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ORIGINAL ARTICLE

Ground subsidence, Quaternary faults and vulnerability of utilities and transportation networks in Thessaly, Greece

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Abstract Ground fissures and subsidence have caused extensive damage in structures and the utility networks (roads, railroad line, Larisa NATO airport, telecommunication network) in the plain of Thessaly, central Greece, in the last 20 years. The fact that these fissures are parallel to Quaternary faults controlling the structural evolution of the Thessaly basin, marked by intense recent seismic activity, led some scientists to regard them as manifestation of tectonic creep, even premonitory phenomena of major future seismic events. A careful study of the geometric characteristics and of the kinematics of these ground fissures, however, revealed that they only reflect shear failure of the ground due to compaction of loose sediments following significant decline of the groundwater level due to over-pumping; i.e. a geotechnical and not a tectonic process. Furthermore, theoretical considerations and modeling predict surface fissuring along zones of anomalous basement, normal-fault controlled topography. This explains the correlation between ground fissures and active Quaternary normal faults.

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Introduction

The region of Thessaly in central Greece (Fig. 1), famous for Mt. Olympus and its ancient gods, was affected between 1930 and 1980 by an unusual cluster of seven earthquakes of magnitude 6.0–6.8/7.0, succeeding a long period of relative seismic quiescence (Table 1, Papazachos and Papazachou 1997; Ambraseys and Jackson 1990). Some of these earthquakes were responsible for important death toll and widespread destruction, while two of them were associated with the reactivation of major Quaternary normal faults and surface ruptures (Papastamatiou and Mouyiaris 1986; Ambraseys and Jackson 1990; Papazachos and Papazachou 1997; Drakos et al. 2001).

Since 1986, numerous ground fissures appeared in the Thessaly plain, representing the major plain in Greece. These fissures cut roads, the railroad line and houses, and were initially assigned to compaction of sediments following large-scale pumping of water for agriculture. However, since in their majority they were correlating with Quaternary and active normal faults, and with vivid memories of fault-associated earthquakes in Thessaly and other parts of Greece (Papastamatiou and Mouyiaris 1986; Papazachos and Papazachou 1997), these ground fissures caused much nuisance and concern among population and scientists for a future seismic activity. In particular they had been regarded as evidence of aseismic tectonic creep, and even as premonitory phenomena of oncoming strong

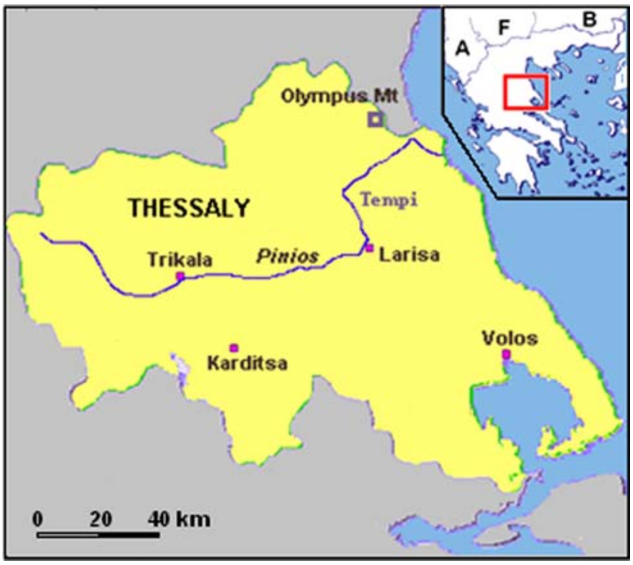

Fig. 1 Map of Thessaly. The Olympus Mt., the Pinios River and the Tempi valley are marked on the map. Inset: Location map for the Thessaly region in Greece. *A* stands for Albania, *F* for FYROM and *B* for Bulgaria

Table 1 Earthquakes in Thessaly between 1930 and 1980

Year	Epicentral area	Magnitude	
		Papazachos and Papazachou (1997)	Ambraseys and Jackson (1990)
1930	Offshore	6.0	5.9
1930	Offshore	6.0	6.0
1941	Larisa	6.3	6.1
1954	Sophades	7.0	6.7
1955	Volos	6.2	6.2
1957	Velestino	6.8	6.6
1980	Almyros	6.5	6.4

earthquakes, while several studies on this topic were funded by OASP, the Greek earthquake planning and protection organization (Kaplanides and Fountoulis 1997).

In this article we try for the first time to summarize and analyze the available information on these fissures and shed some light on the mechanism of their formation, especially their correlation with Quaternary, conspicuously active faults. Furthermore, information on other ground effects observed as sinkholes and evidence of land subsidence across the plain is discussed. An implication of our research is that these fissures represent a major threat for the utility and transportation networks crossing the Thessaly plain (roads, railroad, water channels, telecommunication fiber-optical cables, etc.), mostly of national importance.

Geological background

Thessaly is dominated by a vast plain, the largest in Greece, bounded by Alpine ranges. This plain, divided into smaller NW–SE trending plains, is a relict of a Pliocene Lake which was partly drained since the Lower Quaternary, after the opening of the Pinios River valley though incision along the flanks of Olympus Mt. (Fig. 1). The Eastern Thessaly Plain examined in this paper corresponds to a gently SE-dipping, nearly planar surface covered by a thick (up to 50 m deep) alluvium layer, relict of a Quaternary Lake, which was gradually restricted to the Karla Lake, at its lowest, SE part. This last lake was artificially drained in the 1960s to provide cultivated land.

The Eastern Thessaly Plain is bounded to the east by fault-controlled flanks of coastal ranges, more than 1,000 m high, in the SE continuation of Olympus Mt. All these ranges originate from rapidly exhumed and uplifting mantle rocks. To the SW, the Eastern Thessaly Plain is bounded by a ridge of Neogene hills and Alpine rocks (Fig. 2).

The stratigraphy and evolution of the Eastern Thessaly Plain are known from the results of extensive, drilling-based hydrological studies (mostly by SOGREAH 1974; Konstandinides 1978) as well as more recent morphotectonic studies (Caputo and Pavlides 1993; Caputo et al. 1995). These studies reveal that the Eastern Thessaly plain represents a tectonic depression of Quaternary age. Basement rocks are found at a depth of 50–250 m, although some deeper, probably tectonic depressions with the basement at a depth of 500–700 m, have been noticed. In some parts, however, basement rocks crop out slightly above the ground surface.

Quaternary sediments overlay basement rocks, mostly carbonate rocks and schists, except for a narrow strip of Neogene sediments along the western margin of the plain. Representative cross sections of the plain stratigraphy are given in Fig. 3.

The East Thessaly Plain Graben was mostly filled with fluvial and torrential deposits, especially at its northern and western part. Boulders and large masses of marble and limestone identified in these strata testify to high energy deposits, and represent the most important aquifers. On the contrary, at the SE part of the plain (former Karla lake), lower energy deposits, mostly clay and silt predominate, deriving from erosion of Neogene sediments at the SW margins of the plain.

From the point of view of hydrogeology, two major types of aquifers have been found: conglomerates and sandstones, mostly at the northern and western parts of the plain, and tectono-karstic depressions in the base-

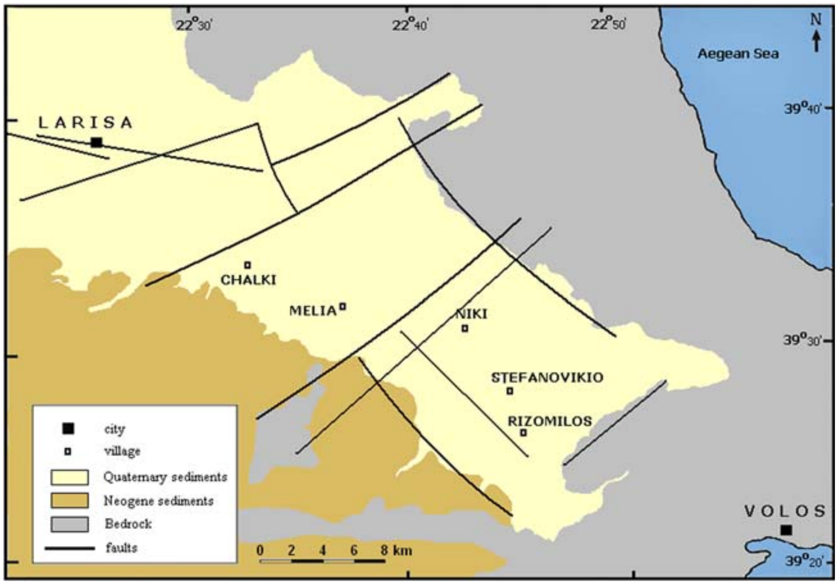

Fig. 2 Geological map of the eastern plain of Thessaly. Light shading (*light yellow*) corresponds to Quaternary sediments, medium shading (*brown*) to Neogene and dark shading (*gray*) to bedrock. Main faults marked are from SOGREAH (1974) and Caputo and Helly (2005)

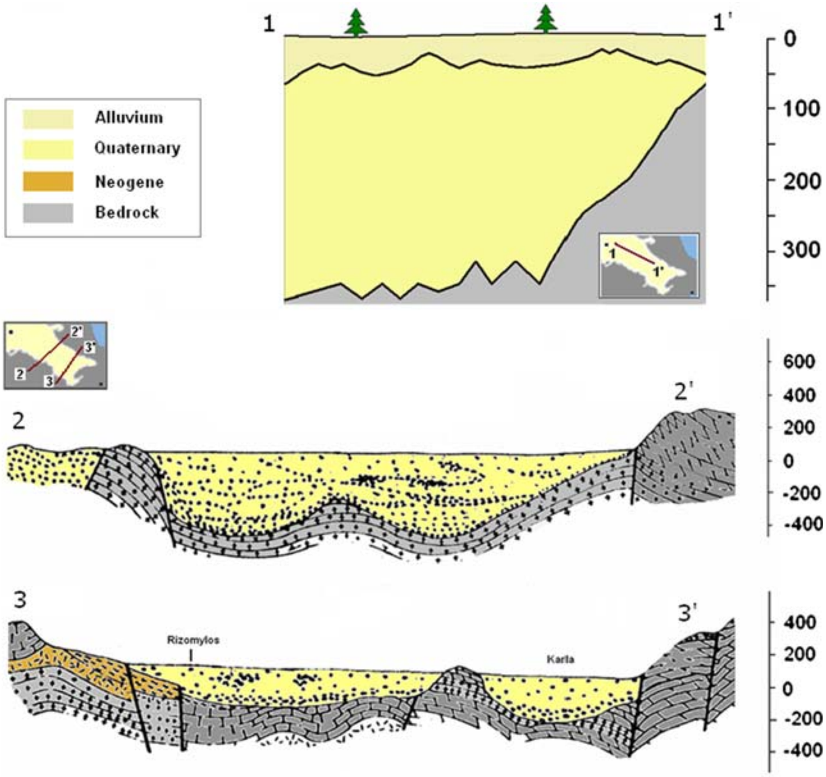

Fig. 3 Geological cross-section along the eastern Thessaly plain, based on data of Konstantinides (1978). For location see Fig. 9

ment and the margins of the plain. The majority of these aquifers, however, seem to be rather isolated and in most cases this hinders from their recovery following intense exploitation.

The amount of tectonic subsidence, several hundreds of meters during Quaternary (see above), earthquakes (see Table 1), fresh scarps (Caputo and Pavlides 1993) and continuing uplift of the Olympus mountain range (Stiros et al. 2005) reveal that the tectonics of the area are very active.

Land use and water pumping

The Eastern Thessaly Plain covers an area of > 450 km^2, and represents a region of fertile land with

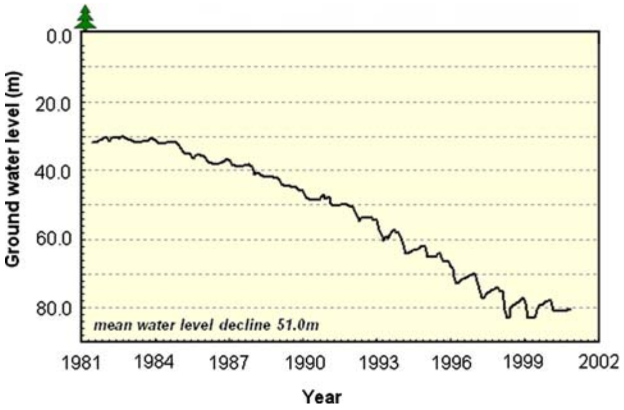

Fig. 4 A typical graph of groundwater withdrawal versus time at a borehole at Niki village area. Mean water level drop measured from the ground surface (at 0.0 m) is about 51 m in 20 years (1981–2001). Seasonal fluctuations of the groundwater table are also evident

high water resources, appropriate for hydrophilic agricultural production. The draining of the Karla Lake and of its swamps, covering the SE part of the plain, re-allotment of land in the 1970s and automation of farming led to a boom in farming, and increased the need for water. Since surface water could not cover such needs, thousands of uncontrolled drillholes and wells were bored for water pumping in the last 30 years. It is characteristic that only in 1984–1985 more than 5,000 new drill holes are known to have been bored (Gouvi 2003; unpubl. data of the Land Reclamation Services, Larisa). The uncontrolled exploitation of the groundwater led to progressive decline of the aquifer head and a continuous need for opening deeper drillings to exploit deeper aquifers. Between 1978 and 2003 the mean aquifer head level dropped between 10 and 50 m, with a maximum of 100 m (Fig. 4; see also Fig. 3 in Kaplanides and Fountoulis 1997).

Ground deformation

Since 1986, three types of ground deformation have been observed in the Eastern Thessaly Plain: (1) ground fissures, (2) sinkholes, and (3) land subsidence.

Ground fissures

In the last 20 years numerous fissures opened across the eastern Thessaly plain, cutting cultivated land, highways, roads, houses and even a strip of the Larisa NATO airport. Their main characteristics are summarized in Fig. 5 and Table 2.

Most of the fissures are characterized by a vertical component of displacement of up to a few tens of cm, while others are tension cracks, with an opening of up to several tens of cm. Fissures with both tensional and vertical displacement have been also registered. The fissures observed are a few to several hundreds of meters long.

A basic characteristic of most of these fissures is that they tend to expand, both as far as their length, their opening and their vertical offset are concerned. An example is shown in Fig. 6. Evidence of the fissures' expansion may derive from their effects on structures. Such an example is the destruction of a brick wall at Niki village: the wall broke suddenly in 1993 when a fissure (no. 12 in Fig. 5 and Table 2) appeared and movement of the wall, corresponding to the fissure

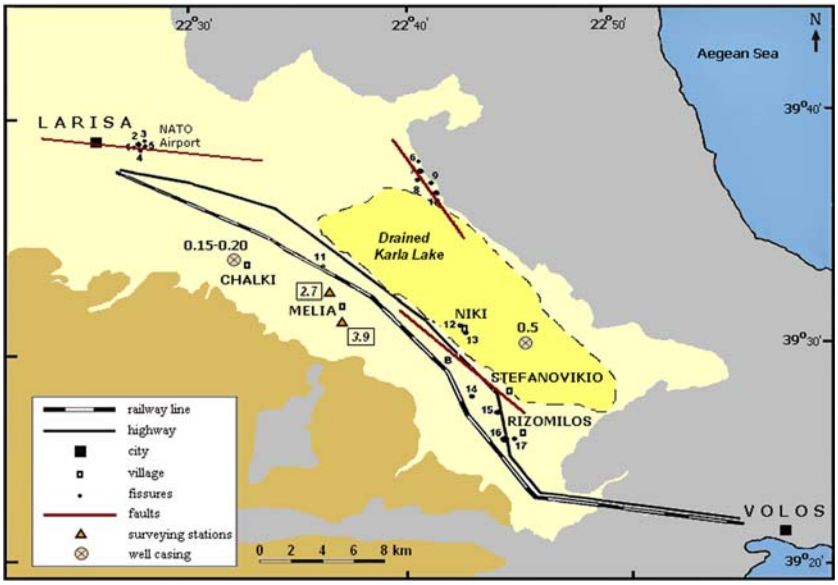

Fig. 5 Simplified geological map of the eastern plain of Thessaly of Fig. 2 with the drained Karla Lake. Ground fissures registered on Table 2 and data for land subsidence based on well casing protrusion and satellite surveying are marked. The railway and the highway lines crossing the plain are also drawn

Table 2 A list of the ground fissures recorded in the plain of Thessaly since 1989. Fissures' characteristics and their effects on structures and networks are noted. *TC* stands for tension cracks and *N* for normal cracks

Fissure no.	Date of first appearance	Place	Type of fissure(s)	Length (m)	Direction	Effect	Ref.
1–5	1996	Larisa NATO airport	TC	Up to 1,100	N 138°E	Damages to the airport installations	Kaplanides and Fountoulis (1997)
6	20/8/1990	Kastri	TC	~50	N 10°E	Cracks on houses	Eleytheriou and Aggelidis (1990)
7 and 8			TC	~200	N 70°E		
9	1/8/1990		TC	~200	N 25°E	Cracks on house walls and concrete yards	
10	1/8/1990		N	400	N 70°E N 80°E		
11	1993	Melia	TC/N	600	E/W	Damage to the railway	Kaplanides and Fountoulis (1997), this study
12	1993	Niki	N	450	N 120°	Cracks on house walls, sinkholes	
13	1994	Niki		>450	N 120°	Cracks on house walls	
14	4/10/1989	Stefanovikio	N	200	Various	Cracks on the national road	Eleytheriou (1989)
15	3/10/1989	Stefanovikio	N	400	N 70°E	Cracks on the national road	
16	1992	Rizomilos	TC	a few meters	N/W	Cracks at concrete yards	Aggelidis (1993), Pavlides (1998), this study
17	1993	Rizomilos	TC/N	300	N70°/80°E	Several cracks on house walls, concrete yards and the highway	

vertical offset, continues accumulating till today. Both an annual vertical offset of 2–3 cm, and a cumulative vertical offset of ~28 cm in the last 12 years can be derived from observations in this wall (Fig. 6c). It is remarkable that the observed 2–3 cm movement per year occurs between August to October, when groundwater pumping and lowering of the water table are maximum.

Quantitative estimates for fissure expansion are also available from precise leveling of the railway lines at Melia (for location see Fig. 5), after a ground fissure first cut the lines in August 1993. Increasing vertical ground movement resulted in curvature of the lines several months after first appearance of the fissure and was recorded through levelling. However, since vertical movements of the line were not allowed to exceed 15 cm, a limit for train safety, repeated control leveling surveys were made (Fig. 7) and the line was repaired once the curvature reached 15 cm. Hence, it was possible to document the continuity in fissuring but not its precise cummulative amount (Fig. 7).

Another characteristic of some, at least of these fissures, is that they appear (or increase) abruptly. Pavlides (1998) in particular reported a suddenly formed fissure (no. 17 in Fig. 5 and Table 2) which produced vertical offset in the Larisa-Volos highway and caused a car accident.

Sinkholes

In certain areas, for instance in Niki village, several small diameter sinkholes appeared (Fig. 6d). Close to this area, certain fissures (no. 12 in Fig. 5 and Table 2) have been observed.

Land subsidence

Well casing protrusion was probably the first effect of ground subsidence observed in Thessaly. For instance, protrusion of 20 cm in 4 years and bending of ~200 m deep pipes at a depth of 75 m at Chalki and protrusion of 50 cm at Magoula have been reported by Kaplanides and Fountoulis (1997). In most cases there was no sign of ground fissures or of differential settlements of buildings or of roads, indicating that associated land subsidence was rather uniform, or with a small gradient of deformation.

Geodetic evidence of land subsidence

No systematic studies of ground subsidence are available, but a preliminary comparison of differences between GPS data collected in 2005 and triangulation data of the 1980's revealed elevation differences to the order of 3–4 m in the Melia area (see Fig. 5 and Table 3). Certainly, these types of data are not directly comparable, but since the geoid gradient is very small in the area (H.M.G.S. 1983) and measuring sites nearby, such differences are likely to indicate post-1980 subsidence of several meters. A systematic geodetic study for the measurement of the land subsidence in the area is in progress.

Discussion

Ground subsidence due to sediment compaction following fluid withdrawal is an effect widely known

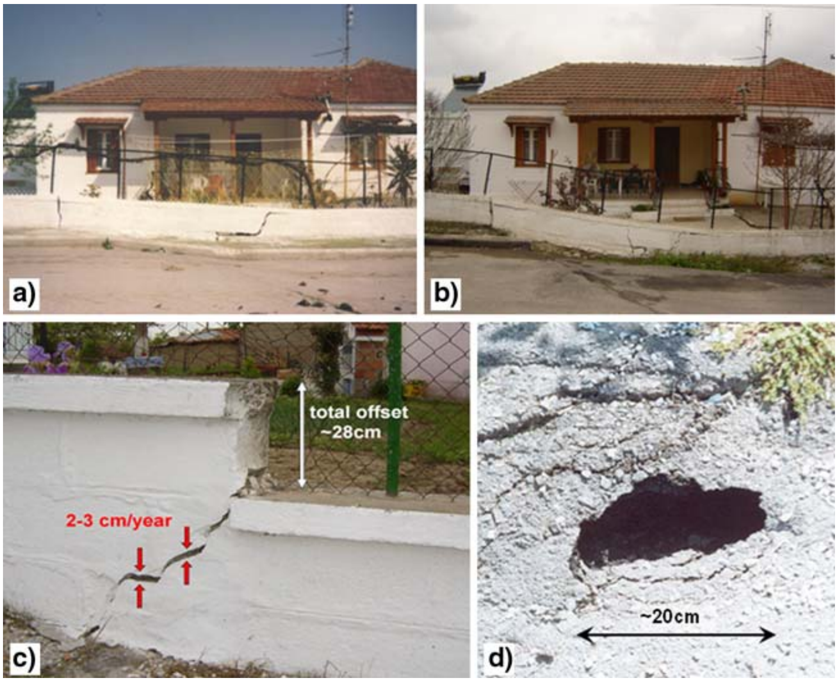

Fig. 6 Evidence of progressive ground subsidence at Niki village (for location see Fig. 5). **a** Photo taken in 2001, **b** photo taken in 2006, **c** vertical offset of a brick wall at Niki village. A cumulative offset of ~28 cm is measured on the wall since its first breakage in 1993. This subsidence originates from steps of 2–3 cm, occurring between August and October of each year, when maximum groundwater pumping takes place. Photo taken in spring 2006, **d** typical sinkhole at a concrete yard at Niki village. Photo taken in 2003

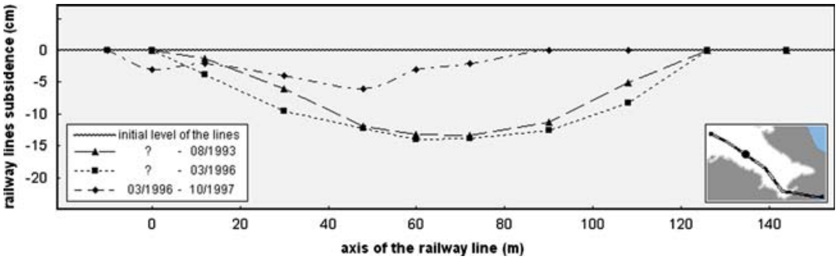

Fig. 7 Summary of results of three levelling surveys showing vertical deflection of the railway line at its intersection with a ground fissure (no. 11 in Table 2 and Fig. 5). When vertical offset exceeds the amount of 15 cm, the railroad line is repaired. Apparently, subsidence exceeded 50 cm between 1993 and 1997, but this is only a lower bound of total subsidence. Based on unpublished data from OSE S.A

Table 3 Data for land subsidence at the plain of Thessaly based on well casing protrusion and surveying studies

Date	Place	Land subsidence	Technique	Ref.
?–1997	Magoula Chalki	>0.5 m >15–20 cm	Well casing protrusion	Kaplanides and Fountoulis (1997)
1980–2005	NW of Melia S of Melia	~2.7 m ~3.9 m	Precise levelling, GPS surveying	Unpublished data

Question mark corresponds to the time of well casing installation (not known)

(Gambolati et al. 1974; Bell and Helm 1998; Sheng and Helm 1998; Thu and Fredlund 2000; Gambolati et al. 2005; Teatini et al. 2005), and under certain circumstances the amount of subsidence can be very high (for instance in the USA, Bull 1975; Lofgren and Klasuing 1969); for the Bangkok area, in particular, it was estimated that ground volume loss may be as high as one tenth of the drained water (Phien-wej et al. 2006). Well protrusion, land subsidence and ground fissures, typical manifestation and result of compaction of sediments, have been observed in Thessaly and can unambiguously be associated with an important aquifer level decline, especially in basins with limited groundwater circulation.

Still, the problem remaining is the correlation of active faults with ground fissures, a correlation which

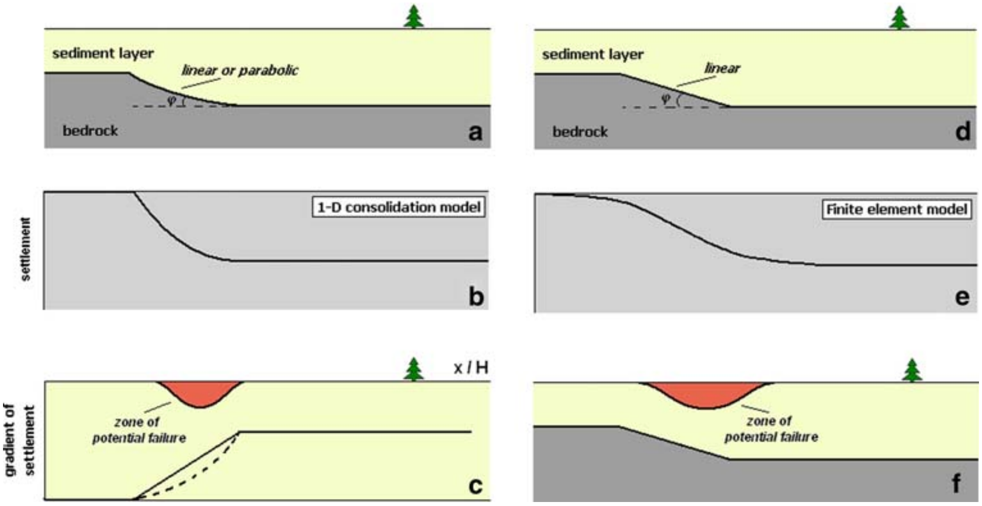

Fig. 8 Ground subsidence and locations of potential ground fissures due to compaction of a one-layer basin left: based on a simplified 1-D consolidation model, right: based on based a finite element analysis. **a**, **d** Basin models; **b**, **e** patterns of ground subsidence; **c, f** gradient of ground subsidence and position of potential fissures. In **c** the linear and parabolic line correspond to linear and parabolic pattern in (**a**), respectively. Modified after Bouwer (1977) and Skinner and Charles (1999)

led some investigators to interpret the later at least partly as tectonic effects and in particular evidence of pre-seismic creep (for a summary see Kaplanides and Fountoulis 1997).

In order to shed light on this correlation, ground settlements and fissuring related to soil compaction are discussed on the basis of (1) the fundamental one-dimensional Terzaghi consolidation theory, and (2) a finite element model of a basin undergoing large compaction; methods widely used in land subsidence studies (Venice, Gambolati and Freeze 1973; Hanoi, Thu and Fredlund 2000; Emilia-Romagna, Italy, Teatini et al. 2006; Skinner and Charles 1999).

According to well-accepted theories (Gambolati 1973a, b; Gambolati and Freeze 1973) subsidence v on the ground surface in the case of a single sediment layer of thickness s, subjected to significant lowering of the water table and pore pressure dissipation, can be approximated by the following linear simplified one-dimensional consolidation:

$$v = \alpha \cdot \gamma_w \cdot s \cdot \Delta h \tag{1}$$

where α is the compressibility of the soil material, γ_w the specific weight of water and Δh the piezometric change. At a first approximation Δh is a linear function of s:

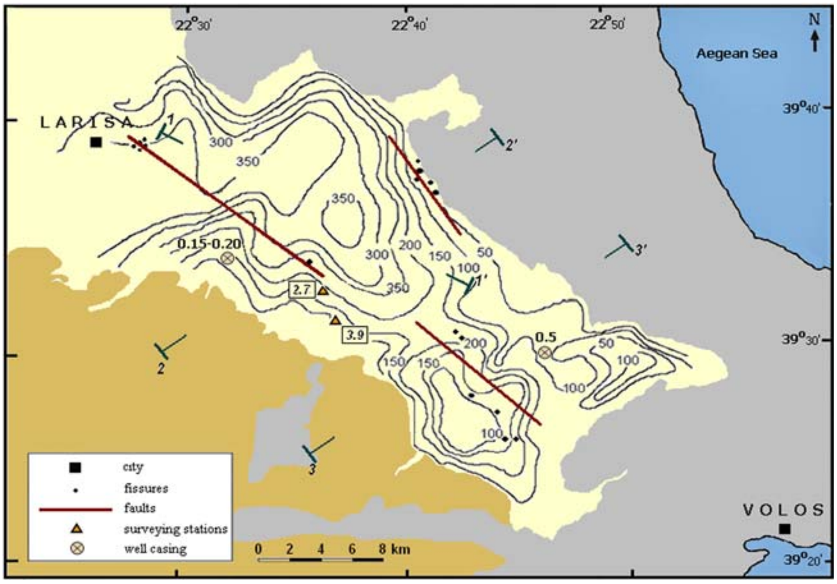

Fig. 9 Geological map of the eastern plain of Thessaly of Fig. 2. Ground fissures and Quaternary faults of Fig. 5 are shown. A correlation between basement topography gradient, conspicuously reflecting NW–SE trending Quaternary faults, is inferred. Evidence of land subsidence based on well casing protrusion and GPS measurements are marked. Positions of cross sections of Fig. 3 are also shown

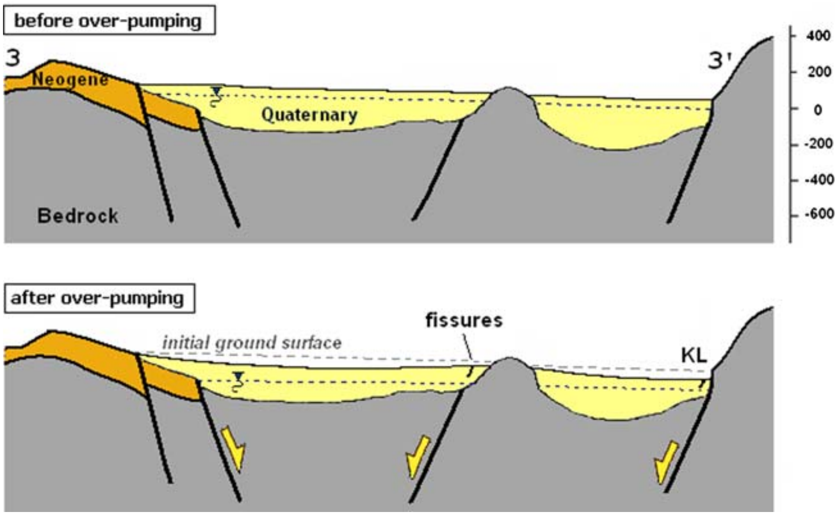

Fig. 10 Schematic profiles to explain subsidence and fissuring along section 3-3′ shown in Figs. 3 and 9. Ground fissures result from differential amounts of ground subsidence at areas of high-gradient of basement topography, controlled by Quaternary faults (see also Bell and Helm 1998). The latter correlates with surface ruptures and gives the wrong impression of fissuring controlled by fault activity

$$\Delta h = k_1 \cdot s$$

where k_1 is a constant, while at the margins of the basin or of basement topography anomalies, the thickness of the compacted layer, s can also be considered as a linear function of the distance x from the plain edge.

Hence:

$$v = k_2 \cdot x^2 \qquad (2)$$

where k_2 is a constant and the gradient of subsidence at the margins of the basin is:

$$\frac{dv}{dx} = c_1 \cdot x$$

while the gradient of sediment thickness is constant and their ratio:

$$\frac{dv/dx}{ds/dx} = c_2 \cdot x \qquad (3)$$

If at a second approximation the relationship of the thickness s and the distance from the basin margin is considered a second order polynomial:

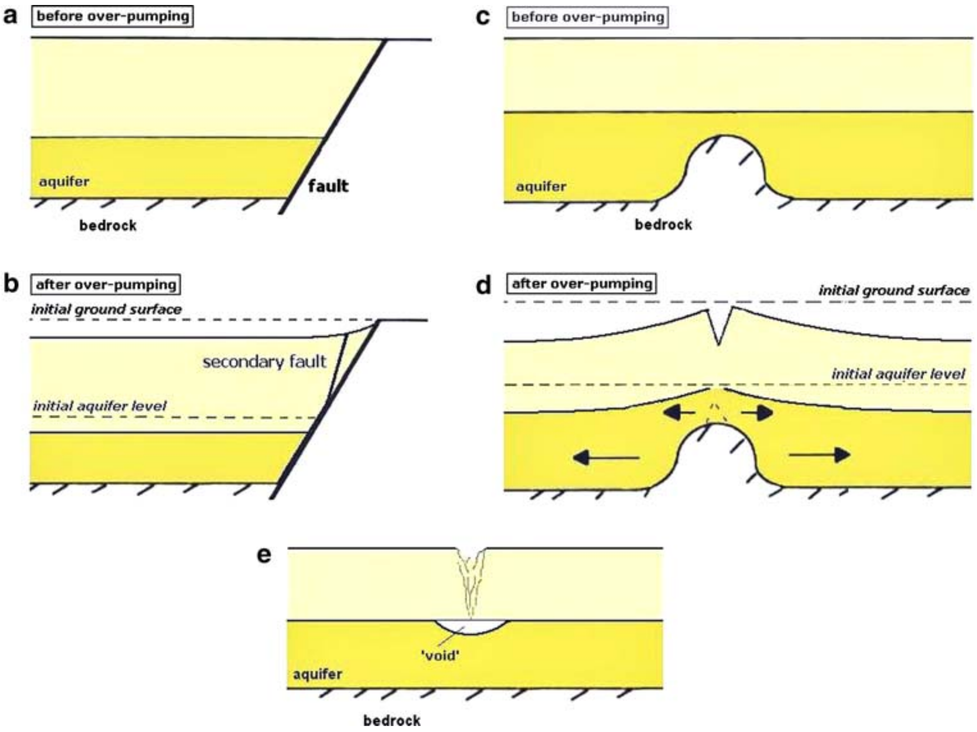

Fig. 11 Cartoons to explain formation of: **a**, **b** fissures (secondary faults) along existing Quaternary faults; **c**, **d** tensional cracks above a subsurface ridge; **e** sinkholes (small diameter craters) above subsurface voids, after groundwater table withdrawal due to over-pumping (modified after Bouwer (1977) and Sheng and Helm (1998)

$$s = k_3 \cdot x^2$$

where k_3 is a constant. Then Eq. 2 becomes:

$$v = k_4 \cdot x^4 \tag{4}$$

where k_4 is a constant. Similarly, the ratio:

$$\frac{dv/dx}{ds/dx} = c_3 \cdot x^2 \tag{5}$$

where c_1, c_2, c_3 constants.

Equations (3) and (5) indicate that at the margins of a basin or in the vicinity of areas of anomalies in the basement topography, subsidence increases more rapidly than the depth of compacted sediments (Fig. 8a, b; see also Bouwer 1977) and the gradient of subsidence increases with distance (Fig. 8c). In all non-ideal media, this increase of gradient of subsidence leads to zones of fracturing, the precise location and dimensions of which obviously depends on the shear strength of the rocks. A similar conclusion can be deduced on the grounds of finite element modelling, if subsidence gradient is calculated from the amount of predicted subsidence along an axis normal to the basin margins (see Fig. 8; Skinner and Charles 1999).

Hence, in the case of sediment compaction due to significant lowering of the groundwater piezometric surface, ground fissures are indeed expected along zones of steep ground basement gradient, and this result is valid for stratified basins, anisotropic soil materials and directed groundwater flows (Bouwer 1977).

Thus, since Quaternary faulting control to a major degree the structural and morphotectonic evolution of Thessaly (Caputo et al. 1995) and the thickness of post-alpidic filling of the Larisa plain, a clear correlation between Quaternary faulting and ground fissures induced by sediment compaction is obviously expected and is indeed observed: Figs. 9 and 10 indicate that in the east Thessaly basin ground fissures correlate with zones of high gradient of Quaternary sediments, conspicuously controlled by Quaternary faulting.

For these reasons, observed ground subsidence and fissuring have nothing to do with deep tectonic effects and fault creep. This does not mean that fault creep does not exist—geodetic data indeed provide some evidence for that, both for the Thessaly area (Stiros et al. 2005) and other parts of Greece (Stiros and Rondogianni 1985). Still, the amplitude of this effect is too small (<1 mm/yr) to explain observed rates of subsidence (see for instance Fig. 7).

In summary, compaction/consolidation of loose sediments after withdrawal of groundwater table is the causative effect of significant land subsidence and different types of ground fissuring over the Thessaly plain. To investigate the mechanisms of fissures formation on earth ground, different patterns of ground deformation, depending on subsurface morphology and ground characteristics, are discussed.

First, fissures resulting from differential settlements at locations of high gradient of sediment thickness (Figs. 10, 11a, b) are developed parallel to known Quaternary faults, as explained above. Their main characteristic is vertical displacement of up to several cm and their traces on earth surface are reminiscent of normal faulting. Clearly, they correspond to shear failure of the ground and appear mostly in summer when ground surface is dry, and hence more susceptible to ruptures. Evidence on the kinematics of such a fissure at Niki village, reveals that the fissure is ‘active’ during water table lows (August to October) and ‘inactive’ during periods of limited water exploitation and of seasonally elevated piezometric levels.

Second, fissures formed in case of tensional forces developed locally after rotational movement of the upper slab around underground ridges. Shrinkage of the ground volume above the ridge induces tension cracks, i.e. opening of the ground ranging up to several tens of cm (Bouwer 1977; Jachens and Holzer 1982; Fig. 11c, d). Such a fissure observed at the SE part of the plain in 1993 (Rizomylos village, fissure no. 17 in Fig. 5 and Table 2) is still apparent on the ground and structures, but was never activated since then.

Third, sinkholes taking the form of small craters on ground surface. Local anomalies of the compacted strata result in creation of ‘voids’ in shallow depth occasionally forming ground cracks and significant subsidence propagated to the ground surface (Fig. 11e).

Implications for the utility and transportation networks

Progressive subsidence and ground fissuring in Thessaly represents a threat for houses (Fig. 7) and civil and military infrastructure (see above). The problem is especially serious for ground fissures occur abruptly, and in one case a car accident was caused luckily without victims (Pavlides 1998). Obviously, it cannot be excluded that new fissuring will not cause serious problems if it occurs during airplane landing in the Larisa NATO airport, for instance, or during a train crossing a critical area.

While this remains a remote possibility, houses and utility and transportation networks seem vulnerable to ground fracturing and subsidence. The railroad line, for instance, needs a rather periodic repair; sewers and water networks may be broken, and drinking water may be contaminated, a situation not rare in Greece. Underground telecommunication networks (mostly fiber-optical cables of national importance) crossing this area roughly along the highway may continue to break because they are not designed to withstand shearing stresses imposed by normal offset ground fissures. Similar effects are not unusual, and have been, indeed, observed at much larger scales for instance in the drained Texcoco Lake near Mexico City, in many regions in Arizona, causing severe damage to the transportation network, and in several areas in California, where irrigational and other utilities were displaced up to several meters due to ground subsidence (USGS 2006).

Conclusions

Although Thessaly is tectonically active and conspicuously vulnerable to strong (magnitude > 6) earthquakes, observed ground fissures, despite their large amplitude and geographical extend, do not represent precursors of oncoming earthquakes and they clearly do not originate from earthquake-related effects; they are simply caused by sediment compaction resulting from rapid groundwater level decline following intensive, uncontrolled water pumping.

Ground subsidence and fissuring is expected to continue, with impacts in housing and utility and transportation networks. Control of such phenomena is not easy, given the listric water exploitation in the Thessaly plain. However, what is more feasible is that having identified the real causes of the phenomenon, to identify (1) areas vulnerable to increasing or future ground subsidence and ground fissuring, (2) the order of magnitude of expected ground deformation, and (3) expected impacts on housing and civil and military infrastructure of the area.

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References

Aggelidis C (1993) Geotechnics and safety evaluation at Rizomilos, Magnesia, after appearance of ground fissuring. Report of the Institute of Geological and Mineral Explorations, Athens, Report No 7122-E (in Greek)

Ambraseys N, Jackson J (1990) Seismicity and associated strain of central Greece between 1890 and 1988. Geophys J Int 101:663–708

Bell J, Helm D (1998) Ground cracks on Quaternary faults in Nevada: Hydraulic and tectonic. In: Borchers J (ed) Land subsidence case studies and current research: proceedings of the Dr. Joseph F. Poland symposium on land subsidence. Assoc Eng Geol Special Publication no 8, Star Publishing company, pp 165–173

Bouwer H (1977) Land subsidence and cracking due to Groundwater depletion. Ground Water 15(5):358–364

Bull W (1975) Land subsidence due to ground-water withdrawal in the Los Banos-Settlement City area, California. Part 2. Subsidence and compaction of deposits. US Geol Surv Prof. Paper 437-F, pp 90

Caputo R, Pavlides S (1993) Late Cainozoic geodynamic evolution of Thessaly and surroundings (central-northern Greece). Tectonophysics 223:339–362

Caputo R, Helly B (2005) Archaeological evidences of past earthquakes: a contribution to the sha of Thessaly, Central Greece. J Earthq Eng 9(2):199–222

Caputo R, Bravard JP, Helly B (1995) The Pliocene-Quaternary evolution of the Larissa plain (Eastern Thessaly, Greece). Geodynamica Acta 7:57–85

Drakos A, Stiros S, Kiratzi A (2001) Fault-parameters of the 1980 Volos (central Greece) earthquake (Mw = 6.5) from inversion of repeated levelling data. Bull Seismological Soc Am 91:1673–1684

Eleytheriou A (1989) Investigation of ground fissuring at Stefanovikio, Thessaly. Report of the Institute of Geological and Mineral Explorations, Athens, Report No 5991-E (in Greek)

Eleytheriou A, Aggelidis C (1990) Geotechnics and safety evaluation at Kastri village, Larisa, after appearence of ground fissuring. Report of the Institute of Geological and Mineral Explorations, Athens, Report No 6229-E (in Greek)

Gambolati G (1973a) Equation for one-dimensional vertical flow of groundwater.1. The rigorous theory. Water Resour Res 9(4):1022–1028

Gambolati G (1973b) Equation for one-dimensional vertical flow of groundwater. 2. Validity range of the diffusion equation. Water Resour Res 9(5):1385–1395

Gambolati G, Freeze RA (1973) Mathematical simulation of the subsidence of Venice. 1. Theory. Water Resour Res 9(3):721–733

Gambolati G, Gatto P, Freeze A (1974) Mathematical simulation of the subsidence of Venice 2. Results. Water Resour Res 10(3):563–577

Gambolati G, Teatini P, Ferronato M (2005) Anthropogenic land subsidence. In: Anderson MG (ed). Encycl Hydrol Sci. J Wiley 158(4):2444–2459

Gouvi C (2003) Ground fissures and subsidence at the eastern Thessaly plain. Diploma thesis, Dept of Civil Engn, Patras University, Greece (in Greek)

Hellenic Military Geographic Services/Geodesy Devision (1983) Determination of the components of relative deviation of vertical and of relative geoid heights N from free air gravity anomalies in Greece (in Greek)

Jachens R, Holzer T (1982) Differential compaction mechanism for earth fissures near Casa Grande, Arizona. Geol Soc Am Bull 93:998–1012

Kaplanides A, Fountoulis D (1997) Subsidence phenomena and ground fissures in Larissa, Karla basin, Greece: their results in urban and rural environment. In: Marinos P, Koukis G, Tsiambaos G, Sambatakakis G (eds) Eng Geol Environ. Balkema, Rotterdam, pp 729–735

Konstantinides D (1978) Hydrodynamique d' un systeme aquifere heterogene. Doctorat these. Universite de Grenoble

Lofgren B, Klasuing R (1969) Land subsidence due to groundwater withdrawal Tulare-Wasco Area, California. US Geol Surv Prof Paper 437-F:90–103

Papastamatiou D, Mouyiaris N (1986) The earthquake of April 30, 1954, in Sophades (central Greece). Geophys J R astr Soc 87:885–895

Papazachos B, Papazachou C (1997) The earthquakes of Greece. Zitis, Thessaloniki, pp 304

Pavlides S (1998) Message to the EQ-GEO-NET no 59, 19/12/1998

Phien-wej N, Giao PH, Nutalaya P (2006) Land subsidence in Bangkok, Thailand. Eng Geol 82(4):187–201

Sheng Z, Helm D (1998) Multiple steps of earth fissuring caused by ground-water withdrawal. In: Borchers J (ed) Land subsidence case Studies and Current Research: Proceedings of the Dr. Joseph F. Poland Symposium on Land Subsidence, Assoc Eng Geol Special Publication no 8, Star Publishing company, 149–154

Skinner H, Charles J (1999) Problems associated with building on a variable depth of fill. Ground Eng 32(7):32–35

SOGREAH Consulting Firm (1974) Study of groundwater circulation in Thessaly plain, Greece. Technical report, Athens (in Greek)

Stiros S, Rondogianni T (1985) Recent vertical movements across the Atalandi fault-zone (Central Greece). Pure Appl Geophys 123:837–848

Stiros S, Triantafyllides P, Chasapis A (2005) Geodetic evidence for active uplift of the Olymbus Mt., Greece. Bull Geolog Soc Greece 36/4:1697–1705

Teatini P, Ferronato M, Gambolati G, Bertoni W, Gonella M (2005) A century of land subsidence in Ravenna, Italy. Environ Geol 47(6):831–846

Teatini P, Ferronato M, Gambolati, G, Bertoni W, Gonella M (2006) Groundwater pumping and land subsidence in the Emilia-Romagna coastland, Italy: Modeling the past occurrence and the future trend. Water Resour Res, 42, W01406, doi: 10.1029/ 2005WR004242

Thu T, Fredlund D (2000) Modelling subsidence in the Hanoi city area, Vietnam. Can Geotech J 37:621–637

USGS —U.S. Geological Survey (2006) Land Subsidence in California. http://www.ca.water.usgs.gov/groundwater/. Cited 10 Apr 2006