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NEOTECTONIC JOINTS OF NORTHERN GREECE; THEIR SIGNIFICANCE ON THE UNDERSTANDING OF THE ACTIVE DEFORMATION

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ABSTRACT

In tectonically active areas, the neotectonic joints affecting the Neogene and Quaternary sediments are very significant structures for the (a) the determination of the contemporary stress field, and (b) the understanding of the shallow brittle deformation processes. This is indicated by the latest and most prominent, E-W trending joint set which affects the Neogene and Quaternary sediments of the Northern Greek mainland. This set comprises barren, mostly vertical, single-layer extensional fractures, less steep-inclined hybrid shear ones, which like to form distinct "joint zones". Their strike is fairly constant at each exposure, but varies from WNW-ESE to ENE-WSW among the different outcrops, but even in the same geographical area. It is commonly linked by the orthogonaly oriented N-S trending non-systematic cross-joints so that to form H-architecture patterns.

The exposed flat-lying Neogene sediments and their overlain Quaternary ones have suffered uplift and denudation, but no burial more than 1 km as indicated by geomorphological features, and the absence of any diagenetic processes. Consequently, the E-W joints of the Northern Greece that their strike fits well with the contemporary N-S active stress field of the area are easily interpreted as unloading neotectonic joints initiated and propagated due to the latter.

However, a new composite type of unloading-release neotectonic joints is proposed here to explain the apparent strike variation from WNW-ESE to ENE-WSW of the E-W joint set. These joints might have been formed as the mechanical response of the uplifted rock to the local deviation of the least principal stress axis (σ_3) (near stress field) caused by the influence of the inherited long length fault zones affecting the pre-Neogene basement.

Finally, the hypothesis that the E-W neotectonic joints may be used as "protofault zones" on the failure propagation towards the earth's surface of the tectonic faults is advanced here.

KEY WORDS: neotectonic joints, shallow brittle deformation, Neogene-Quaternary sediments, Northern Greece.

1. INTRODUCTION

The large number of the destructive earthquakes stricken all over the Greek mainland at least during this century (e.g. Ierissos 1932, Sophades 1954, Agios Efstratios 1968, Thessaloniki 1978, Volos 1980, Platees 1981, Kalamata 1986) with the last one that of the Kozani-Grevena earthquake of 13 May 1995 fairly proves that Greece is a tectonically active area. In such areas the most crucial factors of the active deformation are: (a) the determination of the contemporary stress field and (b) the understanding of the shallow brittle deformation processes.

The neotectonic research in Greece was intensively developed the last three decades and particularly after the 1978 Thessaloniki earthquake having the goal to understand and evaluate the active deformation of Greece. However, it is restricted only to the survey of the neotectonic, active, seismic and mainly the

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earthquake faults in the areas stricken by large earthquakes or fault-bounded Neogene-Quaternary basins. On the contrary, other important and ubiquitous structures even within the Neogene and Quaternary sediments like the joints and especially the neotectonic joints have systematically been neglected of this research. As a result both the aforementioned factors were approached only by the brittle deformation related to faulting.

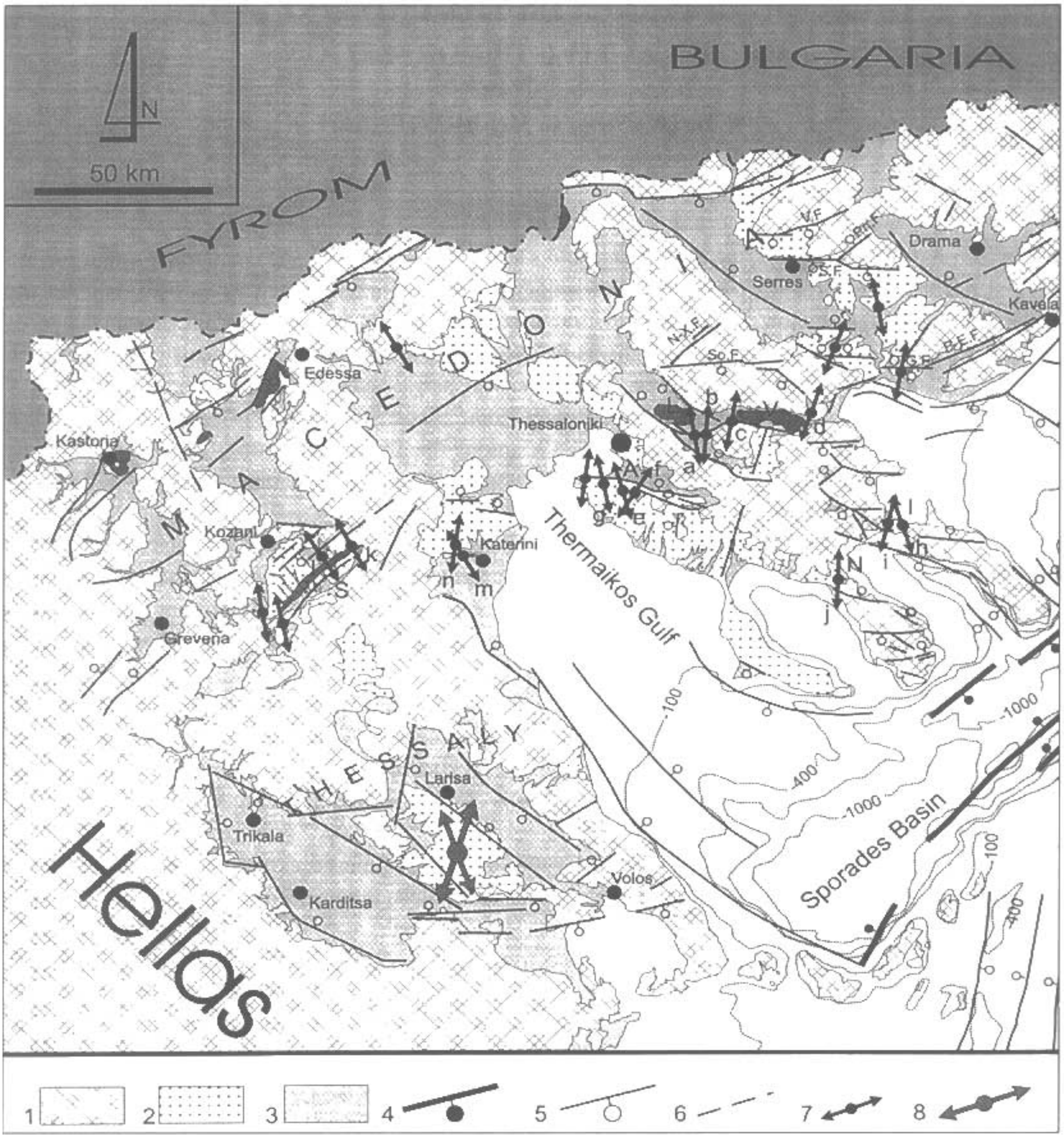

Fig. 1: Generalised geological map of Central and Northern Greece, which outlines basement outcrops, Neogene and Quaternary basins, major faults, and the orientation of the (σ_3) least principal stress axis as deduced from the neotectonic joints. 1. Basement rocks, 2. Neogene sediments, 3. Quaternary sediments, 4. Faults of the North Aegean Trough, 5. Normal faults (open circle on the downthrow side), 6. Possible faults, 7. Least principal stress axis (σ_3) direction as determined by neotectonic joints, 8. Least principal stress axis (σ_3) direction of the Thessaly area as determined from neotectonic joints (data from Caputo & Pavlides, 1993), A: Anthemountas, I: Ierissos, L: Langadas, N: Nikiti, S: Servia, V: Volvi; V.F: Vrontou Fault, S.F: Serres Fault, Pn.F: Ag. Pnevma Fault, P-E.F: Podochori-Eleftheroupoli Fault, O-G.F: Ofrinio-Galipsos Fault, N-X.F: Nikopoli-Xiloupoli Fault, So.F: Sochos Fault; a, b,...n:sites plotted in Fig. 3.

The effort of this paper is: (i) to show that the formation of the joints exposed in the Neogene and Quaternary sediments is easily interpretable, (ii) to describe their general geometry and characteristics and (iii) to argue about the significance of the neotectonic joints to the study of the active deformation and the seismicity problem.

2. THE JOINTS AS STRUCTURES

Joints, the most widespread structures at the Earth's surface, are the most misunderstanding ones, mainly because: (a) the formation of joints has been ascribed to different modes of propagation (Mode I or extension fractures, Mode II or shear fractures) and to different environments and mechanisms, (b) the joints do not exhibit kinematic indicators.

Among these reasons the first one concerns the most fundamental controversies. This is clearly reflected from the existed joint definitions such as those proposed by e.g. Hancock (1985), Pollard & Aydin (1988), Engelder (1993) and Scheidegger (1995), whereby one can find both common as opposed features about the extension or shear origin of the joints. Recently, Pollard (1996) referred to mixed-mode stress fields during failure propagation, e.g. mixed mode I-II, thus showing that the problem is even more complicated.

Unfortunately, these controversies about the origin and formation of joints could indeed be unresolved within the basement rocks, where the deformational history always remains no well established. As a result the most joint surveys that had been carried out in such rocks (i.e. Engelder & Geiser 1980, Bevan & Hancock 1986, Scheidegger 1995) do not prove or establish a widely accepted propagation mode.

As the relationship between the joints and the stress regime depends on the chosen propagation mechanism, we adopt the joint-stress relationship described by Hancock (1985) and Simpson (1996), where three main types have been considered: (i) extension fractures, (ii) shear fractures and (iii) hybrid-shear fractures (or extensional-shear fractures). In addition, we take into account the Engelder's (1985) joint discrimination based on the timing of their propagation in sedimentary basins that suffered burial, lithification, deformation, uplift and denudation, that is: (1) Tectonic Joints, (2) Hydraulic Joints, (3) Unloading joints either due either to tectonic stresses or the residual stresses of older tectonic events and (4) Release joints.

This genetic classification of joints becomes a very useful tool for the joints exposed in post-Alpine Neogene and Quaternary sediments. More precisely, from the aforementioned types that of the unloading joints is the most interesting because it embraces the neotectonic joints, which the latter determine the contemporary stress field (Engelder & Hancock 1989, Hancock 1991, Tranos et al. 1995).

3. JOINTING OF NEOGENE AND QUATERNARY SEDIMENTS IN NORTHERN GREECE

a. Geometry and architecture of the neotectonic joints

The joints affecting the Neogene and Quaternary sediments of Northern Greece (Fig. 1) are generally characterised by simplicity in the geometry and architecture patterns as mostly seen in natural or artificial profiles or sections. At the most joint exposures only one dominant and systematic joint set of various ENE-WSW to WNW-ESE trend (from site to site) is exposed (Figs. 2, 4). Usually, it presents in association with some cross-joints commonly oriented orthogonaly to it (Fig. 2d, e, f). This dominant joint set is called here as E-W trending joint set and along with their orthogonal cross-joints forms mostly H- and more rarely T-architecture patterns.

More precisely the E-W joint set comprises mostly vertical, but also steeply inclined planar single-layer fractures. They present as non-continuous fractures with no uniform distribution, but their spacing is relatively constant (20 cm to 60 cm) in the scale of outcrop. Thus it seems to form distinct "joint zones" of localised brittle deformation both within the Neogene and Quaternary sediments.

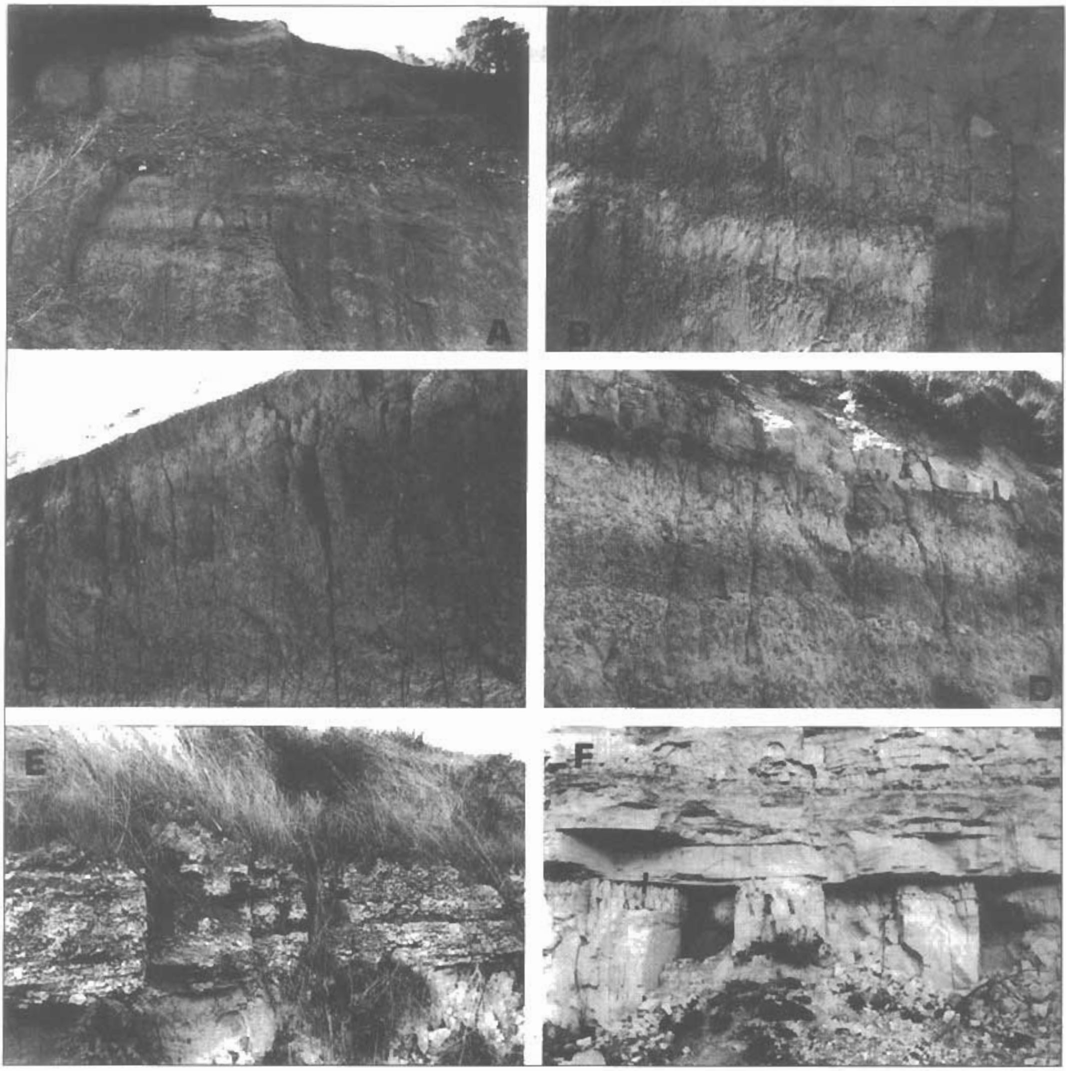

Fig. 2: Field examples of the E-W trending neotectonic joints: (a) vertical extension joints cutting gently dipping Lower Pleistocene red beds (Gerakarou Fm) and the unconformably horizontally overlying Middle-Upper Pleistocene to Holocene sands (Mygdonian group). Notice that they are not observed within the gravel bed (Mygdonian group) just above the angular unconformity, (b) detail view of the vertical extension joints affecting the Lower Pleistocene Gerakarou fm, where it is clearly shown that they are conflicted within the lens bed, (c) vertical extension to steep-inclined hybrid shear joints affecting Late Vallesian-Earliest Turolian sands of Nikiti fm (Nikiti basin), (d) vertical extension joints affecting flat-lying Pliocene(?) marls and marlstones of Ierissos fm (Ierissos basin). It is well observed the joint elimination away from the bed surface on the upper part of the photo and the NNW-SSE cross joints that abut the neotectonic joints, (e) vertical extension joints affecting well bedded sands and calcarenites of Turolian age (Trilofos fm, south of Anthemountas basin), (f) well defined vertical neotectonic joints abutting horizontal bedding in Middle-Upper Pliocene marls of Kozani-Servia basin. (scale: hammer 34 cm long).

The lithology affects the appearance of the joints (Fig. 2a, b) and commonly the latter do not present in gravel beds (Fig. 2a) or abut on them. These joints constitute the latest systematic joint set because: (a) they abut the rare and older NW-SE trending joints, (b) they are present within the Quaternary sediments and even more in the Holocene deposits (Fig. 2a, b). The least principal stress axis (σ_3) determined by these neotectonic joints is similar with that determined by focal mechanisms and *in situ* stress measurements and clearly is shown by matching the T-axis of Kozani-Grevena focal mechanism (T=157°-1°, from Pavlides et al. 1995) with the least principal stress axis (σ_3) deduced herein from the ENE-WSW trending neotectonic joints of the same area ((σ_3=329°-1 & 334°-4°) (Fig. 4k, l). However, in this E-W neotectonic joint set some portion of hybrid shear joints with dihedral angle less than 20° is included (Fig. 2c) determining the greatest principal stress axis (σ_1) in almost vertical position. Their strike usually varies from N60° to N110° at the different exposure sites even in the same geographical area (Fig. 1).

Apart of the E-W neotectonic joints, some NW-SE trending joints very rarely have been observed in some locations. Also, these are barren and planar vertical to steeply inclined extension fractures, but with spacing greater than that of E-W trending joints. They present in the Neogene sediments as geometrically simple discontinuous fractures, with common strike N140°-160°. Their frequency and persistence is generally not good, because their exposures are too few in respect to the total extend of the Neogene sediments. Also, their strike varies from site to site from N130° to N170°. However, this joint set has not been observed in the Quaternary sediments. Similarly to the E-W joint set, the NW-SE one is associated with some orthogonaly oriented cross-joints of NE-SW strike, thus forming H-architecture patterns. Sometimes, the latter NE-SW cross joints can be confused with the E-W neotectonic joints and particularly with those of ENE-WSW strike. Their distinction from the neotectonic ones, however, seems possible, based on their orientation and mostly their appearance as well as their abutting relationships with the NE-SW trending joints. The NE-SW joints as they are observed abutting the NW-SE joints clearly appear as non-systematic cross-joints, whereas the ENE-WSW joints that abut the NNW-SSE joints are fairly characterised as systematic joints.

The cross-joints, which are orthogonaly oriented against the E-W trending neotectonic joints forming H-architecture patterns (Fig. 2d), hence are referred as N-S trending joints. These joints are barren vertical or steeply inclined fractures, but their surfaces are both planar and curve and their orientation as well as their length and spacing are seem to controlled by the presence of the E-W trending joints. Additionally they are not present at all the joint exposures. For these reasons, they are considered as non-systematic cross-joints.

The gradual change in the trend of the least principal stress axis (σ_3) from NNE-SSW in Thrace and Eastern Macedonia to NNW-SSE in Western Macedonia has been implied from the stress analysis of the already studied neotectonic faults s. l. (Mercier et al., 1983, 1989; Pavlides & Mountrakis 1987) and the focal mechanisms of the recent earthquakes (Kiratzi et al. 1991, Papazachos & Kiratzi 1996).

The neotectonic joints as direct stress indicators clearly establish this change of the orientation of the (σ_3)-axis (Figs. 1, 4) and even more they possibly indicate that this change could be attributed to the differentiation of the tectonic fabric in between the Western and Central Macedonia, as already has been shown from the mapping of the Macedonia area (Seismotectonic map of Greece, scale 1:500.000, IGME 1989; Active Fault Mapping of Greece-Macedonia area, scale 1:250.000, Mountrakis et al. 1995). The Western Macedonia area is characterised by the dominant presence of close-spaced large faults trending NE-SW to ENE-WSW (Fig. 1), which are inherited strike-slip faults of an older tectonic event in Macedonia and Thessaly regions during the Lower-Middle Miocene times (Mountrakis et. al. 1993, Tranos, unpublished data). Many of these faults have been reactivated as normal faults during the recent N-S extensional stress field (Mountrakis et al., 1995, 1996, Pavlides et al., 1995). On the other hand, in Central and Eastern Macedonia the observed fault pattern is more complicate. Although there are some large NE-SW to ENE-WSW trending faults, the NW-SE to onwards have modify significantly the strike and the appearance of the former by cutting, arresting (or kidnapping) them. We can mention as example the E-W Serres normal fault that cuts many ENE-WSW to NE-SW faults (Vrontou, Ag. Pnevma, etc.) in the Menikio Mt.; the E-W Ofrinio-Galipsos normal fault that cuts the ENE-WSW Podochori-Eleftheroupoli fault in the Strymonikos gulf; the E-W Sochos fault that cuts the NE-SW Nikopoli-Xilopouli fault system, the E-W Darmeni, Kirki, Maronia faults that cut many large ENE-WSW faults (Xanthi, Soufli, etc.) (Fig. 1).

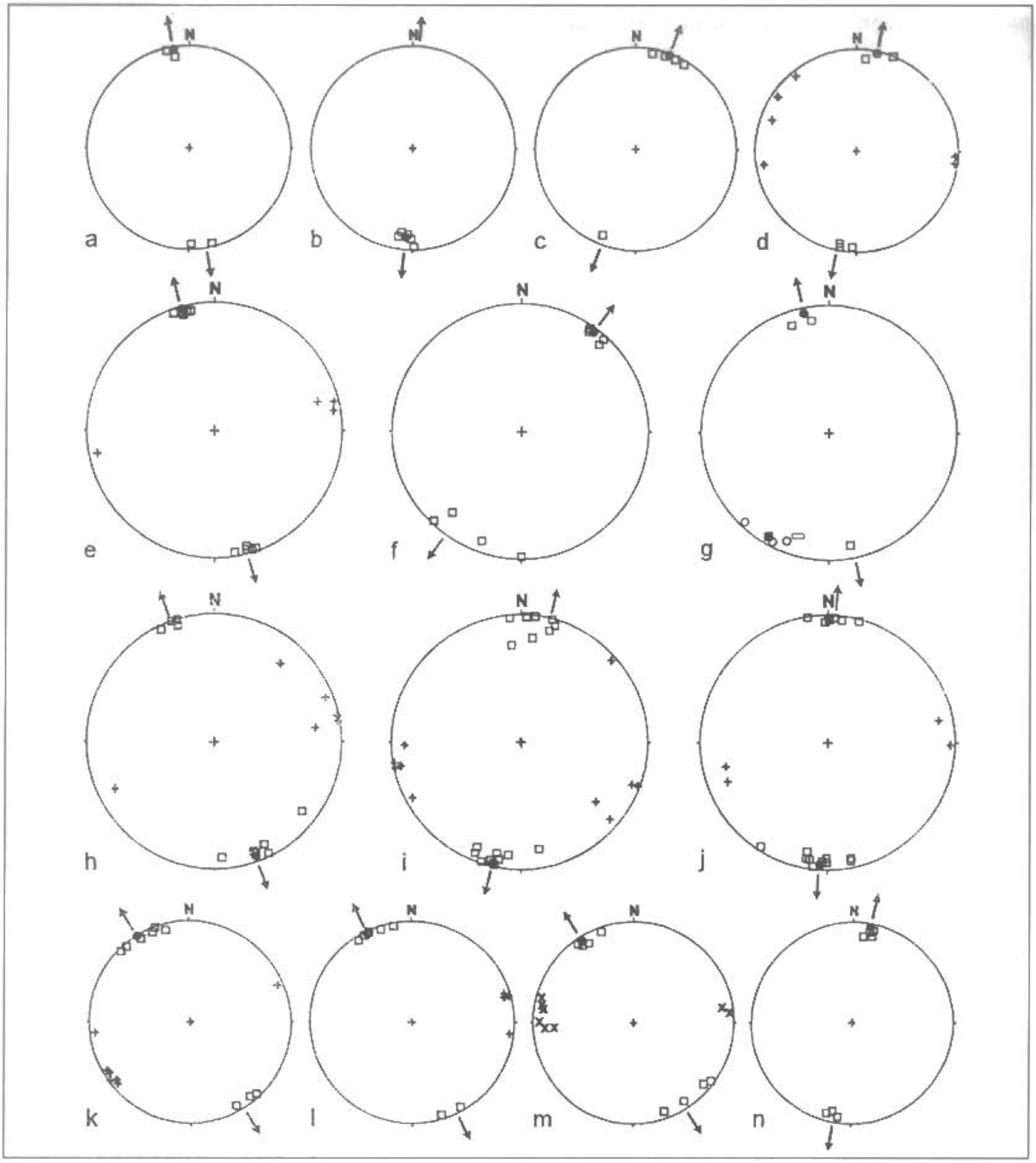

Fig. 3: Equal area, lower hemisphere projections of the poles of the E-W neotectonic joints and the cross-joints. Examples from several areas of the Macedonian region (a-d: Volvi-Langadas area, e-g: Anthemountas area, h-j: Ierissos-Nikiti basins, k, l: Kozani-Servia basin, m, n: Katerini area). Note the strike variation of the neotectonic joints from WNW-ESE to ENE-WSW even in the same geographical area.

The strike of the neotectonic joints exposed in Western Macedonia, where the ENE-WSW faults are close-spaced, is relatively constant in similar ENE-WSW orientation, whereas the strike of the exposed neotectonic joints in Central Macedonia and Thessaly, varies from WNW-ESE to ENE-WSW (Figs. 1, 4) (see also Tranos et al., 1995).

Therefore, the apparent simultaneous failure process forming both WNW-ESE and ENE-WSW neotectonic extension joints in the area favours the aforementioned interpretation with the influence of the strike of the least principal stress axis (σ_3) from the inherited tectonic fabric. In other words, the various orientation of the E-W neotectonic joints is attributed to the contemporary stress field, but which is partly influenced by the relative orientation of the pre-existed faults and mainly the NE-SW to ENE-WSW long length fault zones. It is thought here a linked more synthetic way for the formation of joints during uplift and denudation, which does not separate unloading joints from release joints, but to join them in a composite failure evolution.

b. Neotectonic regime of the area and stress implications of the joints

In Northern Greek mainland a large number of NW-SE, NE-SW and E-W trending basins have been filled up with Neogene and Quaternary sediments. These basins, which have been developed since the Middle-Early Late Miocene are considered to represent the onset of the neotectonic deformational period of Greece. From the recent neotectonic studies carried out in Central and Northern Greece the neotectonic period of deformation relates to an extensional stress regime. More precisely two distinct stress fields have fairly been recognised since the Late Miocene: (a) a NE-SW extension from Late Miocene to Early Pleistocene and (b) an N-S extension from Early-Middle Pleistocene to nowadays (Mercier et al. 1981, 1989; Mountrakis et al. 1983, Pavlides & Mountrakis 1987). Moreover, the N-S extensional stress field is characterised by the gradual change of the trending of its least principal stress axis (σ_3) from NNE-SSW in Thrace and Eastern Macedonia to N-S in Central Macedonia and finally to NNW-SSE in Western Macedonia (Le Pichon et al. 1982, Papazachos et al. 1991, Papazachos & Kiratzi 1996).

Many parts of the Neogene basins of Northern Greece are present now to have either uplift or subside. Thus many Neogene and Quaternary sediments are exposed now higher than their initial depositional level. In Central Macedonia area the uplift since Pliocene is, according to geomorphological criteria, as much as about 1-1.2 km (Psilovikos & Vavliakis, 1983).

The sediments which expose nowadays higher than their initial depositional level and they are being subjected to intense erosion could be considered to have experienced uplift and denudation, but no burial more than about 1km (e.g. the Kozani area that extensively covered by Plio-Pleistocene terrestrial sediments). This consideration is strongly supported by the geomorphological evidence. Consequently, following the Engelder's discrimination, the exposed barren joints of the sediments could be easily interpreted either as unloading joints or release joints.

c. Contribution of the neotectonic joints to the study of the shallow brittle deformation

The neotectonic joints could play an important in the understanding of the shallow brittle deformational processes. Their presence is especially crucial for the hanging wall and the footwall part of the basin's boundary fault. Firstly, because several field studies have documented cases in which faults formed by the linking together of joints (Segal & Pollard, 1983; Granier, 1985; Segal & Simpson, 1986). Consequently, although this re-treatment of joint planes as faults is limited in length, it evidences mechanically the specific failure procedure or propagation. Secondly, because the joints (especially the hybrid- shear fractures) are transitive mechanically not only to the typical Navier- Coulomb faults, but also to the (seismic) ground fissures or ruptures, which thelatter are commonly associated with earthquake events.

The hypothesis advanced here is that the joints, but mainly the E-W neotectonic joints within the Neogene and Quaternary sediments, which the latter constitute the "construction basement" for many buildings may be used as "protofault zones" for the failure propagation of the tectonic faults towards the earth's surface (Fig. 4), and especially where these neotectonic joints are steep-inclined hybrid-shear fractures. This hypothesis links altogether faults, joints and fissures taking into account their formation in relation to the depth and their mechanical continuity in thermoelastic mechanical conditions. Besides, Simpson (1996) has proposed a quite similar model of fault-mesh fracture formation for depths just more than about 1km linking together faults and extensional joints as well as veins.

It is well known that the fissures are surficial cracks formed in the upper 100 m of the Earth crust (Dunne & Hancock 1994), while the unloading and release joints are formed in the shallow crustal levels (less than 1km) (Engelder & Hancock 1989).

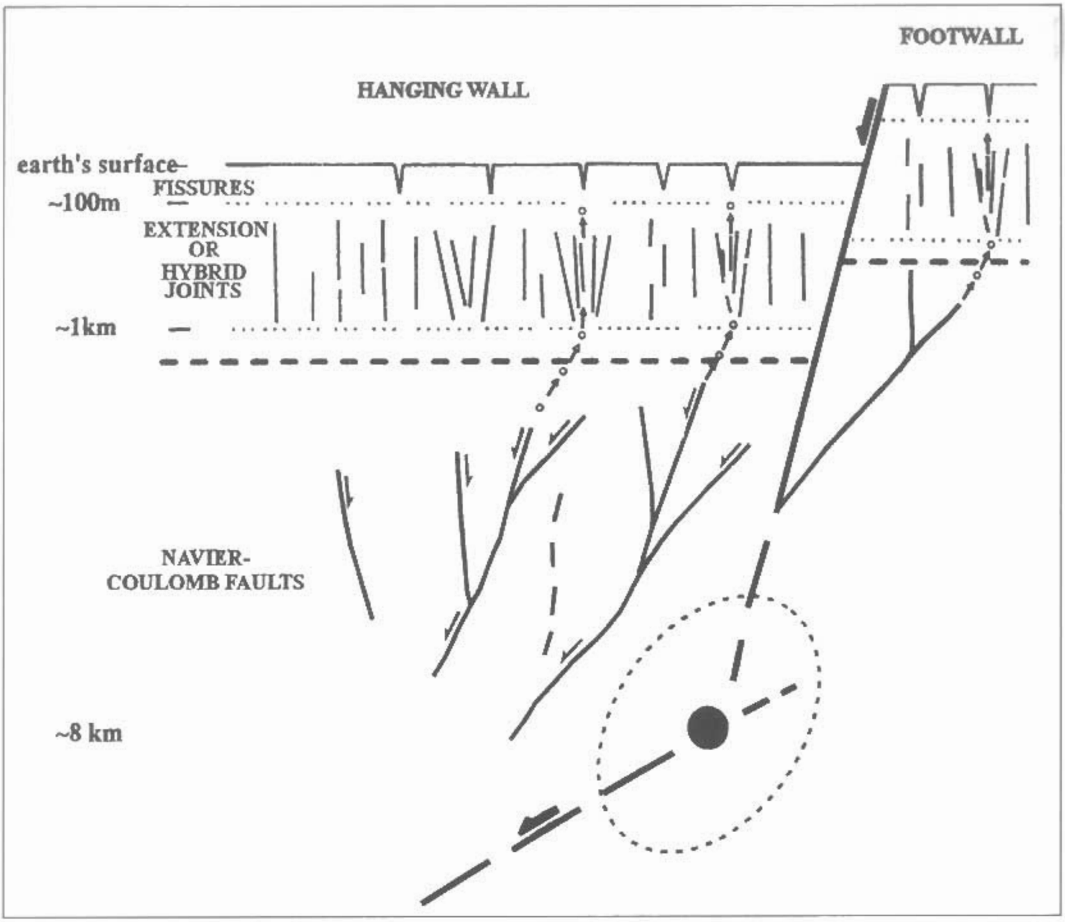

Fig. 4: A proposed model of the tectonic fault propagation into the shallow crustal level comprising interlinked Navier-Coulomb tectonic faults, neotectonic joints and seismic fissures in area suffering uplift and denudation. The secondary typical Navier-Coulomb faults reach the earth's surface through the neotectonic joint level giving rise to vertical or steep-inclined "protofault zones". The basement-sedimentary cover boundary is shown by thich dash line and the hypocenter of the fault earthquake is shown by dark grey circle.

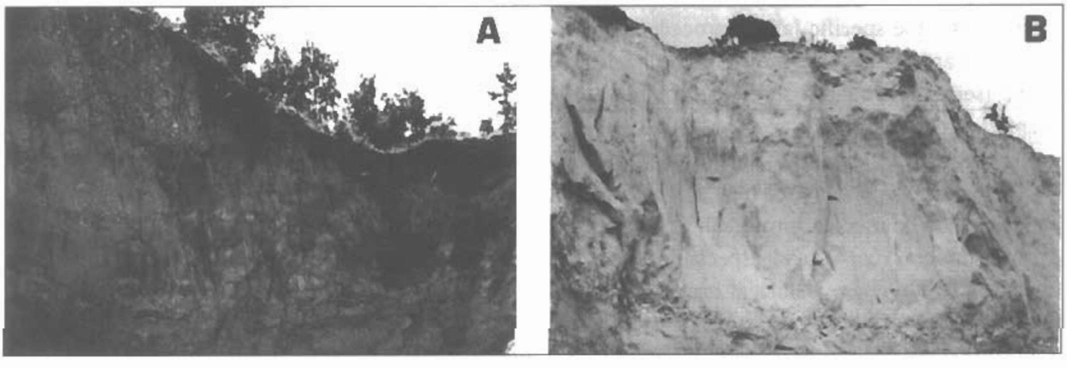

Fig. 5: (a) Localised brittle deformation through extension to hybrid joints, that possibly constitute a E-W trending "protofault" zone (field photograph of the area of Katerini), (b) Sheared or faulted joints with slickenlines, exposed parallel to the neotectonic extension joints in the Lower Pleistocene red beds (field photograph of the Kozani-Servia basin).

The tectonic fault as propagated upwards into this shallow crustal level have to use at least partly the already existed joint planes and especially the planes of the hybrid shear fractures, following that the formation of the tectonic faults results by the localisation and concentration of shear inside a wider 'protofault' zone, whereas it seems very unlikely that the seismicity alone can significantly contribute to this propagation (Mandl 1990). Indeed, NW of the town of Katerini in Central Macedonia, some subparallel E-W trending and S-dipping high angle normal faults have been mapped by the morphotectonic features (fault scarps). However, their length, which totally is about 10 km is rather discontinuous of smaller lengths of ca. 2km. Furthermore, instead of finding large fault surfaces, only some E-W steep-inclined hybrid shear joints and vertical extension joints were observed (a) along the fault trace to form distinct "joint zones" without extending laterally, although the lithology remains similar. As a result these hybrid shear and extension joints may constitute a "protofault" zone for a future active fault. Additionally in some Pleistocene red beds (silty sands) of Kozani-Servia basin some steep-inclined to vertical ENE-WSW trending fractures (b) with appearance and orientation similar to the well observed neotectonic joints of the area have been found to bear vertical slickenlines. These fractures could be interpreted as sheared neotectonic joints (protofault zones), due to the latter increase of the N-S stress loading (i.e. effective stresses). Finally, we mention that many seismic ground ruptures representing the surficial traces of the neotectonic-active faults associated with the recent Kozani-Grevena earthquake sequence of 1995 (Pavlides et al. 1995, Mountrakis et al. 1995) have been mapped to have similar orientations with the ENE-WSW neotectonic joints recorded in the Neogene-Quaternary sediments of the area. Therefore the above hypothesis taking into account the interaction of faults, joints and fissures is well supported.

4. CONCLUSIONS

Joint exposures within the Neogene and Quaternary sediments of Northern Greece are characterised by simplicity in geometry and architecture patterns. At the most joint exposures, only one ENE-WSW to WNW-ESE (in general E-W) dominant systematic joint set of mostly barren vertical extension joints to steeply-inclined hybrid shear joints is observed to form frequently well defined joint zones. This joint set is usually associated with some cross-joints so that to form H-architecture patterns. The ENE-WSW to WNW-ESE extension joints could easily be interpreted as neotectonic joints, since they comprise the latest joint set that affects sediments as young as Holocene deposits.

At different exposures even of the same geographical area the strike of the neotectonic joint set varies from ENE-WSW to WNW-ESE. This strike variation is attributed to the different stress conditions dominating the formation of the joints. Thus, the neotectonic joints are interpreted to form as a consequence of failure in the contemporary N-S tectonic stress field (regional stress-field) dated since Lower-Middle Pleistocene or in the contemporary N-S stress field as the later influenced by the presence of the fault zones (near stress field). As a result the uplift and exhumation of as much as the upper 1 km level of the crust has been mostly happen during the Quaternary and fits well with the estimations derived from geomorphological features.

The contribution of the neotectonic joints to the active deformation is of great importance, because: (a) they confidently determine the contemporary stress directions and (b) they are potential indicators of the contemporary shallow brittle deformational processes giving rise to either "protofault zones" for big faults or simple sheared or faulted joints. In addition, in some areas strongly affected by a recent seismicity (e.g. Kozani, Mygdonia basin), the strike of the neotectonic joints within the Quaternary sediments coincides systematically with the strike of the ground ruptures associated with the earthquake events.

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