# Structural Geology of the Lignite Mines in the Ptolemais Basin, NW Greece

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## ABSTRACT

The active, opencast, lignite mines in the Ptolemais Basin, NW Greece, provide world-class outcrops for characterising and understanding normal fault systems from km- down to mm-scale. We have visited and mapped these mines 26 times at ca. 3 month intervals since October 2009. The data collected during each fieldwork campaign were structural measurements, interpretations, various resolutions of photographs and GPS locations for all exposed faults and related structures observed in each mine. Part of this unique dataset has been imported within a fully georeferenced 3D structural interpretation package and has been used for fault and horizon interpretations. Our motivation for this work is to advance our generic understanding of the structure and development of normal faults, but in this contribution, we focus on some of our findings that might be of more general interest to mine planners and designers.

## 1 INTRODUCTION

The Ptolemais Basin is an elongated intramontane lacustrine basin and is part of Florina-Ptolemais-Servia Basin which is a NNW-SSE trending graben system that extends over a distance of 120 km from Bitola in the Former Yugoslavian Republic of Macedonia (F.Y.R.O.M.) to the village of Servia, south-east of Ptolemais, NW Greece [1]. The basin is filled with a 500-600 m (in a few areas up to about 1000 m) thick succession of sediments which are divided into the Upper Miocene to Lower Pliocene Lower Formation, the Pliocene Ptolemais Formation and the Quaternary Upper Formation. The Ptolemais Formation contains the upper and lower lignite seams which alternate with clays, marls, sandy marls and sands [1, 2].

The basin is bounded by two fault systems which can be related to two extensional episodes [3, 4]. The first, Late Miocene episode resulted in the origin of the Florina-Ptolemais-Servia Basin in response to NE-SW extension, which was subsequently subjected to NW-SE extension during the Quaternary, resulting in the NE-SW-striking faults which currently bound a number of sub-basins, including the basins of Florina, Ptolemais and Servia [3] (Fig. 1).

There is little surface evidence of the Late Miocene NW–SE-striking faults that control the basin margins, although their presence is confirmed from boreholes [3] and from some recent exposures along the western margin of the Ptolemais Basin in the vicinity of Mavropigi lignite mine (Fig. 1). The surface geology is dominated by the Quaternary faults, which have orientations ranging from the expected NE–SW strikes to the north of the region, to NNE–SSW orientations to the north of the Mavropigi Mine, and through to approximately east–west strikes in the vicinity of the Kardia and Notio mines (Fig. 1).

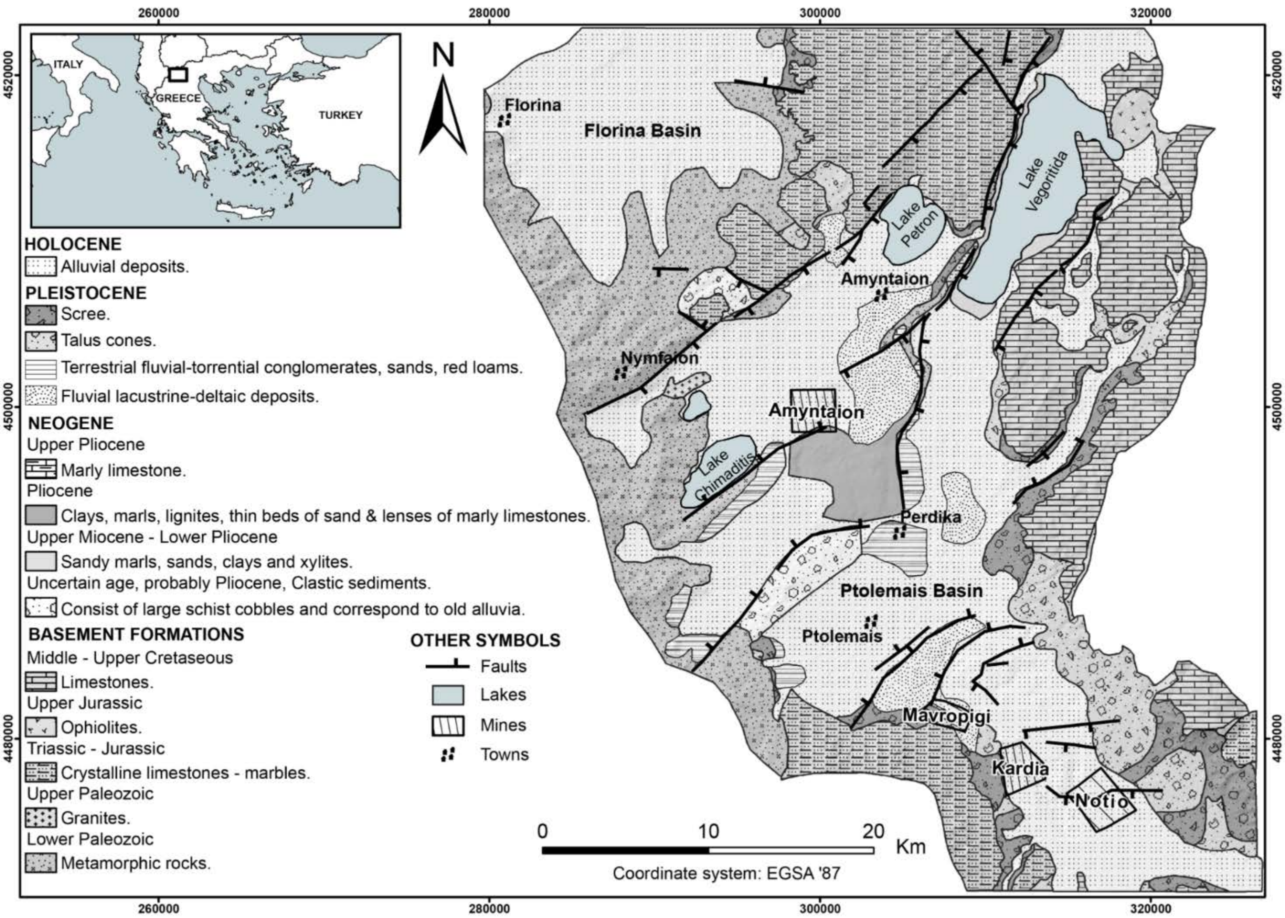


**Figure 1.** Geological map of the Ptolemais Basin showing the major fault structures and the locations of the four active, open-pit lignite mines (modified after [1]).

In this paper we present (1) the general characteristics of the normal faults observed within the lignite mines in Ptolemais Basin, (2) the structures associated with the contemporaneous bed-parallel slip and normal faulting observed in Kardia Mine and (3) our interpretation of the compressional structures observed in Notio Mine.

## 2 GENERAL CHARACTERISTICS OF THE NORMAL FAULTS

The exposed lignite-marl sequence is displaced by numerous normal faults with maximum displacement up to 65 m (e.g. Fig. 2). The faults form soft-linked systems [5], characterised by a prevalence of fault tips as opposed to branch-points, with ductile bed rotations between faults accommodating transfers of strain between adjacent faults. Quantitative analysis of the faults indicates that these systems are extremely soft and that for a given throw, these faults are both shorter and more segmented than many other fault systems [6, 7]. Furthermore, these faults have anomalously high fault displacement to fault rock thickness ratios compared to normal faults in other areas. Wide zones of fault rock (e.g. breccias, cataclasites) are not developed in these faults. Small-scale lenses and splays that, with increasing displacement, would be pulverized and converted into fault rock in other lithologies, are preserved in these rocks, allowing their detailed structure to be examined at high strains.

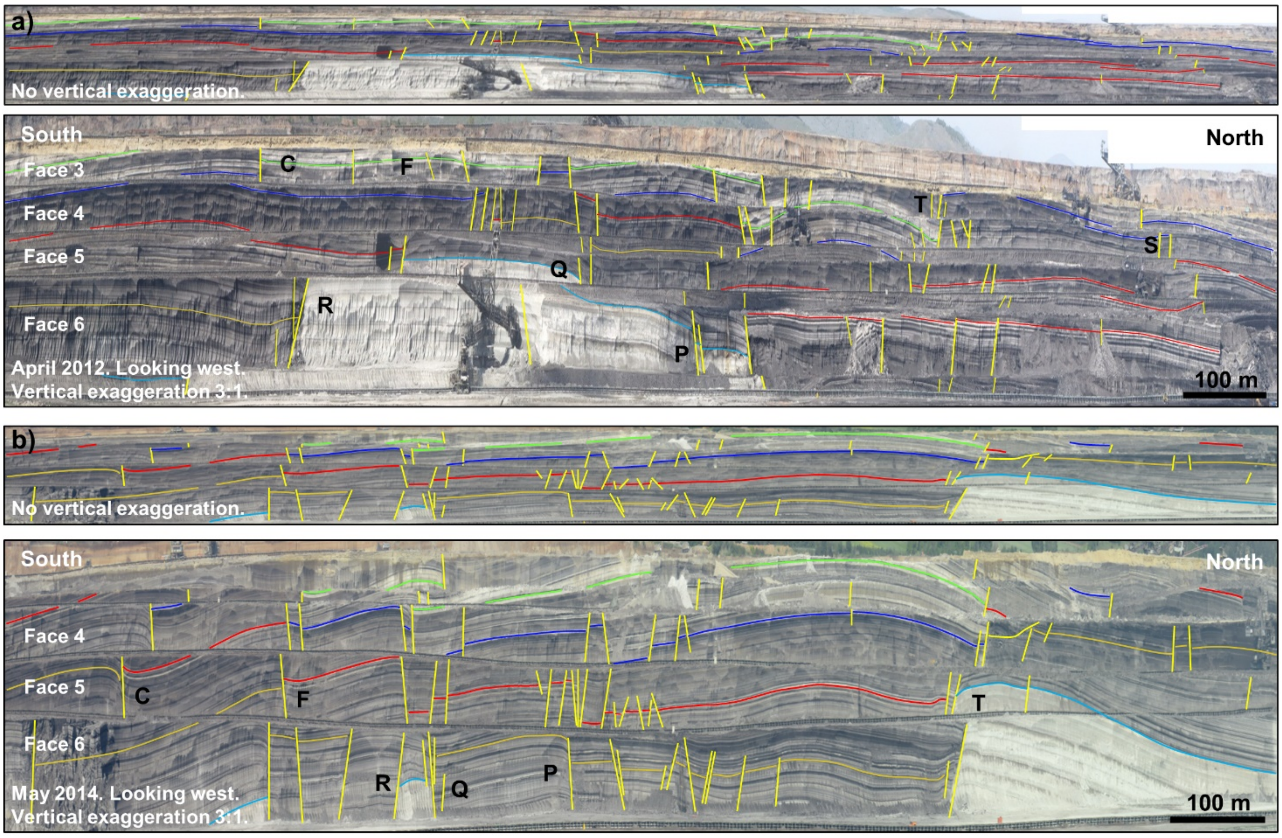


**Figure 2.** True scale and × 3 vertically exaggerated panoramic view of the active, open-cast, Kardia Mine in (a) April 2012 and (b) May 2014. Faults are drawn as yellow lines and a selection of horizons is highlighted. The letters (C, F, R, Q, P, T and S) are the names of the interpreted fault zones. After [8].

Vertically exaggerated field photographs (e.g. Fig. 2) clearly show folds present in these mines. The folds are spatially related to the faults and show normal and reverse drag geometries, which indicates that they are part of the same geological deformation event. Reverse drag refers to folding within the volume surrounding a fault, resulting in layers that are concave towards the slip direction [9], with the development of hanging wall rollover and footwall uplift. Reverse drag is a much larger scale feature than normal drag and defines the displacement field associated with the faults. Often it is difficult to identify reverse drag in the field, especially in areas of high fault density. We expect greater expression of reverse drag on the hanging wall rather than on the footwall of the normal faults in the Ptolemais Basin, as it has been estimated that the footwall uplift/hanging-wall subsidence ratio is 1:2 for these faults [10]. The vertically exaggerated panoramic view of the Kardia Mine (Fig. 2) clearly shows reverse drag structures on the hanging wall of fault zones R and T. Figure 2a also shows the product of opposing reverse drag zones, in the form of an anticline, between the two opposite-dipping large fault zones, P and T. Normal and reverse drag can often occur on the same fault (e.g. Fig. 2b, fault zone T at face 6), with the reverse drag occurring over a much larger distance, but with relatively lower bed rotations.

Another form of folding related to the faults in Ptolemais are monoclines in which a geometrical offset is observed over a localized volume of rock, but where no discrete faults are formed. A partly faulted monocline structure exists in fault zone Q in Kardia mine, overlying an array of soft-linked fault segments. Monoclines are also observed at the tips of individual fault segments.

## 3 BED-PARALLEL SLIP AND NORMAL FAULTING (KARDIA MINE)

The normal faults exposed in Kardia lignite mine formed at the same time as bed-parallel slip-surfaces, so that while the normal faults grew they were intermittently offset by bed-parallel slip [11, 12]. Bed-parallel slip has a persistent top-to-the-north slip direction, ranging from a few centimetres up to 4.5 m, and is attributed to reverse-drag folding (i.e. rollover) in the hangingwall of a north-dipping basement normal fault south of the Kardia Mine. Following offset by a bed-parallel slip-surface, further fault growth is accommodated by reactivation on one or both of the offset fault segments. Where one fault was reactivated the site of bed-parallel slip is a bypassed asperity. Where both faults are reactivated, they propagate past each other to form a volume between overlapping fault segments. These structures contain either a repeated (e.g. Fig. 3) or a missing section of stratigraphy which has a thickness equal to the throw of the fault at the time of the bed-parallel slip event, and the displacement profiles along the relay-bounding fault segments have discrete steps at their intersections with bed-parallel slip-surfaces (e.g. Fig. 3). With further increase in displacement, the overlapping fault segments connect to form a fault-bound lens. Geometrical restoration of cross-sections through selected faults shows that repeated bed-parallel slip events during fault growth can lead to complex internal fault zone structure that masks its origin.

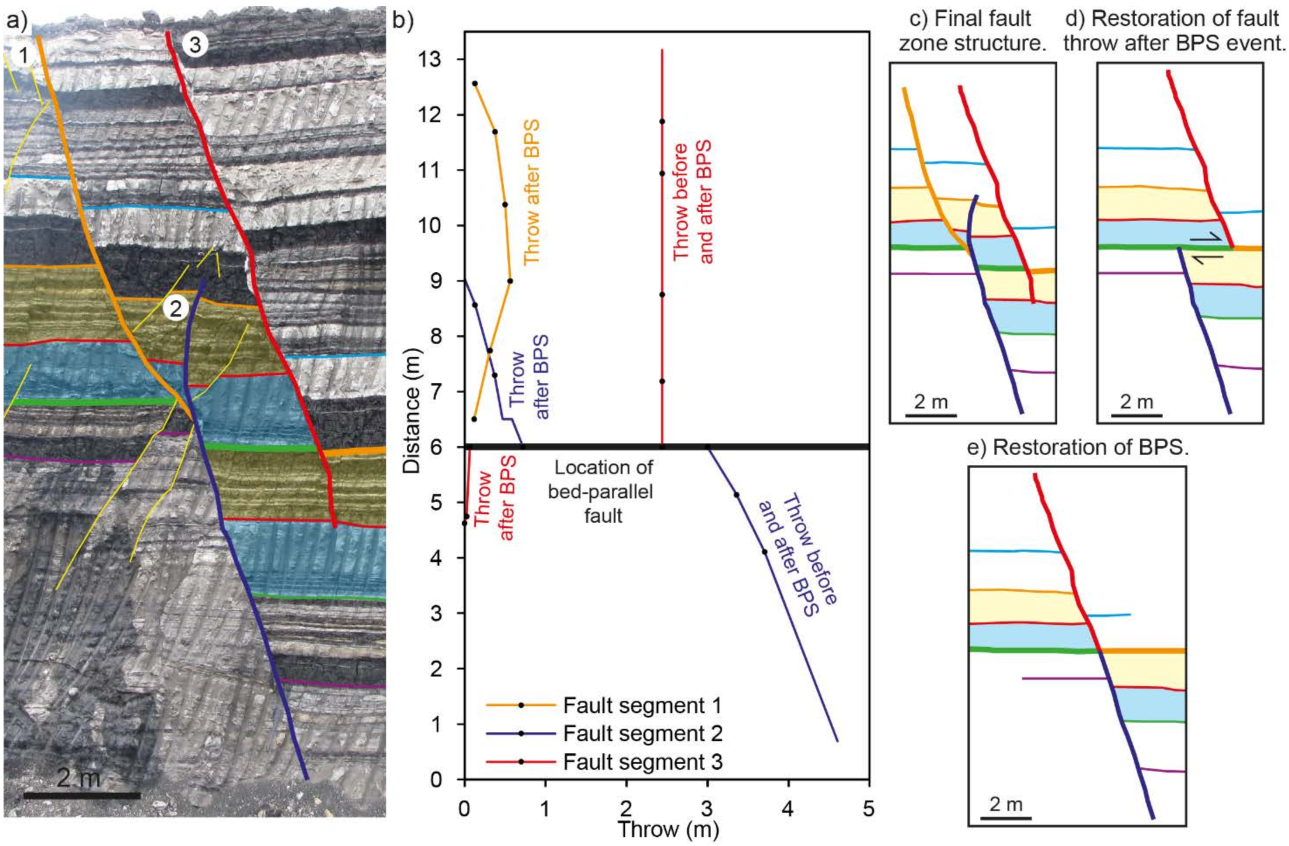


**Figure 3.** a) Outcrop photograph of a ca. 4 m throw normal fault zone which is displaced by bed-parallel slip during its growth. The colour filled part of the sequence is repeated within the fault zone. b) Displacement profiles along the main fault segments showing displacement gradient singularities where they cross the bed-parallel slip-surface that marks the transition from the pre-existing fault segments to the post bed-parallel slip segments. c) Simplified sketch of the final fault zone structure. d) Restoration of the fault throw accommodated after the bed-parallel slip event. e) Restoration of the bed-parallel slip. The bold lines on all figures indicate the bed-parallel slip-surface; these lines change in colour as the slip-surface moves from one horizon to another. After [11].

## 4 SYNSEDIMENTARY SUBAQUEOUS LANDSLIDE (NOTIO MINE)

One of the mines, Notio Mine, contains thrusts that predate Quaternary faults but have identical strikes (Figs. 4 and 5). It has been suggested [13] that the normal faults and thrusts are associated with extension above, and compression below, a neutral surface associated with folds developed in an active transpressional zone.

Detailed mapping, however, shows that the thrusts are constrained within a well-defined approximately 30 m-thick stratigraphic interval [6] (Fig. 4). The base of the interval is a decollement about five meters below the Ptolemais Formation from which the individual thrusts rise. The top of the interval is an unconformity associated with a prominent marl couplet within the Ptolemais Formation. We have not seen any thrusts above this unconformity (where there is extensive outcrop) or below the decollement (where outcrop is sparser) [6].

We interpret this interval to represent a synsedimentary subaqueous landslide, with the presence of geometries similar to, but on a larger scale than, those contained in soft sediments in the Dead Sea described by [14]. Therefore, the thrusts are not associated with tectonic compression, but instead are of very early, synsedimentary gravity-driven origin. The thrusts are consistently cross-cut by the normal faults and occasionally reactivated as normal faults, providing further evidence for the early timing of the thrusts. Our interpretation of synsedimentary slumping followed by normal faulting and fault-related folding is significantly different to the model for these structures suggested by [13], which requires a transtensional-dominated regime.

Apart from the fact that a portion of the sequence being faulted is thrusted, we see little difference in character of the large normal fault zones in the Notio Mine and elsewhere. However, there are cases where the normal faults steepen from a thrust dip (ca. 30°) above the unconformity and into the underlying marl and therefore the normal offsets are demonstrably later than the thrusts (which do not exist above the unconformity or below the decollement) but we have also observed many examples of smaller thrusts reactivated as normal faults within the thrusted interval [6]. The development of this unusual type of reactivation arises from the fact that the thrusts are in the ideal orientation for exploitation by the normal faults (Fig. 5).

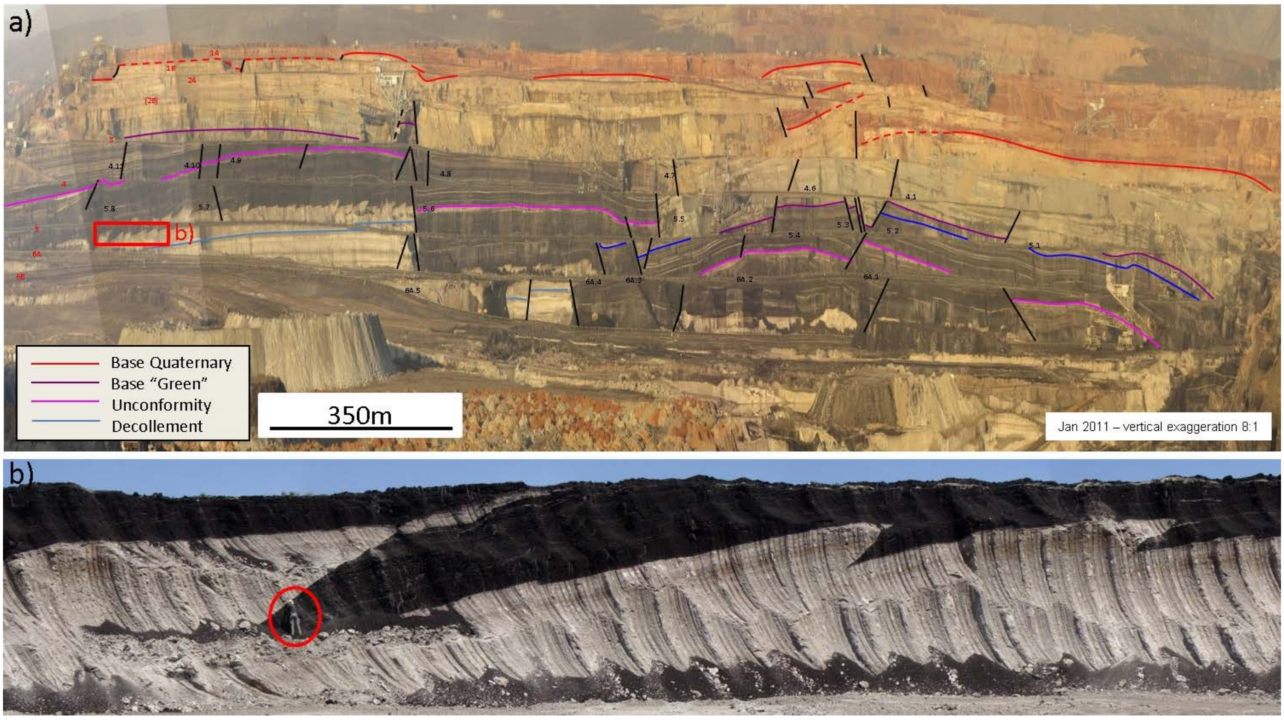


**Figure 4.** a) Photomontage of the Notio Mine. b) Close up view of the area indicated in (a). After [6].

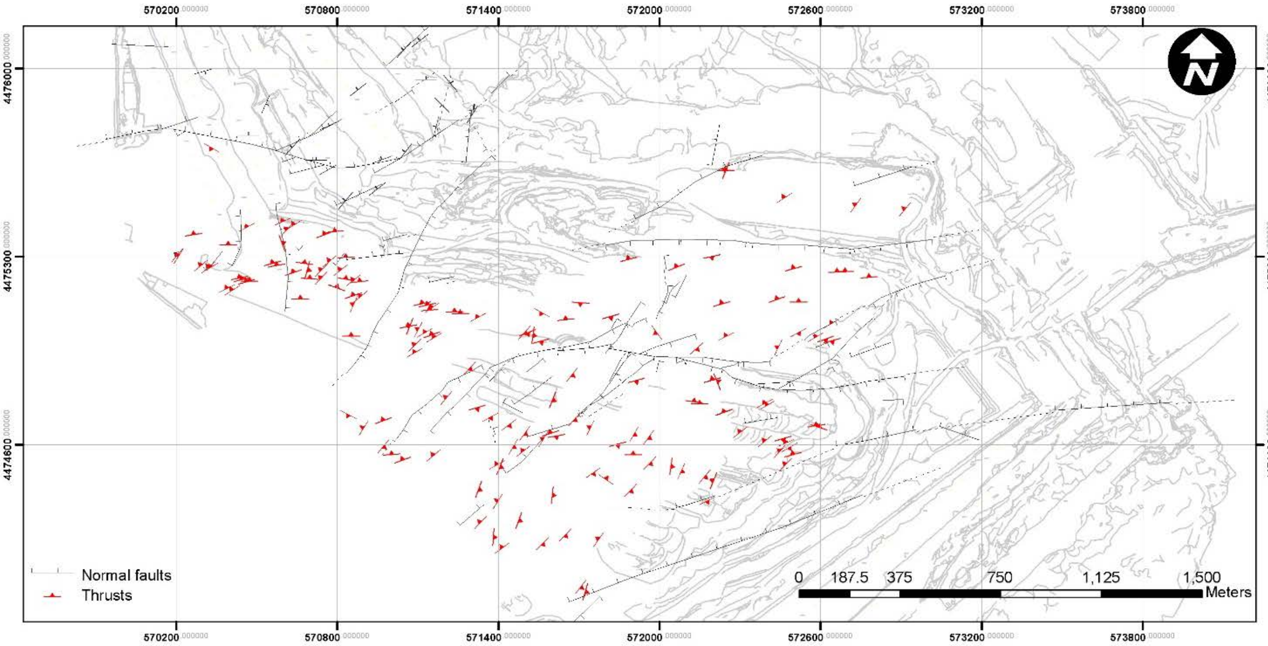


**Figure 5.** Fault map of the Notio Mine.

## 5 CONCLUSION

The exposed lignite-marl sequence of the Ptolemais Basin is displaced by numerous normal faults with maximum displacement up to 55 m. The displacement along each fault surface decreases from a maximum value at the centre of the fault surface towards zero-displacement fault tips. A notable characteristic of these faults is that they have higher displacement gradients (i.e. the ratio between maximum displacement and length) than normal faults in other areas, and are also more segmented at a range of scales. A characteristic of the mines is the presence of gentle folds which often become more pronounced close to the normal faults. These folds are not formed by tectonic compression, but are the result of normal and reverse drag geometries developed during the growth of the extensional normal fault system. Furthermore, in Kardia Mine, normal faulting was associated with contemporaneous bed-parallel slip resulting in further segmentation of the normal faults and in the development of structures that can contain either a repeated or a missing section of stratigraphy. Finally, Notio Mine contains thrusts within a well-defined stratigraphic interval towards the lower part of the Ptolemais Formation. These thrusts have a syn-sedimentary rather than tectonic origin, and are contained within a mass transport complex extending over the width of the mine, and containing an irregular stratigraphy. The thrusts are sometimes reactivated in extension during the later faulting event.

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