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Geometric and kinematic characteristics of the normal fault system in Neogene-Quaternary Ptolemais Basin, NW Greece; Insights from the opencast lignite mines.

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Abstract: *Extensive opencast lignite mining in Ptolemais Basin, NW Greece has exposed a plethora of outcrops within a neotectonic and active normal fault system. During the last eight years, we have been working on data derived from our frequent visits to these mines with the aim to get a better understanding on the controls of fault zone structure and evolution. In this presentation, we discuss some of our findings that relate to the structure, timing, and neotectonic activity of the faults.*

Keywords*: Normal faults, Fault geometry, fault growth, Ptolemais Basin*

1. Introduction

The Florina-Ptolemais-Servia Basin in western Macedonia, NW Greece (Fig. 1), is affected by two normal fault systems related to two extensional episodes (Pavlides and Mountrakis, 1987; Mercier et al., 1989). The first, Late Miocene episode resulted in the formation of the basin following the Alpine orogenic cycle when the continental crust failed under a NE-SW extensional regime due mainly to postorogenic collapse (Pavlides, 1985; Pavlides and Mountrakis, 1987). The second episode, with a NW-SE direction of extension took place during the Quaternary and resulted in the subdivision of the large basin into several sub-basins along NE-SW trending faults (Pavlides, 1985).

The present topography within the basin is dominated by the NE-SW trending normal faults formed during the second extensional episode and exhibits typical geomorphological characteristics of recent neotectonic or either active faults (Pavlides and Mountrakis, 1987; Goldsworthy and Jackson, 2001). Although this region had been considered to have relatively low seismic activity (Papazachos and Papazachou, 2003), on 13 May 1995, a devastating earthquake (Mw= 6.5) occurred at the southern limit of the basin associated with the Aliakmon Fault Zone (Fig. 1; Pavlides et al., 1995; Mountrakis et al., 1998, Papazachos et al., 1998).

Unlike previous studies that are based on large active faults with a topographic expression (e.g. Goldsworthy and Jackson, 2001), this study focuses on smaller faults of the same fault system (e.g. Fig. 2). We examine the geometric and kinematic characteristics of this fault system by using a three-dimensional dataset derived from repeated mapping in the four active lignite mines in the Ptolemais Basin (Fig. 1).

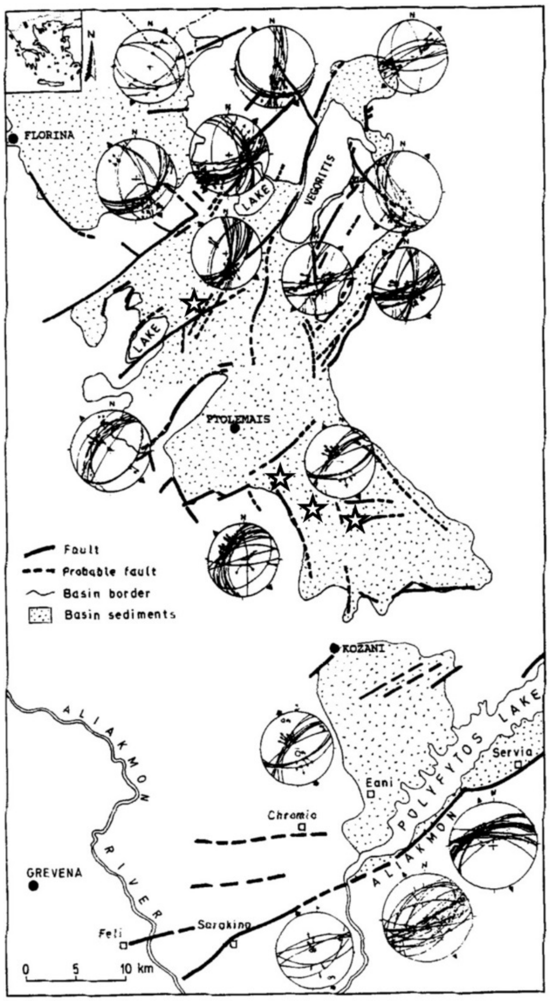

Figure 1: Neotectonic map of the Florina-Ptolemais-Servia Neogene-Quaternary basin showing the main faults, the equal-area projections of measured striated faults and the resulting directions of extension (after Mountrakis et al., 1995). The locations of the four active lignite mines are shown by stars.

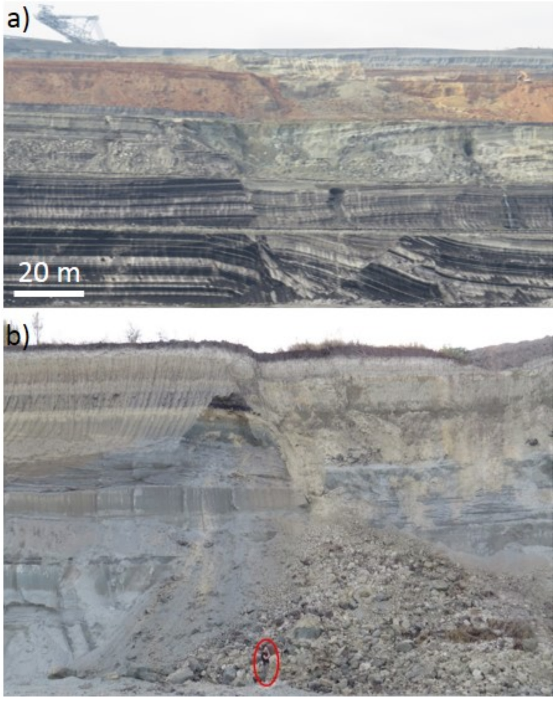

Figure 2: a) Panoramic view of a normal fault zone exposed in Amynteon Lignite Mine. b) Outcrop photograph of the same fault zone exposed at the uppermost mining face showing offsets of the Quaternary deposits.

2. Data and methodology

This study is based on data collected from the four active lignite mines in Ptolemais Basin, at 3-month intervals in the period from 2010 to 2017. The mines operate on ca. 7 principal benches using the continuous surface mining method with bucket-wheel excavators, belt conveyors and stackers (Fig. 3). The ca. 20 m high mining faces are on average 2.5 km long and step back from the bottom to the top, separated by benches that have widths of ca 50 - 100 m (Fig. 3). During each mapping interval, each face was taken back between 20 and 50 m. The data collected during each fieldwork campaign are photographs at various resolutions and accurate GPS locations, structural measurements and interpretations for all exposed faults and related structures observed in each mine, such as normal or reverse drag. Mapping of successive 20 m high mine faces on several benches over a vertical stratigraphic interval of ca. 100 m provides detailed 3D maps of fault displacements and fault zone structure (e.g. Fig. 4; Delogkos et al., 2016).

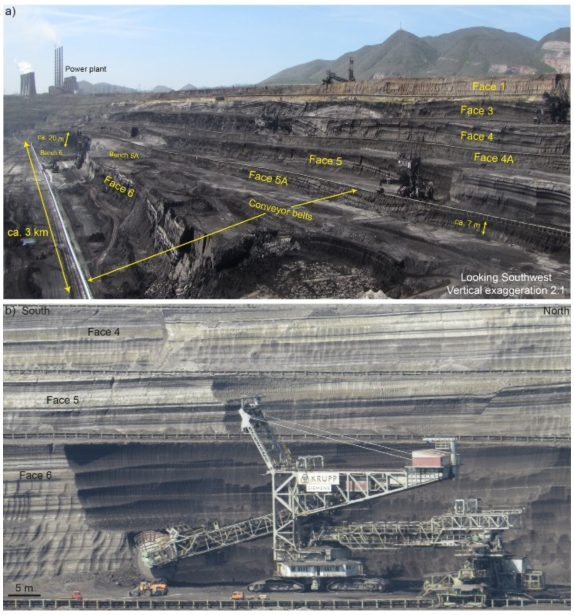

Figure 3: a) Oblique view of Kardia mine, showing the main mining faces associated conveyor belts and some subsidiary faces between them. b) A closer view of the mining faces showing a bucket-wheel excavator used for the selective mining of the multi-layered lignite deposits in Ptolemais Basin.

This work has mostly concentrated on faults in the Early Pliocene Ptolemais Formation, which has a thickness of approximately 110 m and consists of a rhythmic alternation of m-scale lignite and lacustrine marl beds, with intercalated fluvial sands and silts and some 20 volcanic ash beds (Steenbrink et al. 1999).

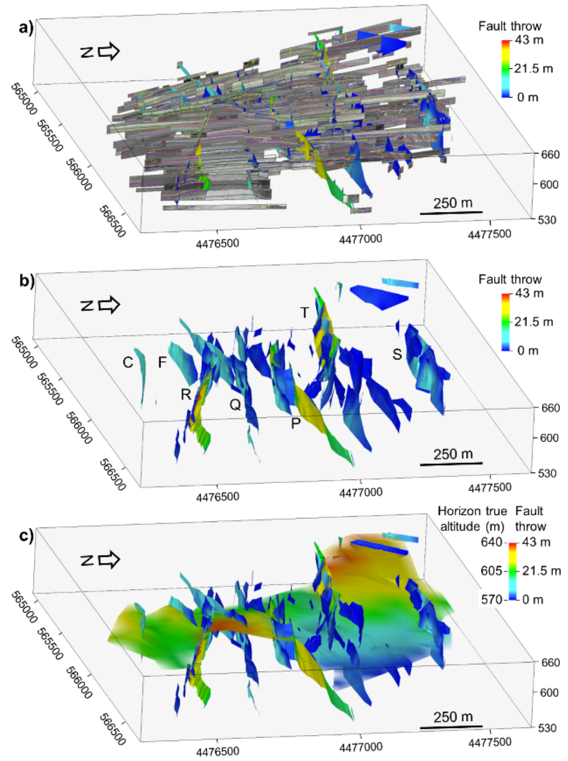

Figure 4: Oblique view of a 3D model of Kardia Mine showing (a) all the mining faces imported into a 3D structural interpretation package, including the interpretation of seven fault zones which displace the lignite-marl sequence by up to 50 m. The colours on the fault surfaces are contours of throw. (b) As (a), but excluding the imported mining faces. (c) As (b), but including one of the interpreted horizons, which is located near the middle of the exposed stratigraphic sequence. The horizon is coloured for height above sea level. After Delogkos et al., 2016.

3. Results and discussion

Three-dimensional mapping of the normal faults reveals high variability in their internal structure. At the largest scale, the faults comprise a few main soft- or hard-linked but interacting slip-surfaces with a zone of associated normal drag occupying a total width of about 100m (Figs. 5, 6). The degree of segmentation and connectivity between fault segments progressively increases with finer scales of inspection (Fig. 6). Continuous deformation constitutes an integral element of the fault structure in all stages of fault growth.

The distribution of the aggregate throw along a fault zone resembles that of a single isolated fault, demonstrating geometrically and kinematically coherent arrays of fault segments. Furthermore, the distributions of throws on individual fault surfaces along a fault zone appear to depend on the size, throw distribution and the 3D arrangement of the other fault zone components.

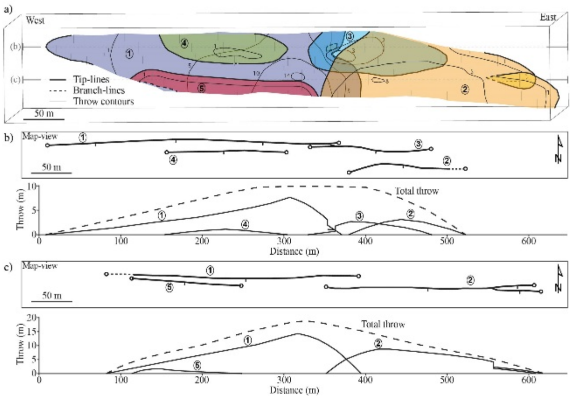

Figure 5: a) Oblique 3-D view of the mapped fault surfaces along a normal fault zone in Prolemais Basin. Fault tip-lines are shown with heavy black lines and branch-lines are heavy black dashed lines. The fault surfaces are contoured for throw (m). The upper and lower edges of the fault surfaces are end of the data unless a tip-line or branch-line is shown. (b) and (c) Map views of the fault segments at the levels indicated in (a). The corresponding throw profiles are also including; dashed lines show the total throw along the fault including throw by continuous deformation and smaller fault segments.

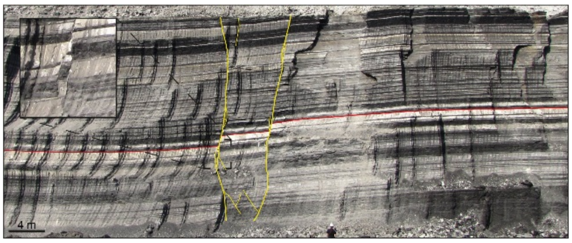

Figure 6: Outcrop through the normal fault zone shown in Fig. 5.

In one of the mines, Kardia, mutually cross-cutting relationships between the normal faults and contemporaneous bed-parallel slip-surfaces provide insights into their growth history (Delogkos et al., 2017 and in press). This analysis indicates that fault interactions restrict fault propagation early during the fault growth history and increase displacement gradients (Fig. 7).

In terms of fault timing, most of the fault displacement occurred after the deposition of the Ptolemais Formation with only a few examples suggesting synchronous faulting during the sedimentation of the Lower Pliocene Ptolemais Formation. In two of the mines, Amynteon and Notio, where most of the overlying sequence is preserved (including Quaternary), the frequency of faulting appears to decrease upwards with only relatively few faults offsetting the most recent deposits. In the other two mines, Kardia and Mavropigi, where the Ptolemais Formation is overlain unconformably by characteristic Pleistocene red-beds, only a few faults propagate and offset this sequence. Displacement differences between the faults above and below this unconformity suggest that most of the throw of these faults predates the unconformity, and generally only the larger faults were still active in the Pleistocene (e.g. Figs. 2, 8).

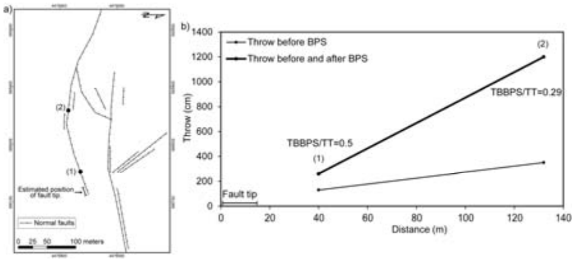

Figure 7: a) Fault map showing the locations (1 and 2) of the recorded bed-parallel slip (BPS) that displaces the footwall fault of a north-dipping normal fault zone in Kardia Lignite Mine. (b) Profiles of the throw before the bed-parallel slip (TBBPS) and the total throw (TT) of the normal fault which has been displaced by the bed-parallel slip, showing the increase in throw gradient with increasing throw along this relay bounding, fault segment. The range of the estimated position of the fault tip is based on the available outcrops. (After Delogkos et al. accepted)

Figure 8: Photograph of the Proastio normal fault exposed at the northwest limit of Mavropigi Mine. The estimated displacement is ca. 350 m based on boreholes. Note that this fault is included as a Seismogenic Source in the GreDaSS database.

Our research to date has mostly focused on fault exposures within the Ptolemais Formation because its fine sequence allows detailed displacement analysis that is essential for understanding fault zone geometry and growth which has been the principal aim of our research. However, we believe that future work on the numerous blind faults that propagated into the overlying sediments could potentially provide information of the fault growth history on shorter time-scales.

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