongeant vers le nord qui ont créé une ligne de partage des eaux temporaires entre les deux grands secteurs. Avant l'endiguement récent du Pinios qui a fixé les conditions actuelles, un cours d'eau, l'Asmaki, fonctionnait comme un déversoir reliant le système de drainage septentrional (bassin de Tyrnavos) au système méridional (lac Karla) à l'occasion des fortes crues. On propose un modèle tecto-sédimentaire à quatre phases pour expliquer l'évolution du bassin de Tyrnavos. a) Le profil en long du Pinios est en équilibre. b) La région est affectée par un paroxysme tectonique qui génère une division de la plaine. c) Des phénomènes d'érosion et de sédimentation fluvio-lacustre localisés se produisent tant que la régularisation n'est pas atteinte. d) Une fois que la sédimentation généralisée a cessé, la plaine alluviale abandonnée subit une pédogenèse diffuse. Ont également été pris en compte et analysés en détail plusieurs facteurs secondaires (prolongement de l'activité morphogénique, subsidence induite par la compaction, subsidence différenciée, processus érosifs extérieurs au bassin, variations climatiques et activité humaine) susceptibles de déranger ou de modifier de manière temporaire et locale le modèle cyclique simple qui a été proposé. Ce modèle permet d'expliquer de manière satisfaisante le paradoxe de la plaine de Larissa dans laquelle le Pinios coule à une altitude de 20 à 40 m supérieure à celle du lac Karla avant de la quitter par le défilé de Rodia entaillé dans le substratum paléozoïque. Pendant les derniers millénaires, ce modèle paléogéographique, caractérisé depuis le Pléistocène moyen par une plaine alluviale logée dans le bassin de Tyrnavos et un grand lac indépendant localisé dans la partie méridionale de la plaine, est devenu instable. Ceci est probablement dû à l'interférence de facteurs interdépendants et concommitants qui sont discutés en détail. La réalisation de l'endiguement du Pinios au nord de Larissa a aujourd'hui fossilisé la géographie actuelle des lieux.

Mots-clés : évolution palaegeographique, morphologie, tectonique, Qaternaire Plaine de Larissa.

I. INTRODUCTION

In order to understand the present-day morphological, geographical and environmental patterns of the Larissa Plain (Eastern Thessaly, Greece; fig. 1), we will first consider the tectonic evolution of the area during the last few million years. We will then consider its morphological evolution during the last thousand years and eventually its geographical evolution during the last centuries.

Since prehistoric times the Larissa Plain has been populated and, particularly from the Neolithic, man began to settle the area. Further information is available from historical times, because the plain has been described by several authors such as Homer, Hesiod, Strabon, Polibius, Titus Livius as well as some travellers of the 18th and 19th centuries. In a separate paper (Helly *et al.*, in press), that can be considered complementary to the present one, we analyse in detail all the archaeological and historical data. The aim of this research is to propose a tecto-sedimentary model in order to explain the somewhat contradictory written evidence and the recent physiography of the area which is somehow enigmatic: the Pinios River flows 20-40 m higher than the apparently contiguous Karla Lake.

Although the Larissa Plain has an articulated geometry at a large scale, it shows a more or less regular flat lying surface. On a distance longer than 50 km between the Rodia Narrow to the North, and the south-eastern extremity, the maximum difference in altitude does not exceed 50 m, thus showing a smooth physiography of the area. Nonetheless, the minor topographic and hydrographic irregularities on which we focused our attention, reveal a complex recent geological and tectonic history.

II. PLIOCENE-LOWER PLEISTOCENE TECTONIC EVOLUTION

From a geological point of view, Eastern Thessaly belongs to the Internal Hellenides which are part of the Greek orogenic belt. The build up of the whole mountain chain is the result of several compressional events. The last of these events was the Alpide tectonic phase (e.g. Aubouin, 1959), which affected Thessaly from Eocene to Middle Miocene times (Brunn, 1956).

After the Alpide orogenesis, Eastern Thessaly, as well as most of the Inner Aegean Region, underwent extensional tectonic conditions. Probably related to the post-orogenic collapse (Caputo & Pavlides, 1993), the area was affected by a NE-SW extensional regime. This caused the formation of a system of NW-SE elongated horsts and grabens bounded by large normal faults. As a consequence of this event, the structural trend of the Hellenides, as inherited from the Alpide orogenesis, was emphasised. In Thessaly, this tectonic regime was active from Pliocene, or possibly from Latest Miocene, to Lower Pleistocene times (Caputo, 1990). In figure 2, are shown the major faults active during this deformational event. Large positive and negative signs show the vertical movements affecting the major fault-bounded blocks.

From a structural point of view, the importance of this tectonic phase is to generate the NW-SE trending Larissa Basin that still dominates the morphology of this area. The present Larissa Plain more or less coincides with this major tectonic structure.

The palaeogeography of the area, as deduced from sedimentological and stratigraphic evidences, is characterised by prevailing lacustrine conditions. According to the variably subsiding sectors and to the climate-related water supply, a large lake, with a probable maximum depth of several tens of meters, extended all over the area. The persistence of marshy or lacustrine conditions at least until the Villafranchian, suggests that no clear or permanent drainage pattern has crossed the Larissa Basin yet (fig. 3).

At the end of the Villafranchian, the Pinios River began to form its delta along the Aegean coast (Faugères, 1977). This event is certainly related to the definitive incision of the Tembi Valley across the Olympos-Ossa mountains that allows a permanent and consistent evacuation of water from the Thessalian Lake. Consequently, the Pliocene Larissa Basin began to empty and a differentiated drainage system began to form.

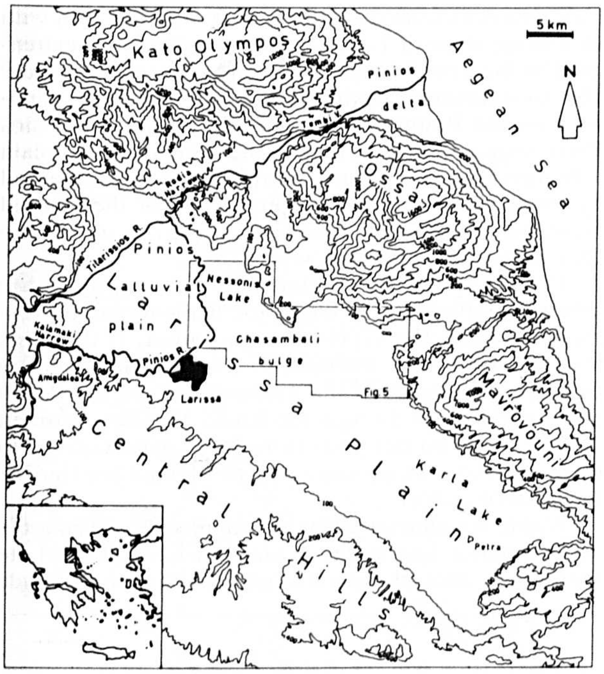

Fig. 1. - **Topographic map of the Larissa Plain (eastern Thessaly).** The major morphological and geographical features are shown. Contour lines every 200 m, plus the 100 m contour.

Fig. 1. - ***Carte topographique de la plaine de Larissa (Thessalie orientale) représentant les principaux éléments morphologiques et géographiques.*** *Equidistance des isohypses : 200 m; l'isohypse 100 m est figuré en complément.*

III. MIDDLE PLEISTOCENE-HOLOCENE TECTONIC EVOLUTION

After a period of geodynamic stability, a new tectonic regime affects the area. It is extensional as the former one but characterised by a N-S to NNE-SSW stretching direction (Caputo, 1990). This tectonic phase started during Middle-Late Pleistocene and is still active nowadays as inferred from the recent and historical seismic activity in the broader region such as the 1954 Sophades earthquake (Papastamatiou & Mouyaris, 1986), the 1957 Velestino earthquake (Papazachos *et al.*, 1982) and the 1980 Volos earthquake (Papazachos *et al.*, 1983).

In 1941, within the study area, an earthquake of the VII-VIII degree of the Mercalli scale was felt (Galanopoulos, 1950; Ambraseys & Jackson, 1990). Although Galanopoulos (1950) tentatively located the epicenter several kilometers NNE from Larissa near the limit between the plain and the mountains, it is not located precisely. Due to the war, no field survey has been carried out immediately after the earthquake in order to look for any ground rupture caused by faulting and thus define the fault(s) activated during the seismic event.

This tectonic phase is very important for the structural evolution of Thessaly and particularly of the northern Larissa Plain. According to the new geodynamic conditions affecting the area, a new system of normal faults, mainly trending E-W to ESE-WNW, forms (fig. 4). Although, most of these faults cut across or ignore the older NW-SE trending ones, it is obvious that the latter played an important role during the nucleation of the new structures. Nonetheless, some of the Pliocene normal faults were reactivated but with an oblique sense of movement (Caputo, 1992). In figure 4 are shown the structures formed and/or activated during this tectonic phase; positive and negative signs indicate vertical movements as in figure 2.

Due to the new tectonic regime, a new depocentre appears in the northern sector of the older Larissa Basin. Exactly then the Tyrnavos Basin assumes its identity. It is not clear when the main palaeogeographic domains and morphological features of the Larissa Plain were formed. But according to the slip rates estimated for some of the faults (Tyrnavos Fault, Caputo, 1993a ; Rodia Fault, Caputo, 1992) and reasonably assuming similar ones for the other major faults, as suggested by our morphotectonic survey, we presume that the Tyrnavos Basin was tectonically well-defined as an individual structure independent from the older Larissa Basin only from Late Pleistocene onwards.

From a physiographic point of view, the inherited topography and the new tectonically uplifting blocks define the basin all around. Only East of Larissa is the Tyrnavos Basin morphologically 'open' and in direct communication with the southern Larissa Plain, the tectonically abandoned sector of the older Larissa Basin.

The Tyrnavos Basin is bounded to the North and South by few major faults such as the Rodia and Gyrtoni faults and the Tyrnavos and Larissa faults, respectively (fig. 4). East of Larissa and coinciding with the morphologically open sector, a set of minor normal faults parallel to and synthetic with the Larissa Fault exists (figs. 4 and 5c). They form a sort of northwards down-stepping structure faced to the North by the antithetic Gyrtoni Fault. The key role played by this set of faults for the geographical and morphological evolution of the whole Larissa Plain during Late Pleistocene-Holocene times will be discussed and emphasised below.

PREHISTORIC AND HISTORICAL MORPHOLOGICAL EVOLUTION

As a consequence of its geodynamic evolution and due to the overlapping effects of tectonics, the Larissa Plain may be divided in three main distinct physiographic sectors (fig. 1) : the Pinios alluvial plain, the Chasambali 'bulge', and the Karla Lake. The first sector more or less coincides with the Tyrnavos Basin.

Results in this chapter are based on our personal geographical and morphotectonic survey joined with the analysis of a 1:75,000 map, prepared in 1905-1907, and

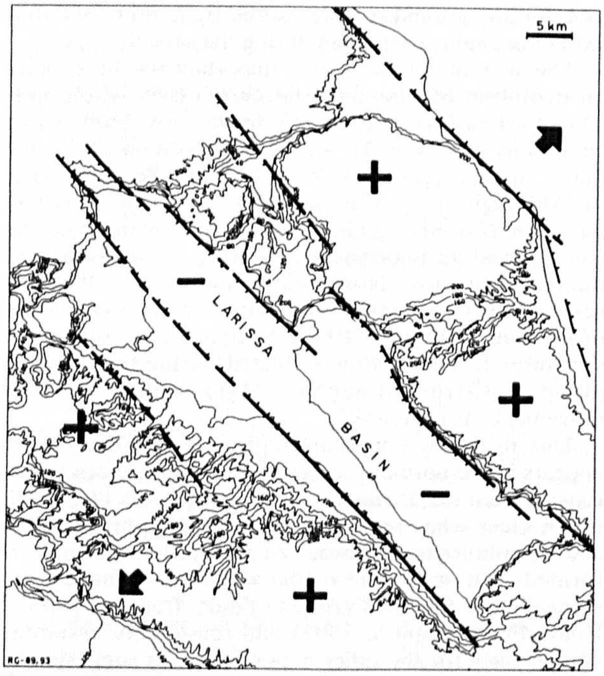

Fig. 2. - **Simplified structural map of eastern Thessaly showing the major normal faults activated during the Pliocene-Lower Pleistocene extensional regime which generated the NW-SE trending Larissa Basin.** Contour lines every 20 m, from 0 to 200 m a.s.l. Barbs indicate the downthrown block, and arrows the regional direction of crustal extension. Plus and minus signs show areas with uplift or subsidence, respectively.

Fig. 2. - ***Carte structurale simplifiée de la Thessalie orientale montrant les principales failles normales activées pendant la phase d'extension du Pliocène-Pléistocène inférieur;*** *elles ont créé le bassin de Larissa d'orientation NW-SE. Equidistance des isohypses : 20 m, de 0 à 200 m au dessus du niveau de la mer. Les barbules localisent les blocs abaissés; les flèches, la direction régionale de l'extension. Les signes + et - montrent respectivement les secteurs de surrection et de subsidence.*

of the maps of the 1970s at the scale 1:50,000. The first maps give back the hydrographic details prior to the hydraulic exploitation and management of this century, while the latter return the present-day topography with the 'anthropically' modified drainage system.

In order to better understand the hydrographic evolution of the Chasambali bulge, the Nessonis Lake and a key sector of the Pinios River, we had the opportunity to use a 1:5,000 topographic maps, established in the early 1960s by the Larissa Rural Engineers in order to carry out the hydraulic exploitation of the Eastern plain (fig. 5a). Because such operations require a very high altimetrical rigorousness, the contour lines are at every one meter and it permitted us a very detailed morphological analysis of this important area (fig. 5b).

a) The Pinios alluvial plain

Along a distance of 14 km between the Kalamaki Narrow and the town of Larissa (fig. 1), the alluvial plain descends from the altitude of 90 to 70 m, thus with an average slope of $1.42.10^{-3}$. The actual plain is entrenched by the river for about 10 m and consequently, older alluvial sediments consisting of clastic materials, deposited by the Pinios River itself and by the Titarissios River, crop out. East of Larissa, the Pinios alluvial plain is limited by a very smooth morphological ridge formed by the gentle Northeast dipping slope of the Central Hills (or Revenia) foothills merging with the Chasambali bulge (see below).

Then, apparently deviated by this topographic salient, the river turns to the North, while further downstream, due to the Gyrtoni escarpment, it deviates towards Northwest. Eventually, a few hundred meters from the confluence of the Titarissios River, the Pinios gets off the plain through the Rodia Narrow. At about 20 km, the plain descends from 70 m, near Larissa, to 60 m, with an average slope of 5.10^{-4} (about one third of the western sector).

Within the alluvial plain, we can grossly consider the 70 m contour line as the geological limit of the Late Pleistocene alluvial deposits. Indeed, above this altitude

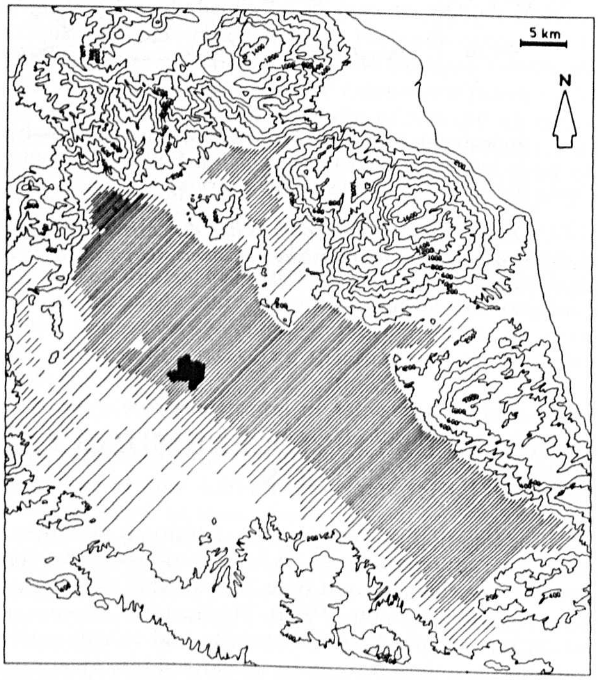

Fig. 3. - **Tentative palaeogeographical reconstruction of eastern Thessaly during the end of the Villafranchian.** According to the more or less subsiding sectors and to the climate-related water supply, the Thessalian Lake, with a probably maximum depth of several tens of meters, extended all over the area. Hatching is tentatively proportional to the depth of the lake.

Fig. 3 - ***Hypothèse de reconstruction paléogéographique de la Thessalie jusqu'au Villafranchien.*** *Le lac thessalien s'étendait sur l'ensemble de la zone; sa profondeur maximale, probablement voisine de plusieurs dizaines de mètres, dépendait de l'intensité locale de la subsidence et de l'alimentation en eau sous contrôle climatique. Les hachures sont proportionnelles à la profondeur probable du lac.*

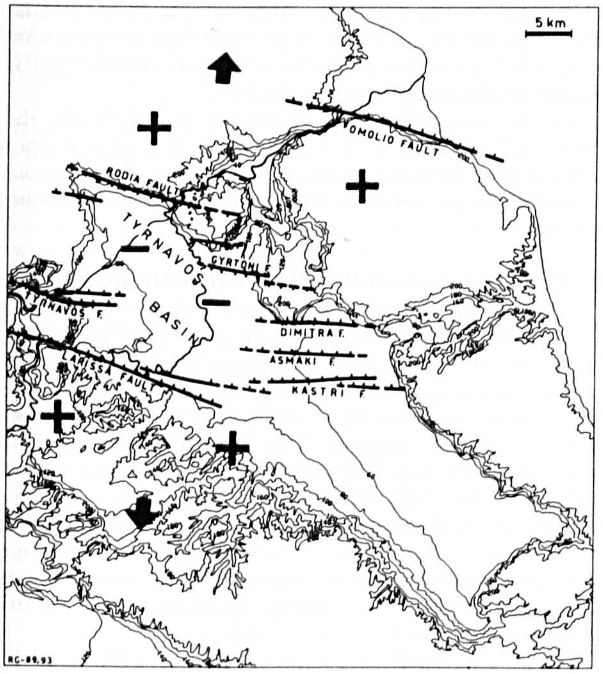

Fig. 4. - **Structural map of eastern Thessaly showing the major normal faults activated during the Middle Pleistocene-Holocene extensional regime which generated the E-W trending Tyrnavos Basin**. Symbols as in Fig. 2.

Fig. 4 - ***Carte structurale de la Thessalie orientale montrant les principales failles normales activées pendant la phase d'extension datée Pléistocène moyen-Holocène.*** *Le régime d'extension a généré l'orientation E-W du bassin de Tyrnavos. Les symboles sont ceux de la Fig. 2.*

they are at the surface corresponding to a large sector of the so called 'Niederterrasse' proposed by Schneider (1968) and more or less coinciding with the 'Agia Sophia alluvium' of Demitrack (1986).

Not localised exactly by Runnels (1988) but estimated at an altitude of +15 to +40 m from the Kalamaki Narrow, West of Larissa the Pleistocene alluvial nappe built up by the Pinios River is visible for a thickness of about 6.5 m at the exit of the narrow where it covers the Pliocene bedrock (Demitrack, 1986).

Close to the Kalamaki Narrow, on the river bank of the present Pinios, upstream from Larissa, at a depth of 4 to 9 m from the local sequence top, some lithic artifacts of the Levallois-Mousterian type as well as some animal bones have been found (Runnels, 1988). The former are the typical product of the Middle to Upper Palaeolithic Thessalian industry (50,000-32,000 years BP). At a depth of 9 m, the findings are undoubtedly the in situ remnants of a prehistoric flint-working atelier and not the result of materials reworked by the currents (Runnels, 1988; French, 1990).

Near the village of Amigdalea, at a depth of 8 m, at the base of the Niederterrasse below the Agia Sophia alluvium, two samples of Unio shells have been collected and dated with the ^{14}C method (Demitrack, 1986). The ages obtained are 38,000 ±1,500 and 42,000 ±3,500 years BP. On the other hand, the base of the soil developed at the top of this alluvial sequence has been dated with the U/Th method and gives an age of 27,000 ± 8,000 years BP. Moreover, according to several find spots discovered in the area, the prehistorians independently suggest the existence of temporary or stable habitats between 55,000 and 30,000 years BP (French, 1990). Van Andel *et al.* (1990) estimate that the Agia Sophia alluvium, the most extended unit of the Niederterrasse, was deposited during the last cold period (ca 40,000-27,000 years BP) and sealed up by a very well-developed palaeosoil.

In contrast to the western sector of the plain standing several meters higher than the river bed, to the East, the nearby Holocene alluvial plain is in morphological continuity and slowly varies from 65 down to 63 m, close to the Gyrtoni terrace (fig. 5a). Indeed, this sector of the Tyrnavos Basin suffered additional subsidence and subsequent sedimentation.

During Early Holocene, two major alluvial events have been recognised, both followed by a long period of pedogenesis. The older deposits form the 2 m thick 'Mikrolithos alluvium' (Demitrack, 1986) with a texture finer than the Agia Sophia alluvium. On top is a non calcareous brown soil and further sediments. The upper temporal limit is fixed by the ^{14}C dating of a Unio shell (5,900 ± 45 years BP) and by a Late Neolithic settlement (6,000-5,000 years BP). But deposition had probably ceased much earlier because the settlement was established after an advanced pedogenesis. A latest Pleistocene-Early Holocene (14,000-10,000 years BP) age of deposition has thus been suggested (Demitrack, 1986).

The second major Holocene sedimentary event, the 'Gyrtoni alluvium', is 2.5 m thick and is well exposed North of Larissa. The use of archaeological criteria, similar to those above, permits the estimation of a Middle Neolithic (7,000-6,000 years BP) interval of deposition (Demitrack, 1986).

The recent Pinios river bed slightly downcuts the early Holocene Mikrolithos and Gyrtoni alluvia that form a 'lower terrace' younger than the Niederterrasse of Schneider (1968). Subsequently, sedimentation resumes in a restricted Pinios valley and in the area of the actually called Nessonis Lake. On the basis of pedological criteria, Late Holocene deposits have been recognised in the active flood plain. They lie in disconformity over a truncated sequence of the lower terrace.

The present-day flooding area is constrained by the artificial damming and has been reduced to 7-8 km^2 between Koulouri and the Gyrtoni terrace (fig. 5). Prior to damming, which was initiated at the end of the 19th century, the flood plain extended to the Nessonis Lake according to modern scholars (Helly *et al.*, in press). There the perfectly flat-lying topography, with an altitude of 61 to 62 m, suggests a smoothing that is typical of repeated flooding and progressive filling up of the lowest sectors.

From the detailed topographic survey of the early 1960s maps, near Koulouri, has been set out an old segment of the Pinios River, called Prenia (fig. 5a). In the 1905-1907 topographic maps, near Kalyvia and Phasoula it is possible to observe strings of small ponds and, departing from the old Prenia, a several km long palaeochannel corresponding to an abandoned meandering segment of the Pinios River (fig. 5b). A similar picture is recognisable in the 1981 aerial photographs at the scale ca 1:33,000 kindly provided by the Hellenic Military Geographical Service. On the contrary, none of this is shown in the 1970s version maps.

In July 1990, a 1.5 m deep artificial trench was excavated near Phasoula, between the foothills and the palaeochannel. Along the trench, light brown shales with frequent fragments of reed crop out. A channel filled up by fine-grained, organic-rich sediments with intraformational clasts and fragments of common ceramic has been observed. This channel is invisible at the surface because it is masked by 60 cm of colluvial materials coming from the hills close by. Radiocarbon dating of a tree branch collected at the base of the organic-rich layer gives an age of 655 ±250 years BP which corresponds to 890-1805 AD, after dendrochronological correction. Though historical, this channel is obviously older than the superficial one described above. Consequently, the area of the Nessonis Lake was not only the flooding plain of the Pinios River but it could be also considered as a sector used by the river for free meandering.

The natural trapping of the river course close to the eastern reliefs and against the Northern morphotectonic escarpment of Gyrtoni, and the picture of a locally, very mobile recent hydrography, support the idea of a zone of higher local subsidence and consequent river attraction. It also indicates very recent tectonic movements in this area that occurred in the last few thousand years or even centuries and are possibly related to reactivations of the Gyrtoni and Dimitra Faults.

The dynamic engine for the drainage of all the plain was the Pinios River. During flood periods, some travellers of the 18th-19th century observed that the river flowed towards the Nessonis and Karla Lakes (see Helly *et al.*, in press, for a more detailed discussion of the palaeogeography of the area in historic times). From the maps of 1905-1907 a similar hydrological scenario can still be inferred (Sivignon, 1975).

At the beginning of the century, near Koulouri, a small dike constrained, to the North, the old Prenia which was later cut off as a peduncle by the 1936-1940 damming (fig. 5b). The first management caused the abandoning of the Nessonis palaeochannel and permitted the agricultural exploitation of the Nessonis area as testified by the Turkish domain (tchiflik) of Paliomylos. The second dike definitely retained the overflows on the right river bank. It induced concentrated sedimentation and the raising of local river embankments. This phenomenon anthropically accelerated, progressively increases downstream and is shown in four topographic sections (fig. 6). At the section of Larissa, the main Holocene flood plain is about 2 km wide. The present-day Pinios River has a sinuosity rate of 2.05. Within the actual artificial embankments, the presence of ox-bow lakes, at different filling-up stages confirms the persisting high lateral mobility. The solid transport downstream of Larissa has probably a limited volume and is mainly composed of sandy materials.

On the contrary, a few kilometers to the North, the Titarissios behaves as a braided river due to a steeper slope and to different hydraulic conditions. It is characterised by larger volumes of solid transport and by coarser materials.

b) The Chasambali Bulge, a transient landscape.

The sector of the plain in between the town of Larissa and the Patoma Hill (437 m) is the Chasambali bulge. It stands out from the Pinios Plain to the West, and the Karla Lake to the Southeast, due to a difference in elevation manifest only in the 1:5,000 maps and not in the 1:50,000 version. This area hydrographically separates the Pinios River and the Nessonis Lake on one side, and the Eleftheri Basin on the other (fig. 5b). During the last centuries and probably a few thousand years prior to the artificial damming and the drainage management, the Eleftheri Basin could be considered as a by-pass zone for the Pinios flooding events before going into the southern Karla Lake.

The Chasambali bulge stands at an altitude of 63-66 m, North of Skouphos (fig. 5a), and continues eastward as a sort of promontory (60-61 m), overhanging by 7-8 m the adjacent lowest sectors of the Eleftheri Basin. Although the magnitude of the altimetrical difference within the Chasambali bulge is just 3-4 m, a careful analysis points out the morphological complexity of the area.

According to the only 3 m thick Holocene deposits on the Chasambali bulge, Demitrack (1986) infers that relative subsidence was reduced since latest Pleistocene. Moreover, the halt of further sedimentation after the Bronze Age, near the Patoma Hill, is testified by an archaeological find spot of that age found at the surface. It implies that, in historical times, this sector of the Larissa Plain has not suffered the continuous Pinios floods or the Nessonis overflows. This is a direct consequence of the Asmaki River formation, a temporary stream that deeply entrenches the relief. Until the last century, this river worked as an overflow convector from the northern drainage system (Tyrnavos Basin) towards the southern one (Karla Lake). In between, the Eleftheri Basin, once filled up by the overflow water or by alluvial deposits, operated as a simple by-pass zone.

With the available geographical and palaeogeographical data we may tentatively describe the recent hydrodynamic evolution of the area during overflow periods. While the above mentioned palaeochannel was active, carrying water towards the Nessonis area, a temporary lake extended at first near the Gyrtoni escarpment (61 m), and then when the water was at about 62-63 m (before the entrenching) it poured off into the Eleftheri Basin across the Chasambali area via Asmaki River. Thus, the northern branch of the Asmaki was temporary working as a Nessonis Lake outlet, while the western branch was a possible direct defluent of the Prenia, a meander of the Pinios River. A fossilised

Fig. 5. - **Topographic (a), physiographic (b) and tectonic (c) maps of the eastern sector of the Tyrnavos Basin.** (a) has been obtained from the 1:5,000 scale maps of the Larissa Rural Engineers. In (b) are shown the main physiographic features (Nessonis Lake, Chasambali bulge and Eleftheri Basin) as obtained from map (a), from aerial photographs at the scale c.a. 1:33,000 and the 1:75,000 scale maps. The contour lines from 48 to 54 m show a telescoping necking of the topographic low, in correspondence with the faults, and clearly delineate the Eleftheri Basin. The artificial embankments around the Pinios (thick lines), abandoned meanders within the Nessonis Lake (dashed lines) and sections location (A to D) are also represented. (c) Faults are shown with thick lines; barbs indicate the downthrown block.

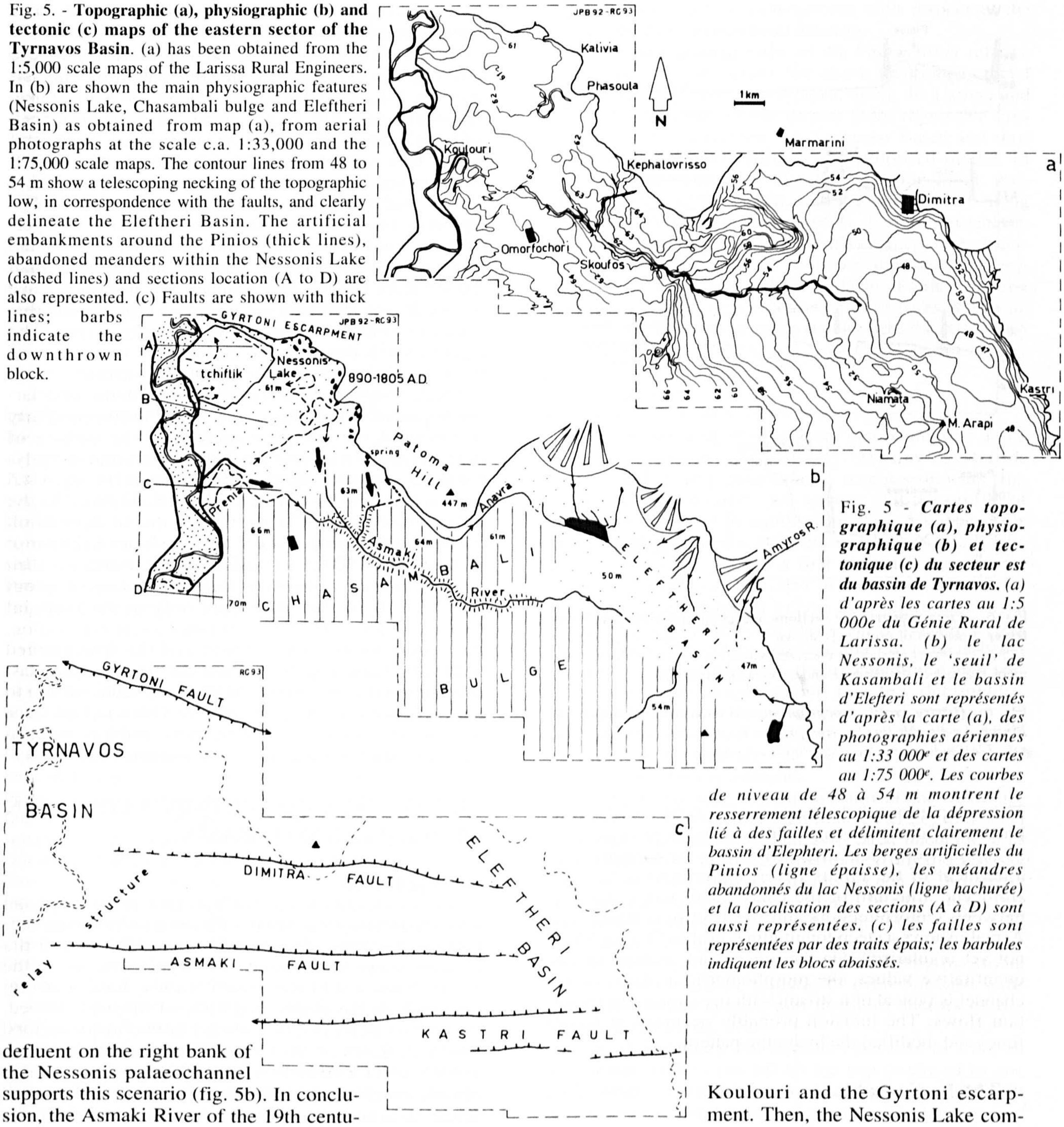

Fig. 5 - ***Cartes topographique (a), physiographique (b) et tectonique (c) du secteur est du bassin de Tyrnavos.*** *(a) d'après les cartes au 1:5 000e du Génie Rural de Larissa. (b) le lac Nessonis, le 'seuil' de Kasambali et le bassin d'Elefteri sont représentés d'après la carte (a), des photographies aériennes au 1:33 000e et des cartes au 1:75 000e. Les courbes de niveau de 48 à 54 m montrent le resserrement télescopique de la dépression lié à des failles et délimitent clairement le bassin d'Elephteri. Les berges artificielles du Pinios (ligne épaisse), les méandres abandonnés du lac Nessonis (ligne hachurée) et la localisation des sections (A à D) sont aussi représentées. (c) les failles sont représentées par des traits épais; les barbules indiquent les blocs abaissés.*

defluent on the right bank of the Nessonis palaeochannel supports this scenario (fig. 5b). In conclusion, the Asmaki River of the 19th century and earlier, transferred a part of the Pinios overflows (i.e. the high-stands of the Nessonis Lake) into the Karla Lake. Moreover, at the foot of the Patoma Hill, a second channel, the Anavra, acted as complementary outlet. An important karstic water supply, sufficient to justify the existence of a mill, also contributed to the total flow.

This hydrodynamic pattern changed with the build up of the first dike at the end of the 19th century, between Koulouri and the Gyrtoni escarpment. Then, the Nessonis Lake completely dried up. The consequent surplus of water flow and solid transport upstream of the dam, forced the western branch of the Asmaki River as the preferential water escape for the Pinios overflows. Neglecting any climatic change and supposing a constant annual water supply, the disruption of the natural equilibrium certainly magnified the outpouring episodes towards the Karla Lake and the related deepening of the Asmaki River.

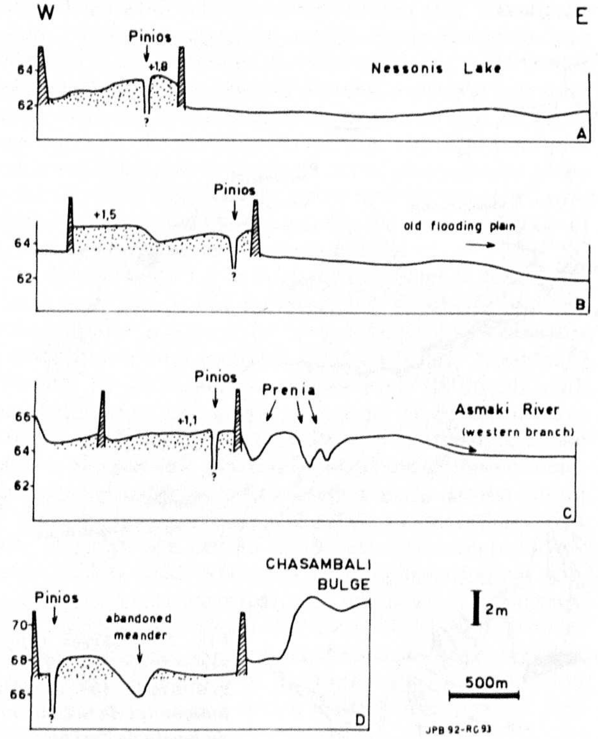

Fig. 6. - **Four topographic sections across the present-day Pinios River**. Location of profiles is shown in fig. 5b. Vertical exaggeration 125:1. The exact altitude of the river bottom is not available from the maps because of the variable and permanent water fill.

Fig. 6 - ***Quatre profils topographiques à travers le lit majeur du Pinios.*** *La fig. 5b localise ces profils. Exagération verticale : 125 fois. L'altitude exacte du lit du Pinios est estimée.*

The completion of the dam, during 1936-1940, up to Larissa definitely interrupted the diversion process.

In this view, the Asmaki River may be considered as a defluent of the Pinios River, entrenched in the soft Holocene alluvium of the Chasambali bulge. Indeed, between Omorphochori and the Eleftheri Basin, the Asmaki shows a steep longitudinal profile (7 m in 5 km) not yet regularised. On the other hand, without giving quantitative values, the morphometric analysis of the channel is typical of a stream with occasional but important flows. The incision probably occurred in recent times and modified the hydraulic pattern.

c) The Karla Lake.

The third physiographic environment of the Larissa Plain, the Karla Lake, covers its southern sector extending for 35 km long at the foothills of the Mavrovouni range. It is a perfect flat-lying surface with an altitude confined between 46 and 48 m. During Late Pleistocene and Holocene, the numerous streams flowing from the Central Hills have eroded the NW-SE trending morphological step and induced a diffuse alluvial deposition thus masking the evidence of the Pliocene-Lower Pleistocene tectonics.

As mentioned above, only in this sector of the Larissa Plain lacustrine or marshy conditions persist after the Villafranchian, thus creating the Karla Lake, whose remnants still visible in the old maps have been artificially dried up. Evidence of an older, larger and deeper lake are confirmed by beach deposits found at 51 m high on the southwestern slope of the Petra Hill, a sort of inselberg at the center of the lake (fig. 1). The deposits consist of sandy materials originating in a periglacial environment and contain fragments of shells. Radiochronological dating provides an age older than 30,000 years BP and thus indicate that the Karla Lake and the Pinios alluvial plain were two separate and distinct environments contemporaneously active. The palaeo-beach deposits are covered by one meter of Holocene shales forming the actual field surface.

Further arguments supporting the existence of a larger nappe of water during the Late Pleistocene-Early Holocene is the complete missing at the surface of beach deposits younger than 30,000 years and the palynological analysis carried out by Bottema (1979). A 4.5 m long carrot drilled near Kato Kalamaki in the Mavrovouni foot hills shows a reduced deposition during the Holocene. Indeed, only the base of the carrot is older than 6,500 years, and *Castanea, Platanus, Olea* and the cereals, appearing in northern Greece about 4,000-3,900 BP, are described only in the surficial layers. Erosion could not be claimed as an explanation, due to the humid environment and the fine-grained materials. According to Bottema (1979), during the last few thousand years deposition has been reduced, due to a progressive drying up of the lake, characterised since prehistoric times by alternating high- and low-stand of the water level certainly related to climatic conditions.

THE TECTO-SEDIMENTARY EVOLUTION OF THE TYRNAVOS BASIN

a) Hypotheses

As mentioned above, the Tyrnavos Basin has been generated during the Middle Pleistocene-Holocene tectonic phase. The new geodynamic conditions and the northern water flow towards the Aegean Sea, across the Rodia Narrow and the Tembi Valley, have a strong influence on the palaeogeography of the area. Indeed, the Larissa Plain is differentiated in two major sectors. The first, South of the Larissa Fault, is inherited from the Pliocene-Lower Pleistocene phase and remains almost undeformed. The second sector, the Tyrnavos Basin, generates, and more or less coincides with, the alluvial plain of the Pinios and Titarissios Rivers. It was strongly subsiding and formed a perfect sedimentary trap. In the following section, we will focus our attention on this area and present a model for its Middle-Late Pleistocene to Holocene evolution.

A few key arguments describing the basic physical phenomena occurring in the area are necessary to introduce the model we propose and its cyclic evolution.

The sedimentary budget

Relative to the basin area, the output of sediments is exclusively at the charge of the Pinios River via Rodia Narrow. Concerning the sedimentary input, most of the material is transported by the same river across the Kalamaki Narrow. Lower amounts come from the Titarissios River and from less important secondary streams which are a few kilometers long. Both major rivers as well as most of the minor ones go into the Tyrnavos Basin cutting across some of the faults bordering the structural low (i.e. Pinios River across the Larissa Fault; Titarissios River across the Tyrnavos Fault; several minor streams across the Rodia Fault). In particular, even the sedimentary output of the basin coincides with one of the major normal faults, the Rodia Fault.

The hydrographic base level

It should be stressed that, within the study area, the base level of the Pinios River and that of the Titarissios River because of the location of its confluence, directly depends on the altitude of the Rodia Narrow entrance. Although indirectly, the Tembi Valley too can produce a variation of the base level. The altitude of both the Rodia Narrow and the Tembi Valley, relative to the equilibrium profile of the hydrographic system, can be strongly affected by tectonic activity. In particular, the Pinios River is very sensitive to any movement occurring along the Rodia Fault (see below).

Subsidence

Because of the geometric and kinematic characteristics of the fault system bordering and affecting the area, any tectonic activity along these structures generates subsidence in part of or in all the Tyrnavos Basin. This fault-related phenomenon is the consequence of repeated, 'morphogenic earthquakes', that is seismic events being able to generate a surficial deformation along the fault they activate (Caputo, 1993b). Consequently, the seismically generated subsidence is instantaneous and causes localised ruptures of the topographic surface and thus of the equilibrium profiles of the rivers. In particular, any seismic activity along the Rodia Fault causes a segmentation of the Pinios River profile upstream and downstream with respect to the fault. Above all, the rise of the base level for the upstream segment of the equilibrium profile is a key point in the present model.

Both the damming effects of the Pinios River due to the Rodia Fault and the general subsidence of the entire Tyrnavos Basin seismically related to the whole fault system, temporarily halt or slow down the water flow, thus causing an overall reduction of the river energy and eventually the deposition of surplus material.

Erosion

Whatever the remote cause, linear regressive erosion is normally associated to a lowering of the local base level. The lowering may be due to eustatic or tectonic phenomena and both at a large and small scale such as regional-wide, post-orogenic uplift and fault-related dislocation, respectively. In the latter case, only when the downthrown block is downstream with respect to the fault, can regressive erosion develop.

If we analyse the profile of the Pinios River relative to the faults it cuts across, the above mentioned crucial conditions only exist in two cases: along the Larissa and the Omolio Faults. In the former case, regressive erosion is produced outside the Tyrnavos Basin and thus has a negligible influence on the proposed model. In contrast, any movement along the Omolio Fault, produces incision in the Tembi Valley and, with time, along the Rodia Narrow via Gonnoi plain. It is not possible to give quantitative indications concerning the rate of erosion, but the characteristic of the substratum under erosion and the distance of the Omolio Fault from the Tyrnavos Basin suggest that this phenomenon has no immediate cause-effect relationships with the study area (see below).

b) The model

The profile of the Pinios River can be divided into a series of segments alternatively crossing crystalline bedrock and poorly consolidated, recent sediments (fig. 7). As initial conditions, we assume that the profile of the Pinios River is in equilibrium (fig. 7a). The cycle begins when the area is affected by a morphogenic seismic activity (fig. 7b). As a first approach, we assume that all the faults are activated in a short time span (for example a few hundred years) thus characterising a local and temporal tectonic paroxysm (Pirazzoli, 1986). According to the dimensions and the mechanical behaviour of the activated faults, the maximum possible vertical co-seismic displacement is a few decimeters. Nevertheless, due to the extreme sensitivity of rivers to vertical movements, this tectonic activity produces a partition of the area (i.e. of the profile) into several blocks with different altitudes.

As a consequence, the equilibrium of the hydrographic system vanishes and each fault generates new local hydrodynamic conditions and associated phenomena as described above. Indeed, upstream from the Larissa Fault, regressive erosion begins to deepen the Kalamaki Narrow and the same phenomenon locally occurs for each of the synthetic minor faults (fig. 7c).

In contrast, subsidence and damming of the river flow by the Gyrtoni Fault, and especially by the Rodia Fault, generate diffuse alluvial or even brackish sedimentation in the central and northern sectors of the Tyrnavos Basin (fig. 7c).

This sedimentary environment persists as long as sedimentation does not fill up the gap produced by the fault offset. When this occurs, widespread sedimentation halts or evenly stops and the alluvial plain reaches temporarily stable conditions (fig. 7d).

During this stage, the Tyrnavos Basin corresponds to a by-pass zone for the Pinios River, with no major input/output of sediments, and the sedimentary balance is in equilibrium. While the river works to completely restore the equilibrium profile it had prior to tectonics, a diffuse pedogenesis occurs on top of the abandoned alluvial plain.

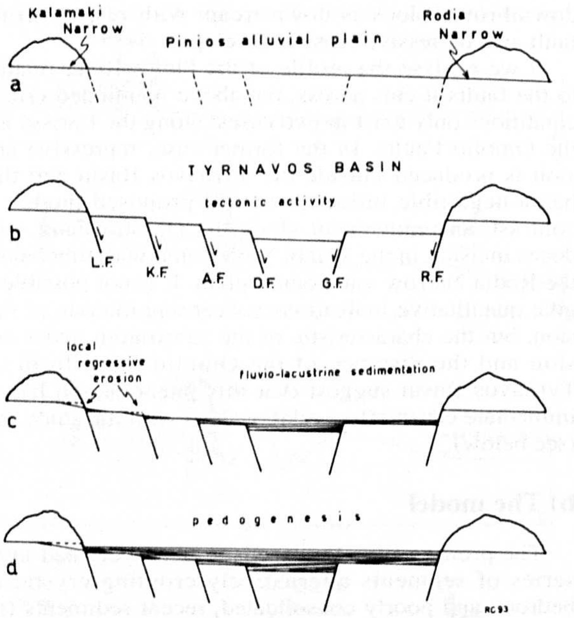

Fig. 7. - Four steps cartoon showing the tecto-sedimentary cyclic evolution of the Tyrnavos Basin. a) Initial stable conditions. b) Tectonic paroxysm which activates the faults of the Tyrnavos Basin. L.F. = Larissa Fault; K.F. = Kastri Fault; A.F. = Asmaki Fault; D.F. = Dimitra Fault; R.F. = Rodia Fault; G.F. = Gyrtoni Fault. c) Sedimentation induced by the damming effect of the Gyrtoni and Rodia Faults. Regressive erosion upstream of the southern set of synthetic faults. d) Filling up of the Tyrnavos Basin and restore of initial conditions, widespread pedogenesis on the abandoned alluvial plain. See text for further explanations.

Fig. 7 - ***Représentation schématique des quatre phases du modèle tecto-sédimentaire cyclique du bassin de Tyrnavos.*** *a) Conditions de stabilité initiales. b) Paroxysme tectonique qui active les failles du bassin de Tyrnavos. R.F.= faille de Rodia; G.F.= faille de Gyrtoni; D.F.= faille de Dimitra; K.F.= faille de Kastri; A.F.= faille de l'Asmaki; L.F.= faille de Larissa. c) Sédimentation induite par l'effet de barrage des failles de Gyrtoni et de Rodia. Erosion régressive à l'amont de l'ensemble méridional de failles synthétiques. d) Remplissage du bassin de Tyrnavos et restauration des conditions initiales, pédogenèse généralisée à la surface de la plaine abandonnée. Voir le texte pour des explications complémentaires.*

Eventually, the tecto-sedimentary cycle is closed up by returning to its initial conditions, ready to start again as a consequence of a new tectonic paroxysm.

c) Secondary factors

In order to better describe the model we made some oversimplifications that we are now going to analyse and discuss in some detail.

First, the contemporaneity or the short time span for the morphogenic seismic activity along all the faults may not always be the case. An important consequence is that the model has not simple cyclicity, but is the sum of several basic cycles with different periods, amplitudes, phases and overlapping zones of influence. For example, the activation of each of the southern faults starts local upstream erosional cycles with variable velocity and magnitude according to the initial seismic offset. In the meantime, local depositional cycles occur downstream of the same faults. The entrenching phenomenon and the thickness of the deposited materials is proportional to the magnitude of the offset. These subcycles practically end off their effects when erosion of the upstream segment and the contemporaneous filling up of the downstream segment restore a local equilibrium profile. On the contrary, the activation of the Rodia Fault starts an important depositional cycle all over the Tyrnavos Basin, maximised in the northern sector of the plain. Activation of the Gyrtoni Fault produces the same phenomenon but over a more restricted area. Also in this case, the thickness of the consequent alluvial deposits depends on the magnitude of the offset and particularly of the damming effects. They will operate until a complete filling eventually ends off the cycle.

The second simplified hypothesis concerns the subsidence that is not exclusively due to morphogenic seismicity. Sudden subsidence initiating a depositional cycle as described is certainly related to tectonics. But subsidence can also be generated by the compaction of the underlying sediments during diagenesis and loading. Indeed, the northern sector of the Larissa Basin, that partly overlaps the Tyrnavos Basin, is a center of deposition since Pliocene times where sediments may locally reach more than 500 m of thickness (Doutsos, 1980). On a geological time-scale, compaction may be an important factor for generating general subsidence in the Tyrnavos Basin as a whole or locally differentiated according to the underlying variable deposit thickness. This phenomenon may persist even some million years after deposition has ceased (e.g. Doglioni & Goldhammer, 1988). Consequently, during the considered time-span (Middle Pleistocene-Holocene), compaction-induced subsidence affected the area as a slow continuous process spasmodically overlapped by the seismically-related subsidence.

The alluvial sedimentation occurred in the area during Middle Pleistocene-Holocene times, generated a load on top of the underlying Pliocene-Lower Pleistocene deposits. These later lithologies consist of prevailing shales and marls. Accordingly, the estimation of the amount of subsidence due to compaction varies not only as a function of the thickness and consequent load of the new surficial overlying sediments, but also as a function of the thickness of the underlying deposits. For example, according to the curves of decompaction prepared by Perrier & Quiblier (1974), the load generated by 20 m (or 50 m) of new deposits can induce a compaction of 7 m (13 m), 8 m (17 m), 10 m (21 m) or 15 m (26 m) in 100 m, 200 m, 300 m or 500 m of underlying sediments, respectively. The importance of these values does not lie in their absolute magnitude but in the difference of subsidence induced by a load of uniform thickness over a variable thickness of underlying sediments which is undetectable at the surface.

Although the compaction-induced subsidence is not a negligible contribution, it cannot account for the total subsidence occurred in Middle Pleistocene-Holocene times. Nevertheless, in the Tyrnavos Basin, the NW-SE trending shape of the underlying northern sector of the Pliocene Larissa Basin is still clearly visible (fig. 1).

Another factor disrupting the simple cyclicity of the model is the lowering of the Rodia Narrow due to erosion. As we said, any tectonic activity along the Omolio Fault will produce regressive erosion upstream from it. To entrench the bedrock is hard and the way to the Tyrnavos Basin is long. Present-day knowledge does not permit to better analyse the phenomenon and particularly not to quantify it, nor does it permit to define the time delay between a faulting event and the lowering of the Rodia entrance. But tens of meters of cumulative dislocation along the Omolio Fault during Late Quaternary will undoubtedly produce their effects within the Pinios alluvial plain. This could account for a progressive and absolute lowering of the equilibrium profile of the Pinios River during the last 30,000 years and explain the formation of a three-step terrace system: the Niederterrasse, the Holocene terrace, and the actual river bed.

A further compliance to the proposed tecto-sedimentary model may be related to external factors such as climate and man. Although the importance of the anthropic factor in the destabilisation and manipulation of the landscape is still matter of discussion, it is well-accepted that it may not have occurred in all pre-Neolithic processes. Thus, there is no tenacious reason to claim for 'local economic and political conditions' for explaining the Middle Holocene and later sedimentary events (van Andel *et al.*, 1990) because this time span (10^3 years) is about two orders of magnitude less than the Tyrnavos Basin life time (10^5 years).

On the other hand, all the above described sedimentary phenomena are related to climatic conditions and particularly to the water supply given by the hydrographic basin. For example, phenomena like the alluviation of the Tyrnavos Basin and the formation of local swampy areas to the North, and the extension or reduction of the Karla Lake in the southern sector of the Larissa plain could have been strongly affected by climate.

The information concerning possible palaeohydrological fluctuations during historical times is provided by the testimony of classical authors and modern travellers, no geomorphic evidence having been documented so far within the study area. Full references, detailed description, and a deep discussion of a large amount of archaeological and historical data have been carried out in a separate and complementary paper (Helly *et al.*, in press) to which we refer the reader.

Different lakes have been named and described since three millennia. For example, Lake Boibe, located in the present Eleftheri Basin, was described by Homer and Hesiod (8th century B.C.) then by Theophrastus (4th century B.C.). The latter tells about the efforts of the Larissa people to control water diversion from the Pinios and related the cooling event, which occurred in this period, to the human influence on the hydrology of the area.

On the contrary, at the end of the Classical Ages and during the Hellenistic period, the Lake Boibe was probably located in the southern part of the plain, close to the sites of Pheres (the actual Velestino) and Armenion in the area of the modern Karla Lake. But Strabon, during the I century A.D., reports of the intermittent flooding of the area corresponding again to the Eleftheri Basin.

Later, Procope described the city of Petra-Diocletianoupolis as forming a peninsula within the Karla Lake (7th century A.D.). Accordingly, we may infer a maximum and minimum altitude of the water table at that time. Then, during the 18th-19th centuries A.D. and possibly earlier, as described by modern travellers, the Karla Lake probably reached its maximum area of extension in historical times. According to Teller (1880) and Sivignon (1975), the Asmaki River could flow between the Pinios and the Karla Lake alternatively in both directions. However, Leake (1835), Stählin (1924) and Philippson (1950) are right when proposing that, because of the lower level of the Karla Lake, the Asmaki was only fed by the floods of the Pinios River. Also according to Philippson (1950), the lake may have been in a relatively high-stand level from 1905 to 1927.

Inferring palaeohydrological evidence from this data which are discontinuous in time and space may be considered illusory and no synchronism with geomorphic events demonstrated on archaeological sites in Greece may be determined with confidence. Indeed, most of the recent scientists who worked in this area insisted on asynchronous anthropogenic factors of destabilisation in the absence of arguments for climate causality (Butzer, 1974; 1980; Bousquet & Péchoux, 1980; Davidson, 1980; Bousquet *et al.*, 1983; Genre, 1988; van Andel *et al.*, 1990), even if the climatic hypothesis was recently defended (Dufaure & Fouache, 1988; Bousquet, 1988). Nevertheless, three periods of large lacustrine area extension related to high-stands of the water level can be proposed for Eastern Thessaly and correspond to periods of wetness or flooding from the Pinios River and the small tributaries directly flowing into the basin. These periods are circa the 8th century B.C., the 7th century A.D. and the 18th-19th centuries A.D. (and possibly earlier). Similar chronology has been proposed by Magny & Richard (1992) for the lakes of the Jura Mountains and the French Western Alps. It is noteworthy to point out the fact that this timing is not contradictory with cool and wet periods which have been determined in western and central Europe during the Early Iron Age, the Early Middle Ages, and the Modern Times. They correspond to three periods of glacial progression in the Alps that have been called Goschenen I, Goschenen II, and Little Ice Age, respectively, by Swiss scientists (Mayr, 1964; Patzelt, 1973; Holzhauser, 1984).

DISCUSSION

The importance of the tectonic structures formed during the Middle Pleistocene-Holocene deformation and even those formed during the previous phase, has been emphasised. Although the actual geological, structural and geomorphological information does not give the possibility to detect events with a life-span shorter than some thousand years, the palaeogeographical evolution of the Larissa Plain and, in particular, of the Tyrnavos Basin since Middle Pleistocene could be reconstructed with some confidence.

The two Holocene alluvial deposits following the Late Pleistocene ones are related to the persisting subsidence occurring in the Tyrnavos Basin. West of the Pinios River, downstream of Larissa, the Gyrtoni alluvium is at an altitude close to that of the Agia Sophia alluvium. On the contrary, upstream from the town, the Holocene deposits lie on a terrace 5 m lower than the Pleistocene surface. This sedimentary distribution forced Demitrack (p. 31, 1986) to claim for a not well-defined tilting of the older alluvial plain towards the Rodia Narrow.

In fact, the Late Quaternary evolution of the area is more complex. As shown and discussed in the previous section, the main cause of subsidence in the Tyrnavos Basin was tectonic and particularly related to the prevailing E-W trending fault system (fig. 4). On the other hand, compaction-generated subsidence has also played a role in the basin history and has been taken into account as well. To better understand the present-day geometry and distribution of the sedimentary bodies, as well as the actual topography of the area, we must recall that the total subsidence occurred in the Tyrnavos Basin is the result of the two components (tectonically- and compaction-generated) which worked independently, with different rates, magnitude and variable geographical distribution.

The present-day altitude of the Tyrnavos Basin is about 20 to 40 meters higher than the Karla Lake. During the Pleistocene, the difference was probably less and it could even be reversed. The continuous trap and sediment accumulation within the Tyrnavos Basin could have created the actual situation. Whatever the initial scenario was, the question of why the Pinios River has never permanently flowed towards the Karla Lake is pertinent and much of the effort of the present research is addressed to answer this problem. The Kalamaki Narrow is now at about 75 m and the Pinios River flows eastwards for several kilometers before abruptly turning to the North, apparently deviated by the Chasambali Bulge. But a key point for understanding the recent evolution of the area is the lower altitude (60 m) of the central part of the Pinios alluvial plain (i.e. the Nessonis Lake and surroundings). It is due to a stronger subsidence of this sector of the Tyrnavos Basin, generated by the maximum tectonically and compaction-induced subsidence, which has always represented a very close and unavoidable attraction for the water of the Pinios River. Nonetheless, this local topographic low is still about 20 m higher than the southern Larissa Plain.

Now, let us analyse in more detail the role of the set of faults East of Larissa (fig. 4 and fig. 5c). This northwards down-stepping structure had three main effects. The first was to produce a local damming that created the morphological separation between the Tyrnavos Basin and the southern part of the Larissa Plain and was sufficient to temporarily impede and contain the water overflows of the northern alluvial plain. The second combined effect was to shift to the North, due to the northward increasing subsidence, and consequently was to delay the potential diversion of the Pinios River towards the Karla Lake. The structural lowest block delimited by the Dimitra Fault to the South, and by the Gyrtoni Fault to the North, incidentally coincides with an inherited topographic high, thus generating further damming and eventually precluding any eastward flow. The remnants of this staircase structure are still detectable in the detailed topographic map presented in fig. 5a. Exactly North of the Dimitra Fault, there exists a relative large area where water cannot drain properly (fig. 5b). If we also consider the 52 to 48 m contour lines, a telescoping necking in correspondence with the tectonic lineaments is evident. The third effect is related to the partial overlap of the Larissa Fault with the Dimitra, Asmaki and Kastri Faults. This E-W trending and left-stepping fault geometry generates a secondary NE-SW trending morphological scarp (not fault-related), connecting the two sets, known in the literature as 'relay structure' (relais de failles, Goguel, 1952). The theoretical surficial effects closely resemble the observed topography.

During the last few thousand years, this palaeogeographic pattern (characterised by an alluvial plain in the Tyrnavos Basin, a small lake or swampy area in the Eleftheri Basin, and by an independent large lake in the southern Larissa Plain) probably became unstable. It may be tentatively related to one or more concomitant and probably inter-dependent causes: a long-term inactivity of the set of faults E of Larissa; a higher sedimentation rate in the Pinios alluvial plain; the progressive eastward migration of the Pinios River; and last, but probably more important, the regressive erosion along the Asmaki River. As a function of the climate-related water supply, this instability produced even more frequent floods across the Chasambali Bulge, thus deepening the Asmaki River and meantime, partly filling up the small Eleftheri Basin. There, an alluvial fan is evident from the satellite imagery.

The build up of an artificial embankment along the Pinios River North of Larissa but especially the dam for the Larissa-Thessaloniki railway (after 1912-1913), definitely fossilised the present-day geography. In fact, the former precluded further flooding into the Nessonis Lake, while the latter impeded the capture of the Pinios by the Asmaki River.

Acknowledgements

The authors are grateful to Markos Thanos (Larissa Hydrological Service) and Kostas Gallis (Larissa Archaeological Bureau) for fruitful and pleasant discussions. Radiochronological dating has been performed at the Radiocarbon Laboratory of the Université Claude Bernard-Lyon 1. Yann Callot and two anonymous reviewers are thanked for improvements of an earlier version of the manuscript. Financial support given by NATO to R.C. and by UPR 310-CNRS to J.P.B and B.H. are gratefully acknowledged.

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Manuscrit déposé le 14 juillet 1993
accepté le 5 mai 1994