A deformation study of Anthemountas graben (northern Greece) based on in situ data and new InSAR results

Article *in* Arabian Journal of Geosciences · June 2020

DOI: 10.1007/s12517-020-05393-9

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Arabian Journal of Geosciences (2020) 13:582
https://doi.org/10.1007/s12517-020-05633-y

CAJG 2018 TOPIC 3

Contradictive mining–induced geocatastrophic events at open pit coal mines: the case of Amintaio coal mine, West Macedonia, Greece

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Received: 15 October 2019 / Accepted: 22 June 2020

Abstract

For open pit coal mines, subsidence of the surrounding area and landslides are among the most common mining-induced catastrophic geohazards. These large-scale geohazards are related to both hydrogeological and geotechnical parameters, and they cause substantial damage. A major challenge to managing these hazards is that the factors that trigger these two phenomena are diametrically opposed. Land subsidence is triggered by the overexploitation of the aquifers conducted for the protection of the slope's stability. Thus, the reduction of groundwater pumping from the draining wells reduces land subsidence deformations but at the same time decreases the stability of the slopes. In the present study, the investigated site is the area at the perimeter of the Amyntaio opencast coal mine at Florina Prefecture, Northern Greece. The overexploitation of the aquifers for the dewatering of the slopes turned the mine into a large-diameter well. The land subsidence caused by the dewatering extended 1–3 km around the mine, affecting the villages of Anargiroi and Valtonera. Furthermore, on June 10, 2017, a massive landslide of approximately 80 million cubic meters occurred at the working slopes of the mine, burying 25 million tons of lignite, resulting in severe damage to a large amount of mining equipment and causing the evacuation of the nearby Anargyroi village. The geometry of the slopes, the preexisting sheared zones, the extensive faults intersecting the site, and the high piezometric loads underneath the floor of the open pit as well as the high groundwater level of the shallow aquifers are the main causal factors of the landslide. The current research, besides presenting the two catastrophic events, aims to correlate the geological, hydrogeological, and geotechnical factors affecting both phenomena, outlining their opposing mechanisms. The study proves the necessity of the establishment of a holistic development plan supported by focused geotechnical and hydrogeological studies. This way, the occurrence and the diametric drivers of both types of catastrophic events can be evaluated and predicted, minimizing their effects on the mining activities and the surrounding environment.

Keywords Mining hazards · Land subsidence · Landslide · Opencast mines · Amintaio coal mine

Introduction

The term "mining hazard" includes all kinds of hazards and catastrophic events related to or triggered by mining activities. Such events can occur at both active and inactive mines and include collapses of underground cavities migrating to the surface (e.g., Wanfang 1997; Gongyu and Wanfang 1999; Caramanna et al. 2008); slope failures in opencast mines (e.g., Vaziri et al. 2010, Carlà et al. 2019); tailing pond failures (e.g., Sammarco 2004; Riba et al. 2006; Rico et al. 2008); land subsidence phenomena (e.g., Bell et al. 2000; Carnec and Delacourt 2000; Stecchi et al. 2012); environmental pollution by toxic waste (e.g., Muezzinoglu 2003; Márquez-Ferrando et al. 2009); and the potential triggering of small earthquakes (e.g., Glowacka 1993; Šílený and Milev 2008). One of the main problems regarding these hazards is that in several cases, the actions taken to mitigate one mining hazard trigger another, potentially generating an endless chain of catastrophes. For instance, the restoration of abandoned opencasts by turning them into lakes increases stability issues for the remaining mining slopes and at the same time amplifies the outflow of pollutants towards the surrounding aquifers. The case study described in the current paper concerns two catastrophic

This paper was selected from the 1st Conference of the Arabian Journal of Geosciences (CAJG), Tunisia 2018

Responsible Editor: Amjad Kallel

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events occurring at the perimeter of an opencast coal mine that had diametric drivers: land subsidence triggered by the intensive dewatering of the slopes and extensive slope failures triggered, among other factors, by the inefficient dewatering of the slopes. Due to this conflict, in this case study, some type of catastrophic event would occur regardless of the dewatering intensity.

Specifically, the current study focuses on the plain surrounding the Amyntaio opencast coal mine. The deep wells draining network for the protection of the slopes has been draining the surrounding area for decades, forming an extensive depression cone. The land subsidence phenomenon extends for 1–3 km around the mine and has damaged infrastructure and several villages since 2002 (Loupasakis 2006, 2010; Loupasakis et al. 2014; Tzampoglou and Loupasakis 2016, 2017, 2018). Besides that, a massive landslide of approximately 80 million cubic meters occurred at the working slopes of the mine on June 10, 2017, leading to the permanent evacuation of one of the villages and causing extremely severe damage to the mine.

The current research aims to (a) describe the June 10, 2017, landslide, which is listed as one of the ten most extensive and catastrophic open pit failures worldwide; (b) provide a brief overview of the widely studied land subsidence phenomenon affecting the area surrounding the open pit; and (c) correlate the geological, hydrogeological, and geotechnical factors driving both phenomena, indicating their diametrically opposed causal factors.

The study area

The Amyntaio opencast coal mine is located in the Amyntaio subbasin of the West Macedonia prefecture. This subbasin is part of the tectonic trench of Elassona-Servia-Kozani-Ptolemaida-Amyntaio-Florina-Bitola, extending from Elassona (Greece) up to Bitola (North Macedonia) and divided into subbasins due to the Pleiocene extensional geotectonic field. The Amyntaio subbasin includes four lakes (Vegoritida, Petron, Chimaditida, Zazari) and a fertile plain area of approximately 220,000 km^2. It was formerly an area of the country with an exceptional natural environment, which has been severely disturbed by the extensive mining activities.

The Amyntaio opencast coal mine, located at the SE part of the basin (Fig. 1), has been operating since 1987, with the first years of its operation dedicated to the modulation of the site and to the removal of the cover layers of the coal seams. Since 1993, an extensive draining network including numerous deep wells has been installed for the protection of the slopes. Currently, the excavation reaches a depth of approximately 210 m. The operation of the mine is expected to cease in a few years, and a replacement mine has already been excavated near the village of Filotas, northeast of the Amyntaio mine.

Geological, geotechnical, and hydrogeological setting

The wider Florina-Amyntaio-Ptolemaida basin is occupied by crystalline-schist bedrock covered by Neogene and Quaternary deposits.

The bedrock formations are either members of the Triassic–Jurassic carbonate cover (karstified and fractured crystalline limestones, marbles, and dolomite marbles) of the Pelagonian zone or Paleozoic metamorphic rocks (gneiss, amphibolite schists, and quartzes). It should be noted that the karstified carbonate formations also occupy the bedrock of Lakes Vegoritida and Petron. There is a clearly identified connection between the karstic aquifers and the lakes underneath the Neogene deposits.

The Neogene deposits are divided into three series (the lower, lignite, and upper) with a maximum total thickness of approx. 450 m (Koukouzas et al. 1979, 1981) (Fig. 2). The lower series consists of sandy clays, clay sands, and, rarely, conglomerates and marls. There is a clear predominance of sands. The upper series consists mainly of sandy clays to marls, fine-grained deposits of fluvial-lacustrine origin. The lignite deposits, with a total thickness of approx. 150 m, are further divided at the upper and lower lignite layers by a sterile layer of marl, up to 15-m thick. Bedding-parallel shear zones filled with clay materials can be identified in the marls at all depths (Leonardos and Terezopoulos 2003). These zones of very low remaining shear strength play a dominant role in the stability conditions of the slopes, as they can act as failure plains (Fig. 3). Considering the hydrogeological behavior of the lower series, the coarse grain layers allow the development of confined aquifers, in communication with the karstic aquifers of the bedrocks, underneath the coal seams.

The Quaternary deposits are divided by Koukouzas et al. (1979) from bottom to top as follows: (A) The Proastion Formation, consisting of alternating layers of loose sand to clayey sand and conglomerates with red clay. This formation, of low-middle Pleistocene age (IGME 1997), overlies the Neogene deposits with stratigraphic unconformity. It is a permeable formation, reaching, at the perimeter of the mine, down to depths of approximately 120 m (Fig. 2). (B) The Perdikas Formation, consisting mainly of intercalations of fine sand with alternating layers of sandy clays, clays and marls. At the perimeter of the mine, this low to middle Pleistocene age formation (IGME 1997) reaches a maximum depth of approximately 70 m. It is a normally consolidated formation with a high compressibility index, and as a result, it is highly susceptible to the manifestation of land subsidence (Loupasakis et al. 2014). (C) The Anargiri Formation, including clayey sand or thin sand interrupted by clay layers or lenses with angular fragments. This Middle Pleistocene formation occupies hilly areas surrounding the plain, and although it is not intersected

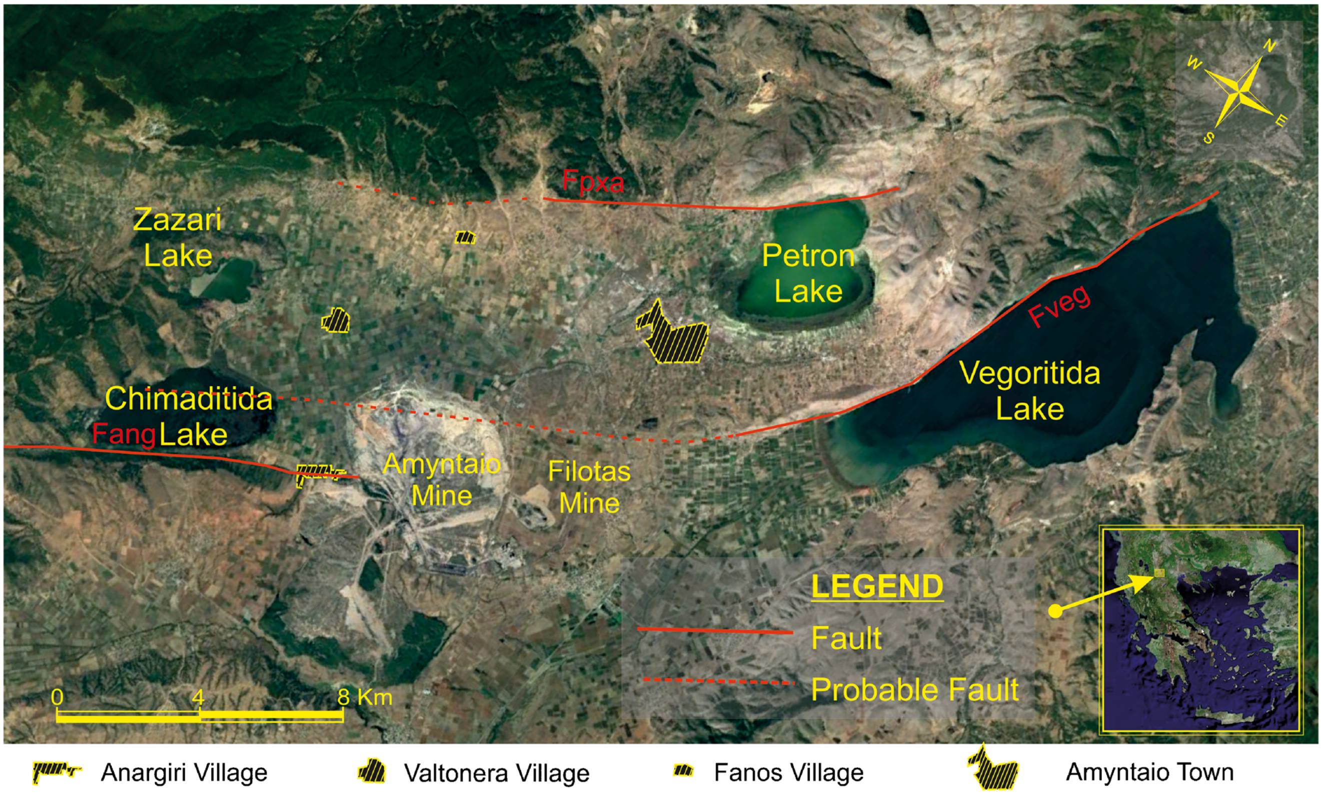

Fig. 1 Location map presenting the Amyntaio subbasin including the Amyntaio opencast coal mine. The active faults (Fang, Fveg, Fpax) intersecting the plain are also indicated

by the slopes of the mine, it forms the foundation of the village of Anagriri.

The dominant tectonic lines, related to the extensional strain field active since the Middle–Upper Miocene, are the Anargiri (Fang), Vegoritida (Fveg) and Petron-Xinou Nerou (Fpxa) normal faults, extending in a NE–SW direction (Pavlides 1985; Pavlides and Simeakis 1988; Mountrakis et al. 1998; Mountrakis et al. 2006). The Anagiri fault intersects the southeastern end of the working slopes of the mine, passes through Anargiri and extends southwest bordering Lake Cheimaditida (Fig. 1). The Vegoritida Fault borders Lake Vegoritida and extends southwest, crossing the Amyntaio plain with several branches. Some of its branches have been identified as crossing through the mine as well as underneath Valtonera village. Finally, the Petron-Xinou Nerou fault follows the northwestern borders of the plain, bordering Lake Petron. The branches of the Petron-Xinou Nerou fault cross underneath Fanos village. Several parallel faults have been identified along the slopes of the mine. It is of great importance to note that almost all of the surface ruptures related to the land subsidence phenomenon are parallel to the main tectonic lines, and some are even located along the projection of the fault lines to the surface (Loupasakis et al. 2014).

Considering the hydrogeological settings of the study area, two aquifer systems can be identified: a shallow semiconfined aquifer system hosted in the Quaternary deposits and a karstic aquifer system in the crystalline bedrock formations (Dimitrakopoulos 2001). The systematic exploitation of the shallow aquifers began after the land redistribution in 1974. The operation of deep draining wells for the protection of the

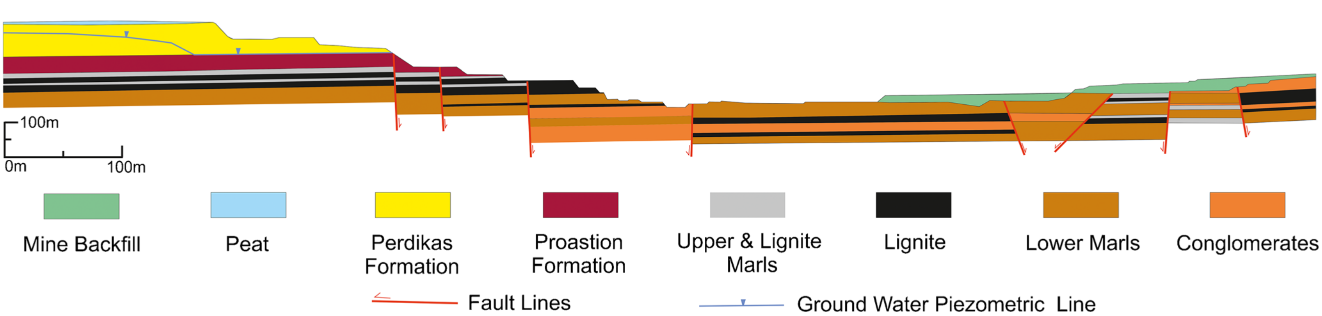

Fig. 2 Schematic geological cross-section of the mine presenting the key geologic formations and the position of the aquifer piezometric surface

slopes beginning in 1993 combined with increasing agricultural irrigation radically changed the setting of the aquifers, finally triggering the land subsidence phenomenon.

Evaluating data obtained from deep drills, the piezometric level of the karstic aquifers system seems to be more than 100 m above the bottom floor of the open pit. Considering the geological structure of the site, it is clear that the piezometric loads of the karstic aquifers were transferred by means of the coarse grain layers of the lower Neogene series close to the excavation's floor (Fig. 2). Obviously, the combination of the high piezometric loads with the occurrence of the bedding-parallel shear zones generates negative slope stability conditions.

Overview of the land subsidence phenomenon

The mining activities as well as the increasing agricultural activities in the study area have led to a significant drawdown of the groundwater level in recent decades, triggering an extensive ground subsidence phenomenon. The subsidence has caused damage to villages, infrastructure and farmlands at the perimeter of the Anargiri mine (Loupasakis 2006; Tsourlos et al. 2007; Soulios et al. 2011; Loupasakis et al. 2014; Tsourlos et al. 2015).

The influence of the mining activity on the aquifer's piezometry can be easily evaluated by studying the diachronic changes in the spatial distribution of the isopiezometric contour lines. As presented in Fig. 4a, during 1992 and before the operation of the deep draining wells, the groundwater flowed from the perimeter of the plain towards its center and finally towards Lake Petron, located at a lower altitude (Dimitrakopoulos 2001). Later groundwater level measurements revealed that due to the draining works at the perimeter of the mine, the flow pattern gradually changed, driving the groundwater towards the open pit. To illustrate, Fig. 4 b and c clearly show the depression cone that formed at the perimeter of the open pit during 2011 (Loupasakis et al. 2014) and 2016 (Tzampoglou and Loupasakis 2016), respectively. Furthermore, the 2016 piezometric contour lines indicate that due to the extension of the depression cone, the groundwater flow towards Lake Petron has been reversed.

By extracting the 2011 and 2016 piezometric surfaces from the initial surface referring to 1992 (Figs. 4 d and e), it is clear that the depression cone extends west of the mine to Lake Chimaditida and northwest to Valtonera village (Loupasakis et al. 2014; Tzampoglou and Loupasakis 2016; Dimitrakopoulos and Koumantakis 2017). Also, during 2016 the maximum drawdown of the piezometric surface was more than 60 m at the southern slopes of the mine and approx. 100 m at the north–northeastern slopes.

The land subsidence deformations were initially recorded at Anargiri village in 2001, and by 2006, the phenomenon affected the entire study area. The strike direction of the surface ruptures is parallel to the NE-SW direction of the main tectonic lines (Fig. 5). Also, the differential vertical displacements identified along the surface ruptures are inversely proportional to the distance from the mine.

The strict confinement of all of the tension cracks within the limits of the depression cone as well as their gradual debilitation in proportion to the distance from the mine connects them directly with the overexploitation of the aquifers. Furthermore, their continuous "aseismic slip", even during periods with no seismic activity, disconnects them from the tectonic activity of the basin.

The mechanical properties of the Quaternary geological formations also justify the occurrence of the land subsidence phenomenon in response to ground water redrawal and pore pressure reduction. In particular, the fine grain horizons of the Perdikas formation present high compression index (Cc) values, reaching up to 0.59 and 1.47 for the sandy silty clay and organic silty clay horizons, respectively (Tzampoglou and Loupasakis 2018). So, the increase in the effective stresses caused by the reduction of the pore pressure clearly triggers the consolidation mechanism, leading to the occurrence of the subsidence.

The mechanism of the June 10, 2017, massive landslide

The massive landslide of June 10, 2017, affected the working slopes of the mine along their entire length. The length of the sliding mass was 2.2 km and the width 2 km (Fig. 6). The foot of the failure has been identified as the base of the 210-m high slope, and the volume of the sliding mass was approximately

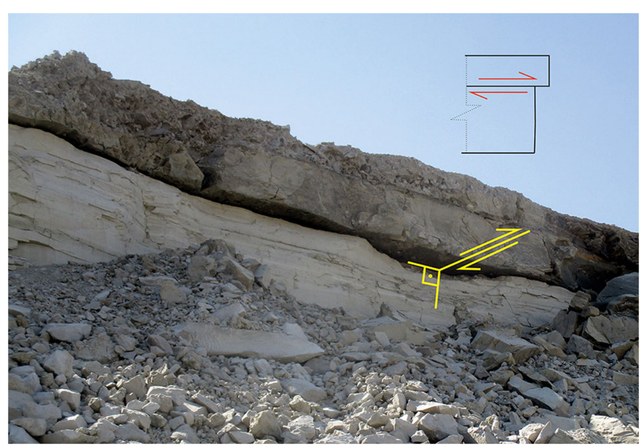

Fig. 3 Bedding-parallel shear zone. The presented sifting along the bedding plane is clearly related to shear movements. Picture taken from the slopes of an open pit mine excavated at the same formations within the wider limits of the basin

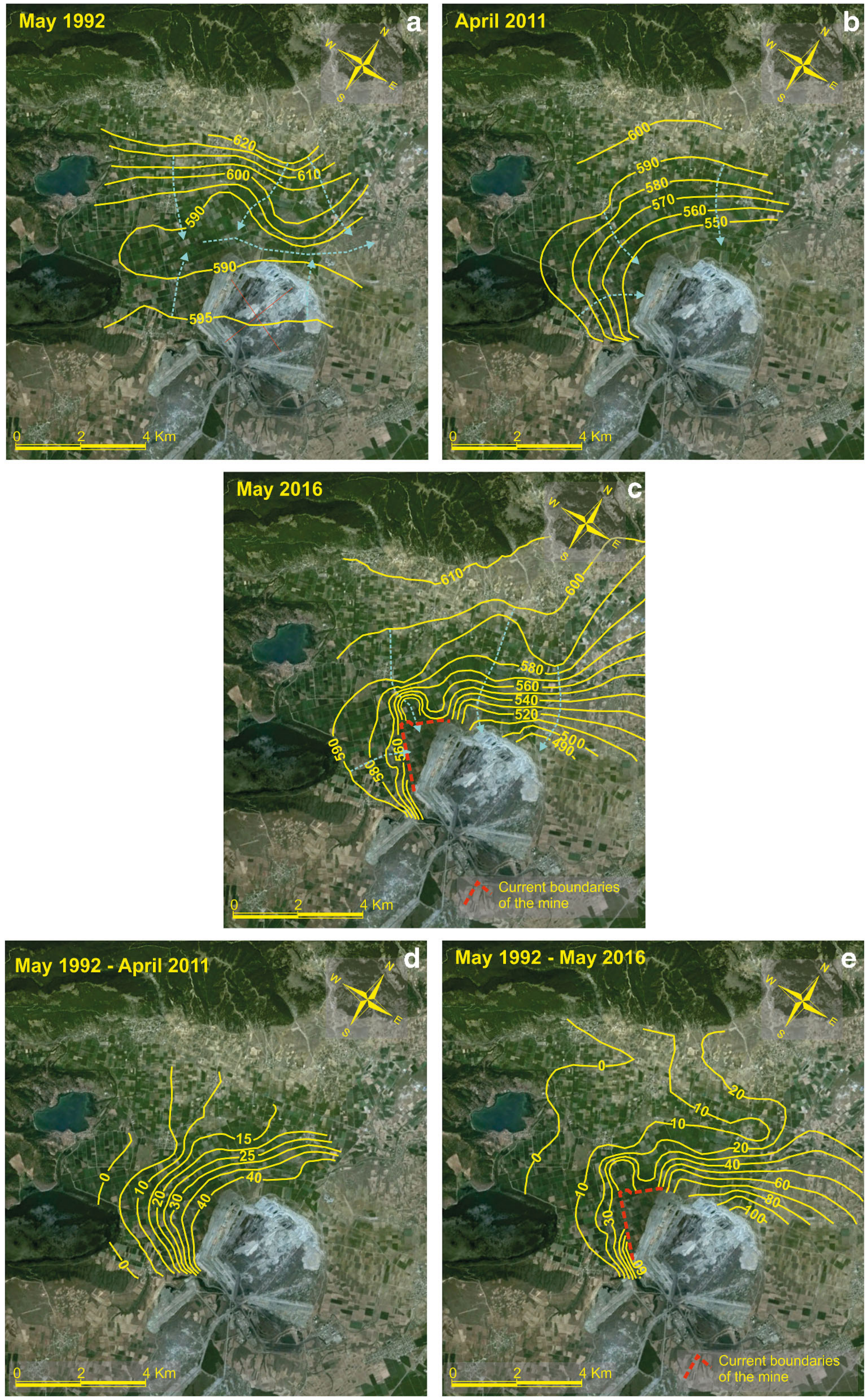

Fig. 4 Piezometric contour lines based on measurements conducted on three dates: **a** May 1992 (Dimitrakopoulos 2001) (The open cast was present at the time as shallow excavations with limited extent); **b** April 2011 (Loupasakis et al. 2014) and **c** May 2016 (Tzampoglou and Loupasakis 2016). Equal drawdown contour lines maps between **d** the piezometric surfaces of May 1992 and April 2011 and **e** the piezometric surfaces of May 1992 and May 2016. The blue dashed arrows indicate the groundwater flow direction

80 million cubic meters, burying 25 million tons of lignite. The failure caused extreme damage to the portable and permanent infrastructure of the mine as well as to the nearby Anargiri village (Fig. 7). In particular, four bucket wheel excavators at the mine (5000 to 1500 tons each) were severely damaged or completely destroyed; several hundred meters of conveyor as well as several smaller trucks and excavators were buried. At Anargiri village, the wastewater treatment

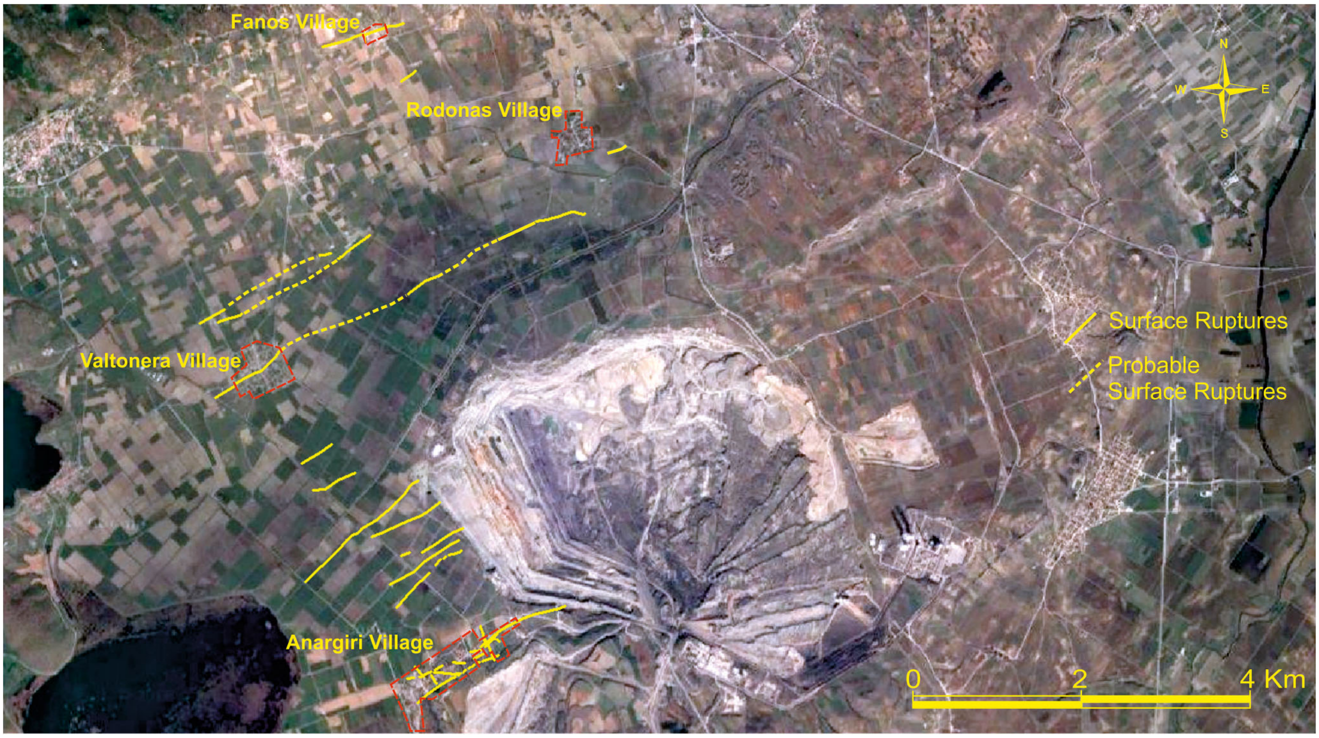

Fig. 5 Spatial distribution of the surface ruptures at the perimeter of the Amyntaio opencast mine before the occurrence of the slope failure (updated by Loupasakis et al. 2014; Tzampoglou and Loupasakis 2016)

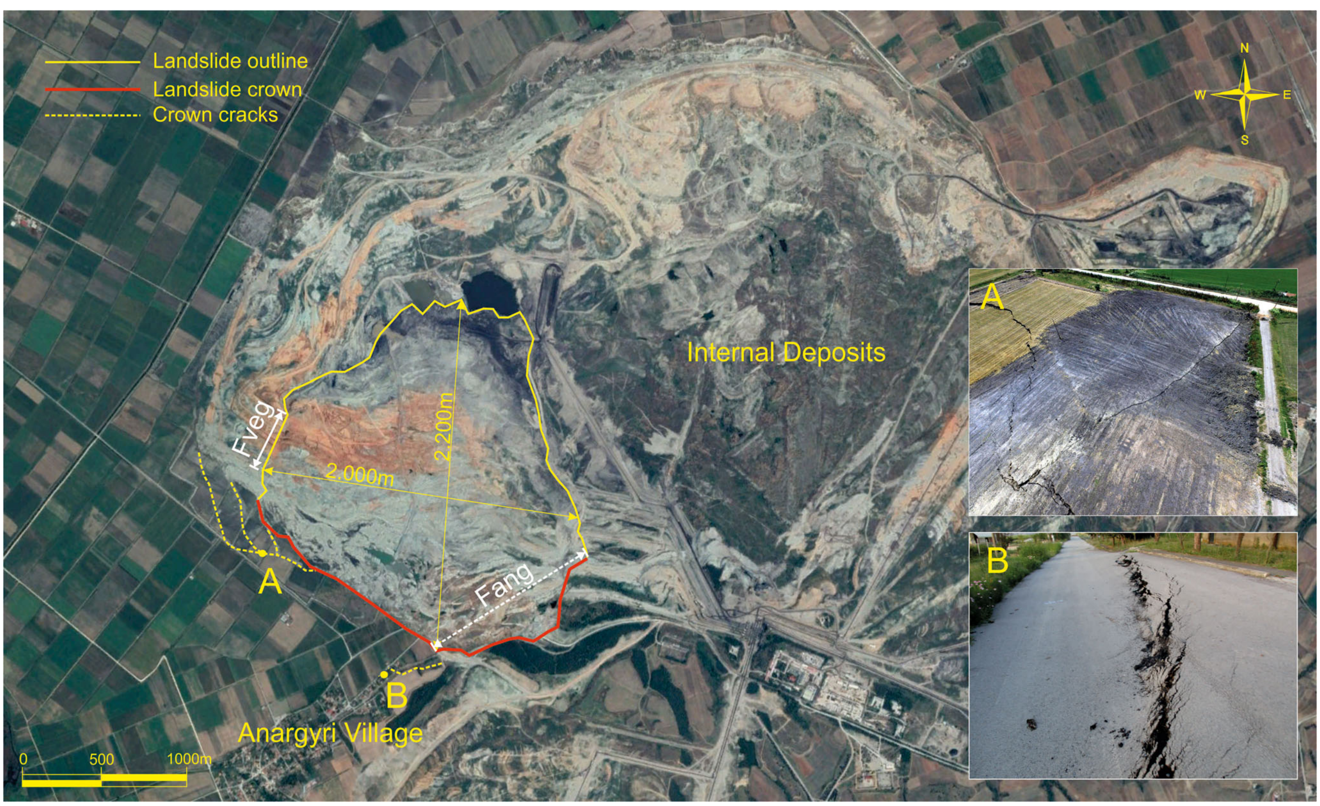

Fig. 6 The June 10, 2017, massive slope failure at the Amyntaio open pit coal mine. The intersection of the active Anargiri (Fang) and Vegoritida (Fveg) faults with the outline of the landslide is clearly indicated

Fig. 7 **a** A closer view of the western boundary of the landslide. Several meters of destroyed conveyor can be identified. The part of the outline coinciding with a segment of the Vegoritida fault is clearly indicated. **b** A 1500-ton bucket wheel excavator buried by the landslide. **c** A view of the part of Anargiri village affected by the landslide. The destroyed road network is also clearly presented. **d** One of the houses in Anargiri village damaged by the landslide. **e** The wastewater treatment plant of Anargiri village collapsed inside the open cast. **f** One of the archeological sites of the lacustrine Neolithic settlements located at the perimeter of the open cast before the occurrence of the landslide. **g** A closer view of an archeological excavation. The preserved traces from the wooden piles used for the foundation of Neolithic houses are presented

plant collapsed into the open cast, an entire neighborhood with houses up to two stories was damaged, the water supply and electricity infrastructure was destroyed, and the main roads connecting the village with the rest of the plain were severely damaged. In addition, several archeological sites of lacustrine Neolithic settlements located at the perimeter of the open cast were destroyed (Fig. 7).

Although the failure lasted 20 min, deformations at the perimeter of the open cast had been recorded for several months before the landslide. According to the Archaeological Services Agency, the archeological site located over the northwestern edge of the working slopes (Fig. 7f) had been subjected to deformations since 2014. At this particular site, the archeological excavations had been halted since November 2016, 8 months before the failure, due to the intensification of the deformations. At the perimeter of Anargiri village, deformations in the form of large surface ruptures affecting the roads and farms had been reported by the local authorities since February 2017, 5 months before the failure. Finally, the gradual increase in the deformation rates led the authorities of the mine to order the evacuation of the mine and the rapid removal of portable infrastructure on June 2, 2017, 8 days before the failure.

Aiming to evaluate the contribution of the active tectonics of the basin to the triggering of the landslide, the national database of earthquakes was indexed. As mentioned above,

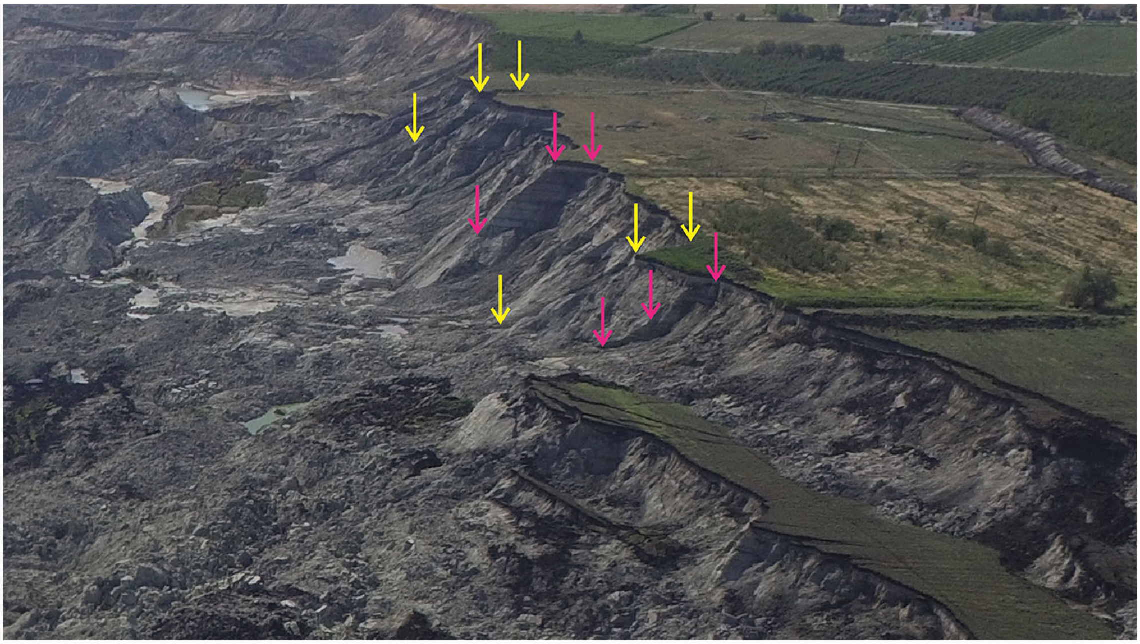

Fig. 8 Secondary faults located between the Anargiri (Fang) and Vegoritida (Fveg) faults (Fig. 1) intersecting the crown of the landslide. The colored arrows indicate the fault plains projected on the main scarp of the failure

three active faults have been identified in the Amintaio sub-basin, and two of them, the Anargiri fault (Fang) and a segment of the Vegoritida fault (Fveg), cross the open pit. According to the national database, the last earthquake with

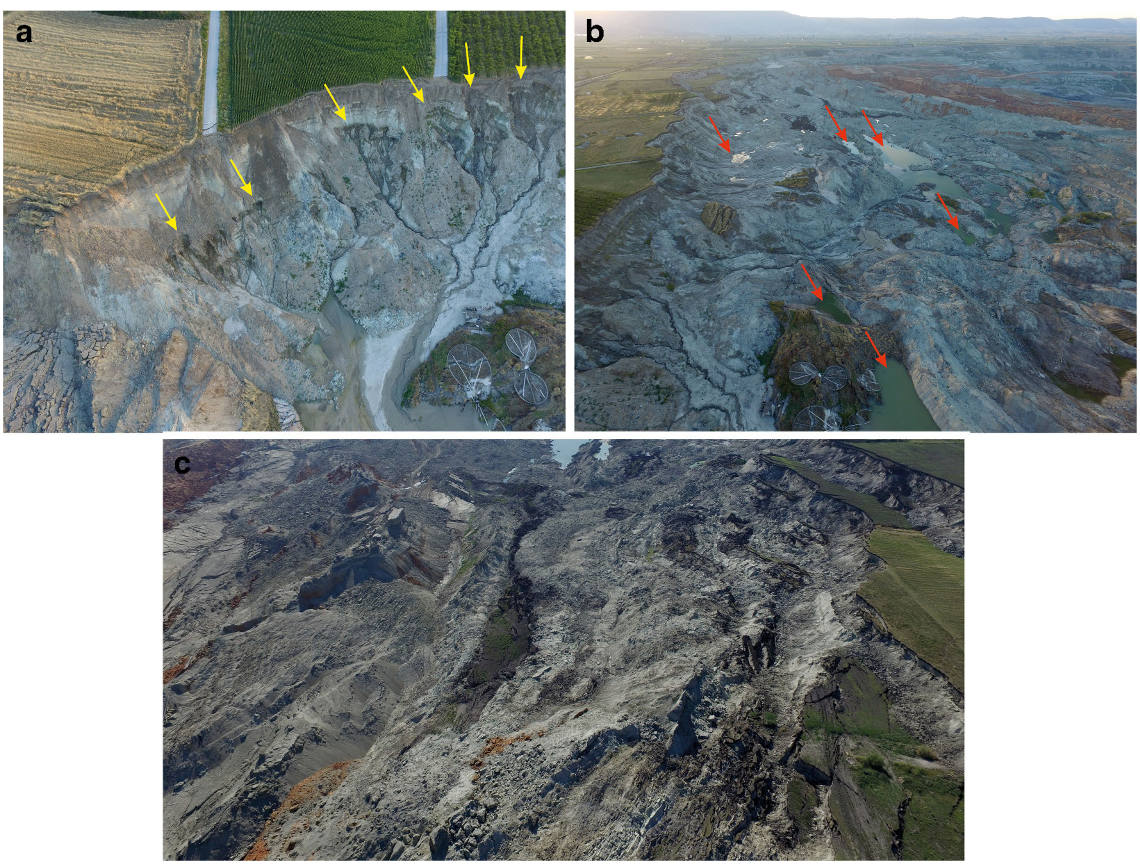

Fig. 9 **a** Groundwater coming out from the shallow aquifers intersected by the main scarp of the landslide (yellow arrows), right under Anargiri village. **b** View of the southeastern part of the scarp showing small ponds formed by the water coming out of the aquifers (red arrows). **c** View of the northwestern part of the scarp, which is totally dry due to the lack of groundwater

a magnitude larger than 2.5 was recorded 18 months before the landslide. With respect to micro-seismic activity, no earthquake with a magnitude less than 2.5 was recorded at the faults surrounding the mine in the 5 months before the failure. Thus, the triggering of neither the landslide nor the prefailure deformations can be attributed to the active tectonics of the site. Nevertheless, the existence of the faults, as presheared surfaces, certainly affected the formation of the geometry of the landslide mass. As indicated in Fig. 6, a segment of the Vegoritida fault defines a small part of the western boundary of the landslide mass, and the Anargiri fault intersects the crown and the eastern boundary of the landslide. Furthermore, several other secondary faults in the same direction intersect the landslide mass, affecting its morphology (Fig. 8). So the faults, active or not, are present at the site but did not contribute to the triggering of this particular failure.

The contribution of groundwater pore pressure to the manifestation of the failure was also evaluated. As mentioned above, the two aquifer systems identified at the site are a shallow semiconfined aquifer system hosted in the Quaternary deposits and a karstic aquifer system in the crystalline bedrock formations. The shallow aquifer system has been systematically overexploited for the protection of the slopes. However, as reported by Dimitrakopoulos and Koumantakis (2017), the intensity of the draining activities was not always the same. Before 2002, the deep draining wells were pumping out 13×10^6 m^3/year. Since then, the exploitation of the groundwater has gradually decreased, reaching 9×10^6 m^3/year in 2009 and 3×10^6 m^3/year in 2016. It is clear that the compaction of the aquifers gradually reduced their hydraulic conductivity, reducing proportionally the need for draining works at the well-established depression cone.

In addition to the decrease in draining activity, due to the damage caused by the land subsidence to Anargiri village, the draining activities in the vicinity of the village were practically ceased beginning in 2016. The effect of this change became visible after the failure, as groundwater was draining from the main scarp of the failure (Fig. 9). Based on this, it is clear that before the failure, the level of the aquifers in the southeastern part of the plain was high enough to affect the mechanical properties of the quaternary formations occupying the

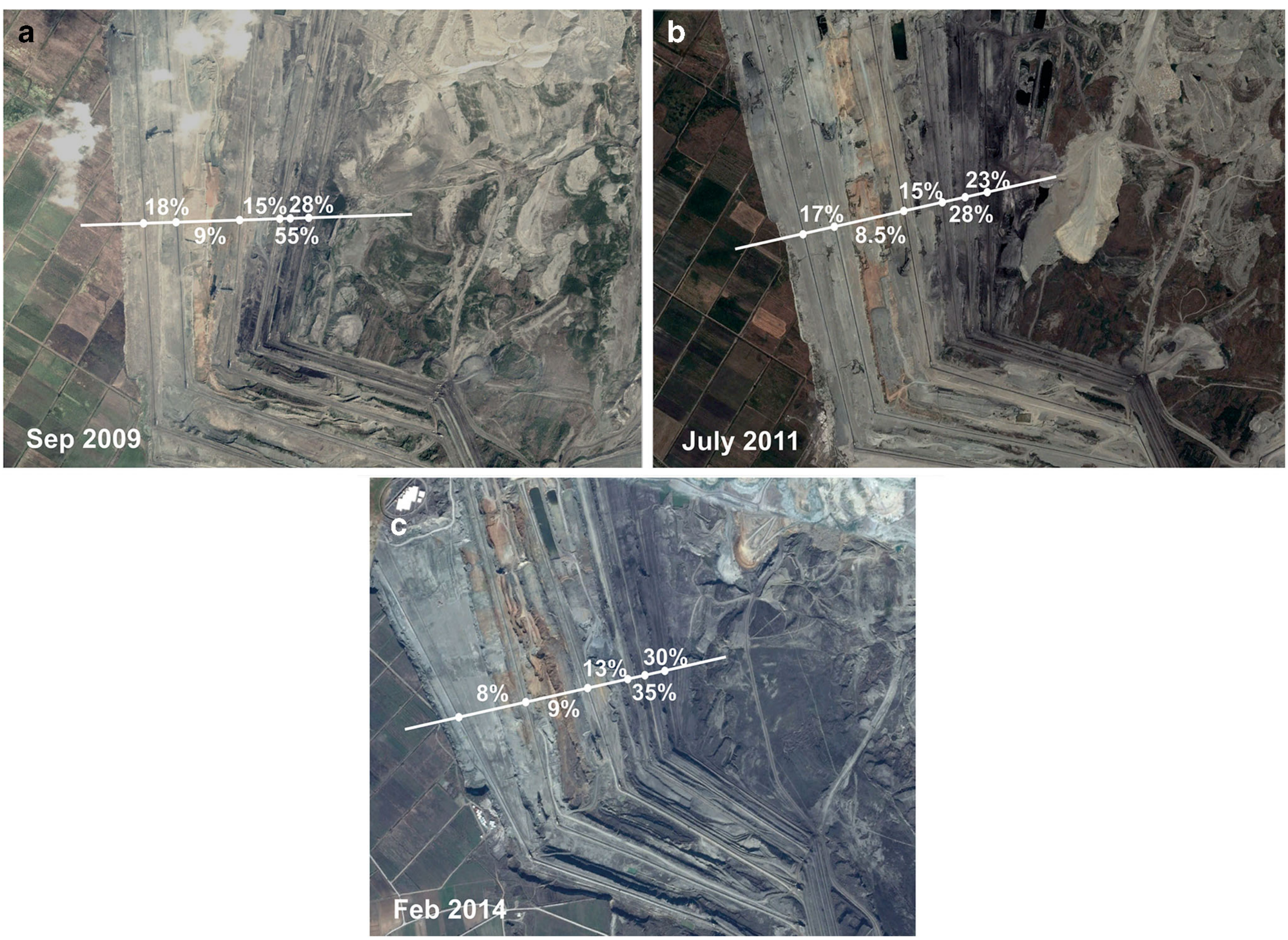

Fig. 10 The inclination of the slopes indirectly estimated based on the distance between successive conveyors (satellite images from Google Earth). The indicated inclination values prove that diachronically, the upper parts of the slopes had been kept gentler and the lower parts steeper

working slopes. In contrast, this was not the case for the northwestern part of the plain, as the operating deep draining wells were keeping the groundwater away from the working slopes. At this point, it should be noted that the June 10th failure started from the southeastern part of the working slopes of the mine.

Furthermore, the conditions established by the piezometric loads of the karstic aquifers, transferred through the coarse grain layers of the lower Neogene series close to the excavation's floor, had also established negative slope stability conditions at the working slopes.

The geometry of the working slopes is another crucial parameter that is able to trigger a slope failure. Reviewing all satellite images of the mine available from Google Earth (Fig. 10), it is clear that, diachronically, the two upper benches were excavated first, aiming to unload the slope. Next, extra priority was given to the excavation of the lower benches of the coal seams, aiming to keep up with the production needs. As a result, the excavation of the middle benches, occupied by the upper Neogene and the lower Quaternary formations, was systematically left behind. So the geometry of the working slopes was not even, as the upper parts had always been more gently sloped and the lower steeper.

Considering that the height of the benches was approximately 30 m, the horizontal distance between the conveyors in satellite images clearly indicates the inclination of the working slopes, as the smaller the distance between the conveyors, the higher the inclination (Fig. 10). The fact that the base of the working slopes is steeper definitely raises issues about the overall safety factor.

In conclusion, in evaluating the geological setting of the working slopes, it is clear that the occurrence of the bedding-parallel shear zones inside the Neogene formations, the numerous faults intersecting the site, the high piezometric loads

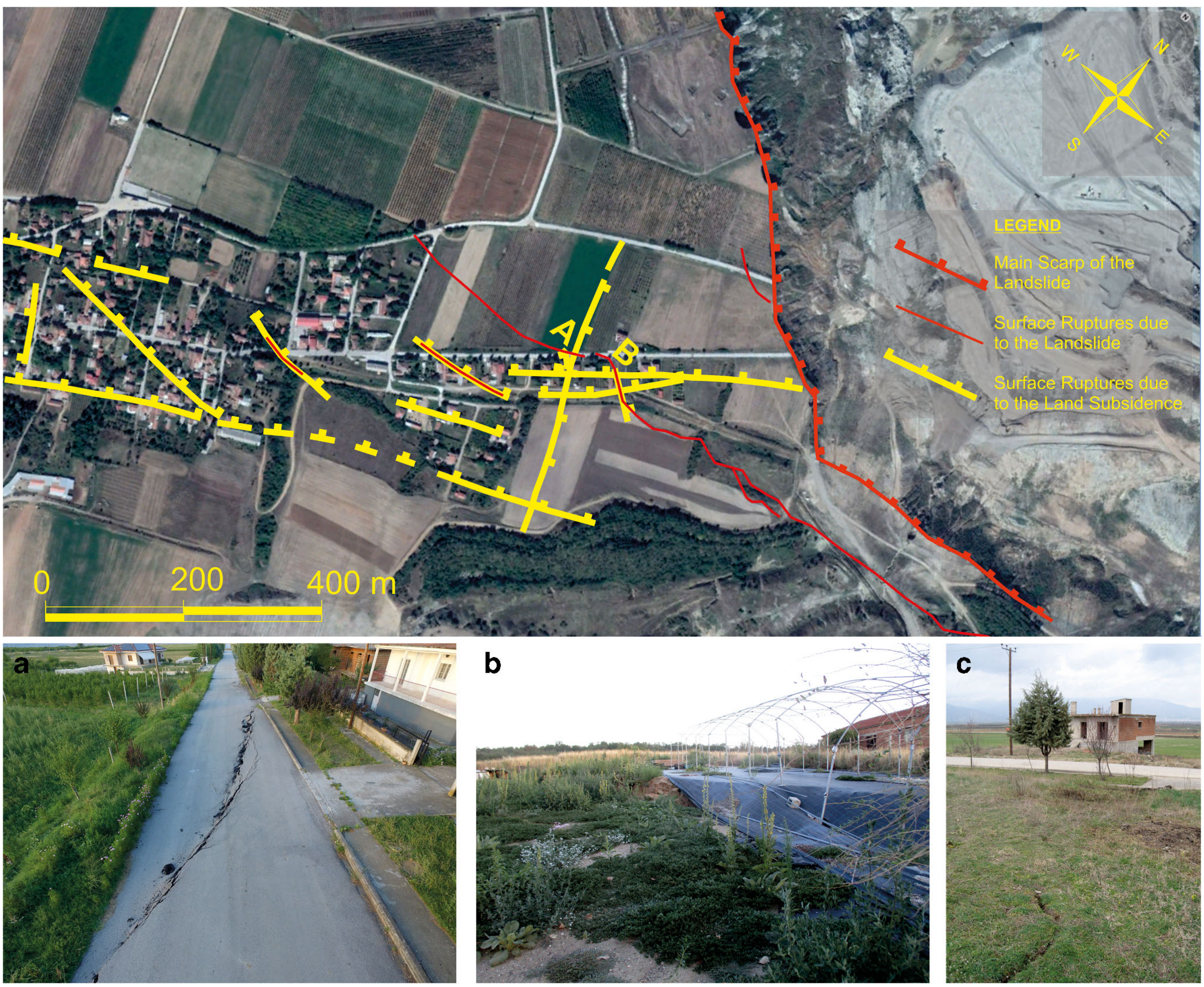

Fig. 11 The overlapping of the surface ruptures caused by the land subsidence phenomenon with those triggered by the landslide proves their interaction at the southwestern section of the working slopes. **a**, **b** preexisting surface ruptures intensified by the landslide event. **c** the surface rupture shown in **b** as it was recorded before the occurrence of the landslide

of the karstic aquifers underneath the floor of the open pit and the pore pressures applied by the shallow semiconfined aquifer were the main natural causal factors of the landslide. Apart from these, the partial failure of the deep wells draining system, resulting in increased pore pressures of the shallow aquifers, can be listed among the triggering causal factors, along with possibly the geometry of the working slopes. All of the above-described factors were adequately studied, but their interaction was not properly considered.

Discussion

Of the above-listed causal and triggering factors, the only factors affecting the driving mechanisms of both catastrophic phenomena are the occurrence of faults along the site and the pore pressure of the shallow aquifer system. Despite the first impression, the effects of those factors on each phenomenon diverge strongly.

In the case of the slope failure, the fault lines act as plains with reduced shear strength, partly defining the failure plain of the landslide. As already mentioned, the Anargiri and Vegoritida Faults as well as the parallel fault lines located between them can be identified along small sections of the perimeter of the failure body, or they can be identified intersecting the main scarp of the landslide.

In contrast, in the case of the land subsidence phenomenon, the faults determine the location of the surface ruptures, as their offset affects the thickness of the compressible Perdikas formation, triggering differential displacements along the projection of the faults to the surface. As was proven by examining the cross sections visible along the slopes of the mine, the bigger the offset of the faults, the thicker the compressible Perdikas formation layer over the hanging wall of the faults. So, the subsidence deformations are larger over the hanging wall, resulting in deferential deformations and surface ruptures along the projection of the faults to the surface.

In recording the surface ruptures generated in the plain area after the failure, it was interesting to note that some of them followed older ruptures generated by the land subsidence phenomenon. As presented in Fig. 5, during the years before the failure, some limited surface ruptures had developed at Anargiri village parallel to the piezometric contour lines of the depression cone, following an E-W direction. As it appears in Fig. 11, those ruptures were subjected to intensive deformations after the occurrence of the landslide, indicating that their reduced shear strength made them disposed towards displacements after the activation of the landslide. Overall, despite the fact that the fault lines affected the mechanisms of the two catastrophic events in different ways, the generated surface ruptures seem to interact with each other, amplifying the deferential displacements at the site.

Concerning the ground water pore pressures applied by the shallow aquifer system, their effects on the manifestation of the two catastrophic phenomena were diametrically opposed. The stability of the slopes is supported by the continuous deep wells' draining of the plain surrounding the open pit. As proven by the June 10th event, a partial failure or intentional recess of the draining wells can lead to a local rebound of the aquifers or even the local development of overhanging aquifers, reducing the shear strength of the geomaterials occupying the slope.

At the same time, the wide depression cone that formed around the mine due to the combined draining action of the open pit and the deep draining drills triggered the land subsidence phenomenon. The fact that the surface ruptures occurred within the limits of the depression cone and grew continuously regardless of the seismic activity of the site, combined with the fact that the deferential displacements along the rupture diminish in proportion to the distance from the open pit, justify the definitive correlation of the subsidence phenomenon with the draining activities.

Considering the possible response options, recessing the draining wells definitely is not the solution to the problem. This action would not restore the depression cone and certainly would not stop the land subsidence phenomenon. The only result of this action would be the slight shifting of the depression cone towards the open pit, as despite the recessing of the wells, the open pit would continue operating as a wide draining well. This shifting would reduce the safety factor of the slopes, as it increases the moisture of the geomaterials and the outflow of groundwater on the slope surfaces. So, the draining network should remain in operation.

Conclusions

In conclusion, among the geological, hydrogeological, geotechnical, and morphological factors affecting both catastrophic events, the main factor triggering them both in opposing directions was the groundwater level of the shallow aquifers. As clarified, the wide depression cone that formed around the mine due to the draining activities triggered the land subsidence phenomenon. In contrast, the failure of the draining wells can lead to a local rebound of the aquifers or even the local development of overhanging aquifers, reducing the safety factor of the slope.

Thus, the mining slopes should not be left unprotected from the groundwater, but at the same time, the human activities in the vicinity of the open pit should also be preserved.

On a practical level, the only solution to the problem can be the proactive establishment of a holistic development plan for the mine, supported by focused geotechnical and hydrogeological studies. That way, the development planners can identify whether and when it will be necessary to relocate villages and infrastructure before various failures affect the local communities. With this approach, the mining activities could continue undisturbed, not only without affecting the surrounding activities but also contributing to the development of the local communities.

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