Abstract

Geographical and geomorphological data was analyzed from a riverbed swamp in the Krathis River, N. Peloponnese. Furthermore, our analysis is based on sedimentological, geochemical and palaeontological analysis of a 6 m sediment core and age data from samples collected from the core. These data enabled the investigation of the possible relationship between the swamp and the 1913 Tsivlos landslide.

Sedimentological analysis showed that the current sedimentation in the swamp is prevailed by fine grain material and occasional coarse-grained beds. Fossils’ analysis indicated that the deeper layers of the core are barren while the upper contain fresh water ostracods, suggesting hydrodynamically a progressively more stable environment. In accordance, radiocarbon C\textsuperscript{14} and \textsuperscript{137}Cs dating showed a progressively decreasing sedimentation rate over the last fifty years. Overall, the results of this study show that the Tsivlos landslide was the possible cause for the modern swamp’s formation. Tectonic movements of the area seem to play a decisive role causing uplift and subsidence in the area near an active fault. Particularly the footwall uplift created a natural barrier in the sediment dispersal. Older similar phenomena have not been identified in the 6-m-deep borehole.

1. INTRODUCTION

Large scale landslides are considered important natural hazards capable to cause long term implications in the ecology and the landscape of a region (Schuster and Highland 2001; Korup et al 2005; Gorp et al 2014; Stoleriu 2015). Blockage of rivers following a landslide constitutes such an implication and thus such an event is considered as a type of geomorphological process. Typical areas for such events are mountainous regions with deep and narrow valleys along which a river runs (Costa and Schuster 1988; Korup 2002; Geertsema 2009). Landslides in narrow valleys many times cause the blockage of the passing river and thus the formation of ephemeral or permanent lakes. These lakes except for the creation of new ecosystems and possible (eco/geo)-tourist value for the site (Stoleriu 2015) can cause great damage and human loss if the dam that has been formed collapses (Korup 2002; Korup and Tweed 2007; Geertsema 2009; Yu-Shu et al 2011; Gorp et al 2014; Stoleriu 2015; Zygouri and Koukouvelas 2018).

In the present study such hazardous phenomena will be researched. The study area is a swamp that develops in the riverbed of Krathis River in the Chelmos-Vouraikos UNESCO Global Geopark, N Peloponnese that constitutes the remnants of a lake formed after a big landslide (Figure 1a, 1b). The area was chosen due to the fact that a large historical landslide that happened in the region and the potential danger from such landslides in the future. More specifically, in March 1913 a massive landslide wasting the Gerakari Mountain caused damages in two villages called Sylivaina and Tsivlos, impounding as well two lakes within the Krathis river basin, one off-stream and one in-stream (Figure 1a) (Zygouri and Koukouvelas 2018). Almost one year after the valley damming the dam of the in-stream lake, called for brevity Krathis Lake, failed and caused a massive outburst flood in the coastal zone of the Gulf of Corinth, near the present day town Akrata. The off-stream lake, called Tsivlos Lake, still remains unaffected and is considered as being in equilibrium state.

The swamp that is under research in the present study corresponds to the remnants of the Krathis lake (Figure 1a). The studied material came from a 6-m-long sediment core obtained using a percussion corer with barrel windows. The core was analyzed in terms of sedimentology, palaeontology and \textsuperscript{14}C and \textsuperscript{137}Cs dating. Based on these data we will try to
highlight the evolution of the Krathis Lake over the recent past and the possibility of similar landslides events before 1913.

Figure 1: a) the study area, with yellow line the present swamp/former Krathis Lake, with white line Tsivlos Lake and with red the 1913Tsivlos landslide . Background picture derived by Google Earth b) the wider tectonic neighborhood of the study area. The study area is marked by the red box (modified picture from Kokkalas & Doutsos, 2001).

2. GEOLOGICAL SETTING

The study area belongs to the geotectonic regime of the Gulf of Corinth (Figure 1b). The Gulf of Corinth is a WNW-ESE directed active graben 120 km long by 30 km wide (Doutsos and Piper 1990; Koukouvelas and Doutsos 1996; Westaway 2002; Lykousis et al. 2007; Zygouri et al. 2008). The graben is dominated by high subsidence rates in the north and high uplift in the south. Most of this deformation is accommodated by high angle south or north dipping normal faults (Doutsos and Piper 1990; Koukouvelas and Doutsos 1996; Westaway 2002; Lykousis et al. 2007; Zygouri et al. 2008).

The study area develops within Krathis watershed which is extended for about 149 km² and is composed by pre-alpine and post-alpine formations (Horafas and Gkeki 2017; Zygouri and Koukouvelas 2018). Based on the separation of Greece in the Hellenides structural chain the pre-alpine formations are represented by formations that belong to the units of Tripolis, Pindos and Tyros (Koukouvelas 2018). The post-alpine sedimentary successions are composed of Vouraikos and Platanos formations and marine terraces (Figure 2) (Hemelsdael and Ford 2016; Zygouri and Koukouvelas 2018).

Four main active normal faults (Figure 2) dissect almost perpendicularly the Krathis drainage basin (Zygouri and Koukouvelas 2018), namely Valimi (VF), Akrata (AF), Platanos (PF) and Vela Fault (VEF) (Fig. 2) (Zygouri et al. 2008). The VF, that crosses the study area, has a length of 9 km, dipping north and forming a kilometer-wide-roll-over anticline (Groumpou 2018).
3. MATERIALS AND METHODS

3.1. Sediment core

For the present study data were collected from a 6 m deep core with a diameter ranging from 50-100 mm which was drilled in the central and north part of the present swamp (former Krathis Lake) (Fig. 3). Geographical position and elevation of the core were determined with a differential GPS ProMark 3 Magellan. The sediment core was drilled by an Eijkelkamp portable vibrating corer with an open window barrel (Cobra TT). All extracted samples from the core were sealed with cling film and transferred to the Laboratory of Sedimentology, in the Geology Department of Patras University, for further analysis. In total, 135 samples were extracted from the core and 60 of them were selected for sedimentological and palaeontological analyses.

3.2. Sedimentology

Standard sedimentological analyses were recorded including grain size analysis, and calculation of moment measures, such as mean, sorting, kurtosis and skewness, Munsell color and RGB measurements, Total Organic Carbon (TOC), Total Carbon (TC), Total Nitrogen (TN), Calcium Carbonate Content (CaCO$_3$) and Total Sulphur (T.S).
Sediment classification was based on grain size analysis and on Folk (1974) nomenclature. All 60 samples were fine grained so they were analyzed with a Malvern Mastersizer 2000 and grain size distributions were calculated. Grain size statistical parameters such as mean, sorting, skewness and kurtosis were calculated using GRADISTAT v.4 software (Blott and Pye, 2001). Based on the grain size analysis results, the samples are characterized as sandy silt and silt (Fig. 4).

Sediment colors were identified using two methods, a Minolta CM-2002 handheld spectrophotometer based on the Munsell colour chart and the RGB measurements were taken throughout the core. Finally, the RGB measurements were plotted in a diagram and correlated with the sedimentological and geochemical data of the core (Figure 5). Magnetic susceptibility was calculated throughout the core in each single cm except for the depths between 2.00 -2.42 m and 3.90-4.25 m using the Bartington Magnetic Susceptibility Meter, MS2. Magnetic susceptibility is the ability of the material to be magnetized. It is a useful parameter for the estimation of the possible source of the lake’s sediment since high elevations of the magnetic susceptibility indicate greater amounts of allochtonous material in the lake (Wetzel 2001).

In addition, TOC was calculated using the volumetric method of Walkley and Black (1934) and CaCO3 using a FOG II/Digital hand-held soil calcimeter Version 2/2014 (BD INVENTIONS). CaCO3 (%) calculation was based on measuring emitted CO2, a modification of the method by Müller and Gastner (1971) and Jones and Kaiteris (1983). Finally T.C, T.N and T.S were calculated by using a CHNS-O EA 1108 Elemental Analyzer (Carlo Erba).

Figure 3: The sediment core of the Krathis borehole
3.3. Chronology

The chronological framework of this study is based on two methods. For the upper part of the core the method of radioisotope $^{137}$Cs was applied in 35 samples every 3 cm across the first meter of the sediment core. For the lower part of the core we dated two samples of wood for radiocarbon age determinations at depths of 2.62 m and 4.20 m. The calculation of $^{137}$Cs activity was carried out in the Laboratory of Inorganic Chemistry, Radiochemistry and Physical Chemistry (Department of Chemistry, University of Patras) while Radiocarbon analyses were performed at Beta Analytic (Miami, USA). The dating results will be used for the average sediment accumulation rate which for the last 63 years was estimated by using the $^{137}$Cs results.

3.4. Micropaleontology

The 60 dried samples were picked from the sediment core for microfaunal analysis. The specimens were washed through 500 $\mu$m and 64 $\mu$m mesh sieves using tap water. Ideally, at least 300 tests per sample (ostracods, gastropods and molluscs in this case) must be handpicked from the 64 $\mu$m mesh sieve sediment fraction. The core analyzed in the present study provided no sample in which 300 tests were detected and all the fauna that was found is considered as subfossilized. Thus, since the fauna does not fulfill the qualifications to characterize them as fossils, they will be referred to, from now on, as microsubfossils. The methodology for studying microsubfossils is the same as microfossils, meaning sorting the collected specimens, counting them and finally determining them, if possible, to the species level. Due to the small populations found in the present study, only qualitative analysis i.e. identification of the ecosystems that they represent was possible and no quantitative analysis i.e. no percentage diagrams is presented.
3.5. Geomorphology

Topographic maps and aerial photos were used for the detection of fluvial geomorphology at active environments. Such geomorphologies could be meanders in rivers, swamp formations, regional widening or narrowing of a river’s bed, regional thick river/lake sequences, turns or curves in the river bed etc. Several of these markers have been recognized in the study area such as the Krathis deep gorge that indicate active tectonics (Figure 8). Another active deformation index is the river bed sinuosity of the Krathis river before its channel to cross the Valimi fault trace (Figure 9).

4. RESULTS

4.1. Sedimentology and Micropaleontology

Regarding the micropaleontological results the maximum population throughout the core was represented by 96 microsubfossils. Despite the small number of findings, the fact that there were both plenty of juvenile and mature ostracod valves shows that they represent in situ environments. The small number of fragmented valves possibly reveals the existence of a stream with moderate transportation energy.

Based on the sedimentological and micropaleontological results the core was divided into four units (Figure 5): Unit 1 is the lowest part of the core starting from 6.00-4.85 m, Unit 2 is the lower middle unit starting from 4.85-3.85 m, Unit 3 is the higher middle unit starting from 3.85-2.45 m and Unit 4 consists the upper part of the core starting from 2.45-0.00 m. In the following we describe each unit individually.

The lowest unit (6.00-4.85 m) consists mainly of poorly sorted, olive grey fine silt. Values of sorting range between 1.453 and 1.708 Φ, with mean values ranging between 6.951 and 7.372 Φ (Figure 5). Skewness values indicate mostly a fine skewed distribution and kurtosis values show a mesokurtic distribution (Figure 5). The carbonate content ranges between 4.770 and 6.146%, TOC between 0.37 and 1.29 %, CaCO₃ between 17.1 and 21.7 %, T.N. between 0.073 and 0.486 % and finally T.S. between 0.000 and 1.174 % (Figure 5). The T.S. range was not considered in the division of the core in units since its content was mostly close to 0.000 % throughout the core. No subfossils were detected in this unit. Based on the sedimentological data this unit possibly represents flood and swamp deposits.

The lower middle unit (4.85-3.85 m) consists mostly of poorly to very poorly sorted, medium to fine silt with a small but noticeable amount of sand. Colour is mostly characterized as olive grey and few appearances of grey, dark grey, brown and weak red. Values of sorting range between 1.484 and 2.644 Φ, with mean values ranging between 5.840 and 7.254 Φ (Figure 5). Skewness values indicate a fine to coarse skewed distribution, kurtosis values show a leptokurtic to platykurtic distribution (Figure 5). The carbonate content ranges between 4.584 and 7.094%, TOC between 0.28 and 0.98%, CaCO₃ between 15.2 and 21.6 %, T.N. between 0.038 and 0.097% and finally T.S. between 0.000 and 0.937 % (Figure 5). The microsubfossils detected in this unit were mostly gastropods. More specifically eight gastropods of the genus Pseudamnicola sp. were found and four valves of ostracods from which the two are identified as Candona neglecta and the other two, due to their very early stage of life, could not be identified (Figure 6). Combining the sedimentological and palaeontological data, this unit represents swamp deposits of fresh water in cool temperatures between 6-22º (Frenzel et al 2010; Ruiz et al 2013). Furthermore, a karstic spring probably
existed in the area since *Pseudamnicola* sp. lives exclusively in such environments (Szarowska et al. 2016).

**Figure 5:** The sedimentological, geochemical, magnetic susceptibility and RGC colours. With red line the highest picks of $^{13}$C elevations in the corresponding years and depths of the sediment core.
Figure 6: Distribution of microsubfossils throughout the sediment core. The vertical axis showing the depth and the horizontal the abundance of each species. With red line the borders of the 4 Units.

The higher middle unit (3.85-2.45 m) consists mostly of poorly sorted fine silt and a small amount of medium to coarse silt, while sand is almost absent except for 3.05 m depth where an increase is noticed. Colour is mostly gray and few appearances of brown, dark gray and olive gray are noticed. Values of sorting range between 1.447 and 2.859 Φ, with mean values ranging between 5.751 and 7.510 Φ (Figure 5). Skewness values indicate a fine to very coarse skewed distribution, kurtosis show mostly mesokurtic distribution and leptokurtic is observed only where coarse silt appears (Figure 5). The carbonate content ranges between 3.350 and 7.530 %, TOC between 0.29 and 1.98 %, CaCO$_3$ between 12.5 and 19.3 %, T.N. between 0.039 and 0.126 % and finally T.S. between 0.000 and 1.076 % (Figure 5). This unit also represents swamp deposits.

The higher unit (2.45-0.00 m) consists mostly of poorly to very poorly sorted medium silt, a small amount of clay and a noticeable content of sand. Colour is mostly olive gray with appearances of dark gray, gray, brown and weak red. Values of sorting range between 1.508 and 3.045 Φ, with mean values ranging between 4.208 and 7.084 Φ (Figure 5). Skewness values range between fine and very coarse skewed distribution, kurtosis show leptokurtic to platycurtic distribution (Figure 5). The carbonate content ranges between 5.260 and 9.318 %, TOC between 0.14 and 2.88 %, CaCO$_3$ between 15.1 and 24.7 %, T.N. between 0.027 and 0.244 % and finally T.S. between 0.000 and 0.930 % (Figure 5). This unit represents the richest unit with respect to microsubfossils since ostracodes, gastropoda and bivalvia are detected. Ostracods are represented by Candona neglecta, Paracandona sp. and Ilyocypris gibba, gastropoda by Vallonia enniensis, Vertigo moulinisiana and Radix peregra and bivalves by Pisidium casertanum (Figure 6). This unit also represents swamp deposits based on the sedimentological and micropaleontological results (Frenzel et al 2010; Karanovic 2012; Ruiz et al 2013; Williams et al 2014; Bespalaya et al 2015). In addition, microsubfossils Vallonia enniensis and Vertigo moulinisiana, provide information for the swamp’s substrate which is limestone, there were reeds and the swamp bordered with rivers banks (The IUCN Red List of Threatened Species). Microsubfossils also indicate a variation in water’s temperature, more specifically in the depths 0.00-0.35 m and 1.57-2.27 m where Candona neglecta and Paracandona sp. dominates, the water was cooler than 0.35-1.15 m where Ilyocypris gibba dominates (Frenzel et al 2010; Ruiz et al 2013).
4.2. Chronology

Elevations of $^{137}$Cs activity range between 0.5 Bq/Kg and 102.8 Bq/Kg (Figure 7). All the years (1986, 1963 and 1954) with the highest elevations in the radioisotope $^{137}$Cs were detected across the first meter of the sediment core. More specifically, the year 1986 ($1^{st}$ high elevation) is detected at 0.09 m depth, 1964 ($2^{nd}$ high elevation) at 0.40 m depth and 1954 ($3^{rd}$ high elevation) at 0.84 m depth. (Figure 7).

Radiocarbon $^{14}$C age determination results are reported with the units “pMC” rather than BP (Table 1). “pMC” stands for “percent modern carbon”. Results are reported in the pMC format when the analyzed material had more $^{14}$C than did the modern (AD 1950) reference standard. The source of this “extra” $^{14}$C in the atmosphere corresponds to the thermo-nuclear bomb testing which was on set in the 1950s. Its presence generally indicates the material analyzed was part of a system that was respiring carbon after the on-set of the testing (AD 1950s). On occasion, the two sigma lower limits will extend into the time region before this “bomb-carbon” onset (i.e. less than 100 pMC). In those cases, there is more probability for 18th, 19th, or 20th century antiquity. In more detail the $^{14}$C results of this study are presented in Table 1. In addition these results suggest that the Krathis Lake during the 1950s, at least in its northern part, was a lake with a depth in the order of 4 m. This result is in accordance with the air-photos of the 1945 showing that the Krathis Lake is still existing until before its siltation in 1967 (see Fig. 6 in Zygouri and Koukouvelas 2019).

<table>
<thead>
<tr>
<th>Depth</th>
<th>Measured Radiocarbon Age</th>
<th>Radiocarbon Age</th>
<th>Isotopes Results</th>
<th>Conventional Radiocarbon Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.62 m</td>
<td>113.2 +/- 0.4 pMC</td>
<td>113.4 +/- 0.4 pMC</td>
<td>d13C = - 26.0</td>
<td></td>
</tr>
<tr>
<td>4.20 m</td>
<td>103.7 +/- 0.4 pMC</td>
<td>104.8 +/- 0.4 pMC</td>
<td>d13C = - 30.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Radiocarbon $^{14}$C age determination results.
5. DISCUSSION

Based on the sedimentological, micropaleontological and chronological results of this study it seems that over the last 106 years in the Krathis Lake four units of fine grained sediments were accumulated, interrupted by coarser grain materials. This indicates that despite the collapse of the natural dam that caused the formation of Krathis Lake, the lake remained identifiable for about 40 years until 1950. Over this period the sedimentation rate is rapidly
decreasing along with the siltation of the Lake that is progressively changing into a swamp. The existence of all three high elevations of the radioisotope $^{137}$Cs in the sediment core indicates that the deposition of sediment continued after the year 1914 in which year the dam forming Krathis Lake collapsed. From this we conclude that Tsivlos landslide is not the only cause of the formation of the swamp in the study area as it was believed up to the present day. Furthermore, microsubfossils indicate changes in the lake’s temperature which also confirms that the source of the sediment in the swamp is not only the landslide but mainly later sediment accumulation in the area. Since this swamp is developed at the forefront of the footwall of Valimi Fault it is considered that the fault is active and is controlling the lake - to - swamp evolution.

The transformation of the Krathis Lake - to - swamp along with the steepness of slopes in the area and the Krathis river bed sinuosity indicates that the swamp is accumulating sediments at high rates overcoming at present the Valimi Fault uplift rate.

Findings in the Krathis swamp make unclear whether the Krathis Lake in the past accumulated the debris of the 1913 Tsivlos landslide. Based on this puzzling evidence we suggest two possible scenarios for the Tsivlos landslide event along the sediment core. First, the 1913 landslide event could be located at 2.45 m depth of the core. This scenario is based on the existence of a greater population of organisms and a continuous increase in the class of sand located at this depth. However, this scenario is impossible based on the $^{137}$Cs chronological results and the radiocarbon $^{14}$C age determination as well. The second scenario that locates the Tsivlos landslide event is greater than the 4.20 m deep core. At this depth there is an increase in the class of sand which also agrees with the radiocarbon $^{14}$C age determination results at 4.20 m depth where the sediment corresponds to an age of 60-100 years. The 1st scenario gives us a motivo of sediment accumulation rate in the study area that would look like the one in Figure 10 which means that there might have been a time delay in the increase of sediment accumulation rate after the landslide event and then the sedimentation ratio increased rapidly. The 2nd scenario as shown in Figure 10 suggests a direct increase of the sediment accumulation rate after the landslide which is progressively decreasing until today.

![Figure 10: Pattern of the evolution of sediment accumulation rate (cm/yr) a) for the 1st scenario: Tsivlos landslide located at 2.45 m depth of the sediment core b) for the 2nd scenario: Tsivlos landslide located at 4.85 m depth of the sediment core](image)

### 6. CONCLUSIONS

Although we are not able to answer with certainty whether similar hazardous phenomena took place in the study area before 1914 as the drilling of the core has not reached the final depth of the lake of Krathis and the radiocarbon chronology at 4.20 m depth is highly influenced by the nuclear tests in the 50’s, our results have highlighted three main conclusions. Further investigation such us deeper drillings and at different spots in the study
area are required in order to being able to reach a better understanding of the geomorphological behavior of the area.
1) The Krathis Lake formed during 1913 and remained as a lake for about four decades.
2) The sedimentation rate within this lake remained high causing the accumulation of 4.85 m of sediments in about 100 years.
3) Topical meanderisms of Krathis River and the formation of the swamp indicate that the Valimi fault is active. More specifically, the Valimi fault is playing a decisive role in the formation of Lake Krathis since it was formed at the base of the fault. The former lake is progressively becoming a swamp under the continuous uplift and tilting to the south of the Valimi Fault footwall block.

References


Strom, A. 2015. Natural River Damming: Climate-Driven or Seismically Induced Phenomena: Basics for Landslide and Seismic Hazard Assessment. *Engineering Geology for society and Territory Volume*: 2 DOI: 10.1007/978-3-319-09057-3_3


