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English version

MULTI-PHASE BRITTLE - DUCTILE NEOTECTONIC DEFORMATION AND NORMAL FAULTING CAUSED BY COMPRESSION: THE CASE OF ZIMBELI FAULT SURFACE (MESSINIA SW PELOPONNESE, GREECE)

by

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INTRODUCTION

Zimbeli fault surface is perhaps unique case of fault surface, at least in S. Peloponnese (SW Greece) in which many deformation features of the neotectonic period have been printed in successive stages.

The studied area is situated eastern of Kalamata (SW Peloponnese) about 2 km eastern of Eleochori village at the road from Eleohori to Dimiova monastery (**Fig.1**). The Zimbeli fault forms the tectonic boundary between the eocene neritic limestones and the flysch of the Tripolis geotectonic unit.

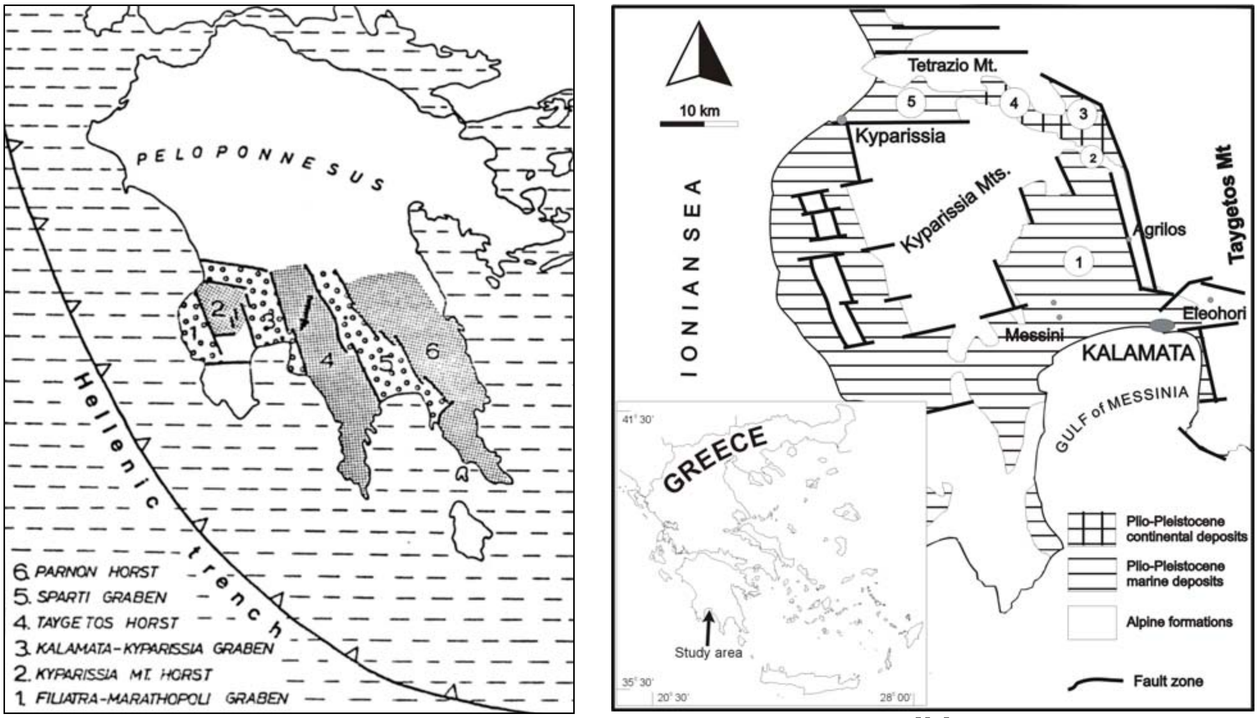
The main characteristic of this NW-dipping fault surface, most of which was uncovered after a landslide, is that its strike isn't constant, ranging from NE-SW to ENE-WSW. This fault surface has been deformed under a local stress field, which differs from the regional one. Its formation is placed at the first stages of flysch sedimentation (U. Eocene) as a synsedimentary fault or even earlier, as it has been described from many places of Peloponnese (Mariolakos 1976). Since then, it has been repeatedly reactivated, which is proven by successive generations of striations and tectonic breccia sheets. The shape of the fault surface is not plane but undulated.

The occurrence of many striation sets plunging in different directions, the successive tectonic breccias, the sets of fractures that cut the fault surface in an en-echelon arrangement, as well as the curving of the fault surface give us the opportunity to understand the deformation processes of area.

The neotectonic regime of the broader area

The Neotectonic structure of the SW Peloponnessos is characterised by the presence of tectonic grabens and tectonic horsts (1st order structures) striking NNW-SSE and E-W (Mariolakos et al., 1987). Such 1st order neotectonic macro-structures are e.g. the Kalamata - Kyparissia graben, the complex morphotectonic unit of Kyparissia Mts. the complex tectonic horst of Lycodimon Mt. (**Fig. 1b**). At the margins or inside the 1st order neotectonic macrostructures, neotectonic structures of minor order exist, the strike of which is perpendicular or parallel to the trends of the 1st-order ones. All these macrostructures are dynamically connected, as they have resulted from the same stress field, whereas from the kinematic point of view, there are differences that appear either at the primary stage of their creation or during their evolution (Mariolakos et al., 1989).

Such 2nd order neotectonic macro-structures within the Kalamata - Kyparissia graben are the following: (Fig. I-1) (i) Kato Messinia graben; (ii) Meligalas horst; (iii) Ano Messinia graben; (iv) Dorion basin, and (v) Kyparissia - Kalo Nero graben.



(a) (b)

Fig. 1 (a) The main (1st order) neotectonic structures of South Peloponnese and location of the study area and (b) The 2nd order neotectonic structures of the Kalamata – Kyparissia graben 1: Kato Messinia graben, 2: Meligalas horst, 3: Ano Messinia graben, 4: Dorion basin, 5:Kyparissia – Kalo Nero graben

At the eastern margin of the southern part of Kalamata-Kyparissia graben neotectonic macrostructures of smaller order exist (2nd and 3rd order) (**Figs. 1b, 2**). Some of them are parallel to this 1st order graben, whereas others are more or less normal to it. Neotectonic macrostructures of 2nd order have been developed inside the Kalamata-Kyparissia graben as well (MARIOLAKOS et al. 1987).

The studied area belongs to the so-called **Dimiova-Perivolakia** graben, which is a 2nd order neotectonic macrostructure at the eastern margin of the Kalamata-Kyparissia Graben with an E-W trend (**Figs. 1b, 2**).

Big fault zones bound this graben. One of the main characteristic of these zones is that the displacement along the fault zones is different, which is the result of an anticlockwise rotational movement, around a N-S striking principal axis and a secondary one in a E-W direction (MARIOLAKOS et al. 1987).

Fractures and fault surfaces striking in different directions have also been observed inside the Dimiova-Perivolakia graben. The studied fault surface is one of them.

THE ZIMBELI FAULT SURFACE

As it has been already mentioned the **Zimbeli fault-surface** represents the tectonic boundary between the neritic Eocene limestones and the flysch formation of the Tripolis unit. The main characteristic of this fault surface is that its strike isn't constant, as it ranges from NE-SW to ENE-WSW, whereas the mean dip of the fault surface is towards NW (**Fig 2b**).

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Although the dimensions of the fault surface that can be observed is about 300mX30m the existing small structures on it (slickensides - tectonic breccias etc.) are few because of the erosion

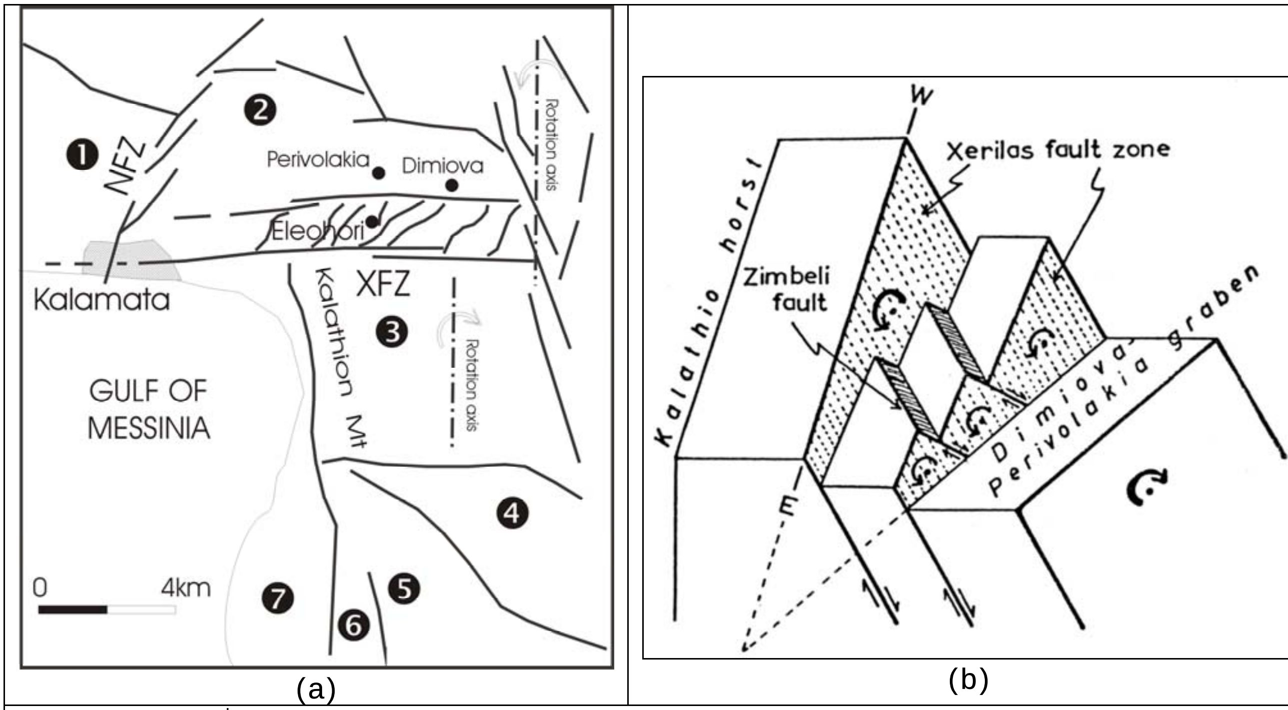


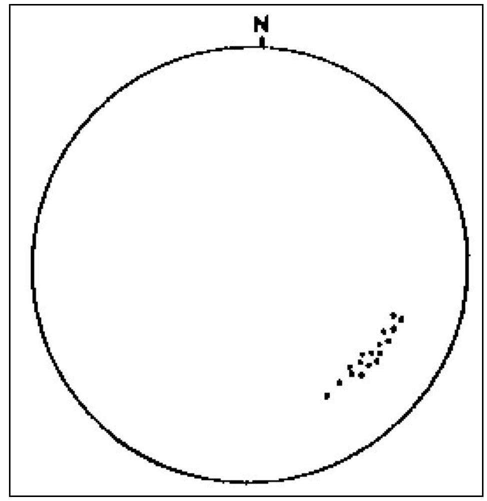
Fig. 2 The 2nd order neotectonic macrostructures at the eastern part of the Kalamata – Kyparissia graben (a), and the geometry of the southern border of the Dimiova – Perivolakia graben where the Zimbeli fault is located (b).

A recent landslide at the slope of the road from Eleohori to Dimiova's Monastery revealed a big part (20x6 m) of the fault surface. On this part that hasn't been eroded yet, a great number of small brittle structures can be seen. These structures give information about the evolution of the concrete fault (reactivations, etc.), as well as, about the deformation type of this fault surface. So the above mentioned fault surface is studied even as a surface that has been deformed under the action of a local stress field, which is different from the regional one. Concerning the time that this surface has been created, it is considered that it started at the first stages of the flysch sedimentation as a syn-sedimentary fault or even earlier, as it has been described from many places of Peloponnese (RICHTER -MARIOLAKOS 1973, MARIOLAKOS 1975). Since then, up to the present time it should have been reactivated many times as the different generations of slickensides and tectonic breccias prove

The shape of the fault surface is not plane but curved, convex and concave (**Figs.3 and 4**).

(a)

Fig. 3 Panoramic view of the Zimbeli curved fault surface.



(b)

Fig. 4 Lower Hemisphere pole projection of the fault surface measurements showing the concave curvature of the fault surface.

The main minor structures on the Zimbeli fault surface are the following:

a) Many generations of striations (slickensides),
b) Tectonic breccias and
c) Small fractures and faults, which intersect the bigger Zimbeli fault surface (**Figs. 3, 5, 6, 8**).

(a)

Fig. 5 The successive tectonic breccia and 2 sets of striations.

(b)

Fig. 6 Sets of striations with different plunge.

The presence of **striations** of different strikes and dips and successive tectonic breccias, is an evidence of repeated reactivation of the fault in different periods, probably since the upper most Eocene. This is one of reasons that we believe that, in spite of the incomplete stratigraphic data, the fault should have been reactivated during the neotectonic period.

Taking into account the above mentioned minor structures and the curved shape of this surface, we are doing some comments concerning the type of the stress field and the kind of

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the structures that can be created always taking into account the lithology, the conditions and the type of deformation. In the following paragraphs, a full description and analysis of the mesoscopic structures developed on the fault surface is given and a first approach of the kind of deformation during the neotectonic period will be attempted.

TECTONIC BRECCIAS SHEETS

The **tectonic breccias sheets** observed on the fault surface (**Figs. 5, 6**) can be distinguished in four (4) different categories taking into consideration the material they consist and their relative age. In fact, in many parts of the fault surface, tectonic breccias exist in successive sheets, whereas the presence of fragments of older tectonic breccias in some of them simplifies the determination of their relative age in many cases.

The oldest tectonic breccia is compact and oligomictic and consists exclusively of very small angular particles of the neritic eocene limestones. The thickness of this brecciated sheet does not exceed the 5 mm. This breccia can be observed all over the fault surface, but it is better exposed at the southwestern part of the fault surface. This tectonic breccia, is covered by a thin calcitic sheet (central and south-western part of the surface) the thickness of which in some places exceeds 0,5 cm, but usually is thinner. A compact calcitic crust consisting of fragments from Eocene limestones and from the previous tectonic breccias as well covers this calcitic film. This occurs mainly at the central part of the fault surface and its thickness locally exceeds the 5 cm.

The last and relative younger tectonic breccia (**Fig. 5, 8**) is polymictic and consists of fragments of flysch materials and those of Eocene limestones, whereas in some places of the surface fragments from the older tectonic breccias are present as well. The size of this angular coarse material varies from 1 to 5 cm. the origin of the cement is from flysch fine material. In contrary to the previous tectonic breccias, this one isn't very compact. Its thickness varies from 5 to 10 cm, whereas locally is greater than 50 cm as it happens at the northeastern part of the fault surface.

STRIATIONS

The next structure indicating successive reactivation of the fault is the presence of in different direction striking and dipping striations (**Fig. 7**). They are distributed all over the fault surface, independently if the fault surface intersects the limestones or older tectonic breccias. This fact combined with the presence of striations of different strikes and dips at the same area it makes possible the timing although this is not everywhere easy. **Fig. 7** shows the statistic analysis of the measured striations.

The older set (I) seems plunges 25/252. It always occurs beneath the tectonic breccias and the calcitic crusts. The frequency of this set is very low. The next generation (II), whose frequency is relatively low, plunges 48/312. It occurs not only on the eocene limestones, but also on the surface of the first monomictic breccia. The third generation (III) occurs mainly on the central and on the southwestern part of the surface. It is sub-horizontal and its frequency is relatively low.

The next generations of (IV and V) plunge 36/010 and 36/266, respectively. They occur on the surface of the eocene limestones as well as on the first two tectonic breccia sheets. The frequency of set IV is very low. Set V has the highest frequency of all. The problem that arose was whether set V postdates set V or not, as their relationship is not clear.

A sixth set (VI) (14/035) was also detected; however it could not be dated as it did not intersect any other set.

Based on the above-mentioned detailed study and analysis of the field data, we could do the following statement relative to the kinematic of the Zimbelis' fault.

- The fact that the striations are not plunging normal to the strike of the fault surface indicates that the block movement during all the reactivation acts presents a horizontal component. More especially the striations of the IIIrd set, which are almost horizontal, indicate that in this case the block movement is almost horizontal.
- The striations of the IInd set only show actually that the movement is normal to the strike of the fault surface.
- Analysing the horizontal component of the movement and accepting that the block of the flysch is the block, which moves always downwards the Ist and the Vth set indicate a left lateral movement, whereas those of the systems IV and VI a right lateral one (**Fig. 7**).

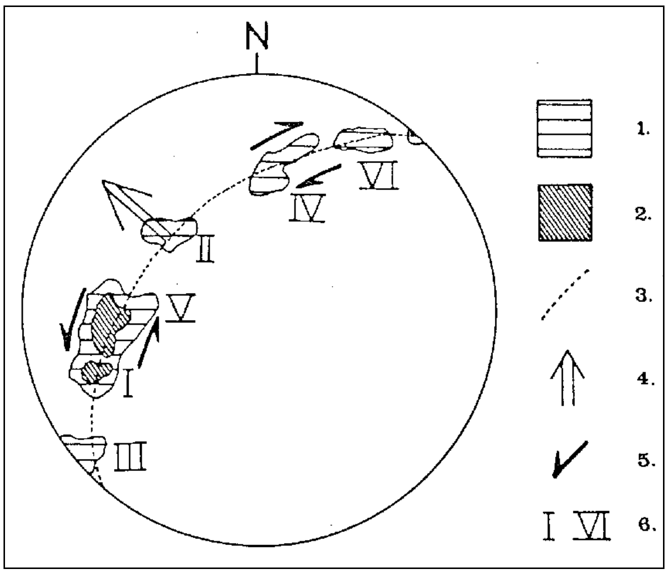

Fig. 7 Equal-area (Lower Hemisphere) projection of striations on the Zimbeli fault. 1: density 10-30%, 2: density >30%, 3: mean fault plane, 4:fault dip direction, 5: strike-slip component, 6: striation sets (After MARIOLAKOS et al., 1987a).

MICRO-FAULTS

Zimbeli fault surface is interrupted by numerous microfaults, most of which postdate the striations and breccia sheets. Their visible length is about 5-6 m. They can be distinguished in several sets or generations according to the following features (a) their size (b) if they have been filled in with calcite or not (c) if they cut one of more tectonic breccias (d) their strike and dip (e) if a fracture set or micro-faults are intersected by another or not.

The general characteristics of these micro-faults based on field observation can be summarized as following.

(i) They are antithetic to the main fault surface.
(ii) They dip towards SE whereas the Zimbeli fault-surface dips towards NW. The average dip is approximately $50^0/130^0$.
(iii) The size of the micro-faults varies from 1 to 15m or even more in few cases.
(iv) Their distribution pattern, as it can be easily observed on the well-exposed Zimbeli fault surface shows a typical "en echelon" arrangement.
(v) Some of them, especially the larger ones are in the form of gashes, while the smaller ones are usually filled with calcite. Their sense of displacement is not uniform, and some have downthrown the SE block or vice versa.

English version

(vi) Many of them and mainly the bigger ones - which are at the same time the younger ones - besides a displacement parallel to the fault parallel to the fault surface they present also a small "opening" in other words a movement normal to their fault surface. In addition to this, there are some fractures - mainly the smaller and older ones -which are filled with calcite.

(vii) The amount of the block displacement and consequently the net slip along these micro-faults differs from place to place and more especially at their extremities there is no displacement at all, whereas towards the central area of the micro-faults the displacement increases gradually reaching its highest amount somewhere at the middle of the distance between the two fault ends.

Fig. 8 The younger fractures and micro-faults cutting the fault surface.

The "relative age" of some fracture sets couldn't be always determined. Generally speaking, the older fractures are relatively small, have small displacement and cut only the two older tectonic breccias. The younger sets are longer (5-15 m), have a maximum displacement of 3-4 cm and occur in the form of gashes, with a 10-cm in the middle. It is remarkable that these fractures intersect all tectonic breccias. In some places, where more than one set of fractures occurs, their "relative age" can be easily determined. In **Fig.9** three sets of fractures are distinguished. The oldest one set 1, 3 being youngest.

In **Fig. 10a** the curvature of the Zimbeli fault surface is shown, as well as the magnitude of displacement along it. All these measurements have been made parallel to the fault surface and perpendicular to its strike. In **Fig. 10b** the size and the shape of the "gap" (opening) between the two segments of the largest observed microfault is depicted. As shown in these diagrams, the magnitude of the displacement decreases gradually towards the extremities of the fracture. Note also that the fault surface itself is curved, which corresponds to a 2-3% NE-SW shortening. The most interesting of all these fractures sets is the younger one (60/135), which represents the larger micro-fault (**Fig. 9**).

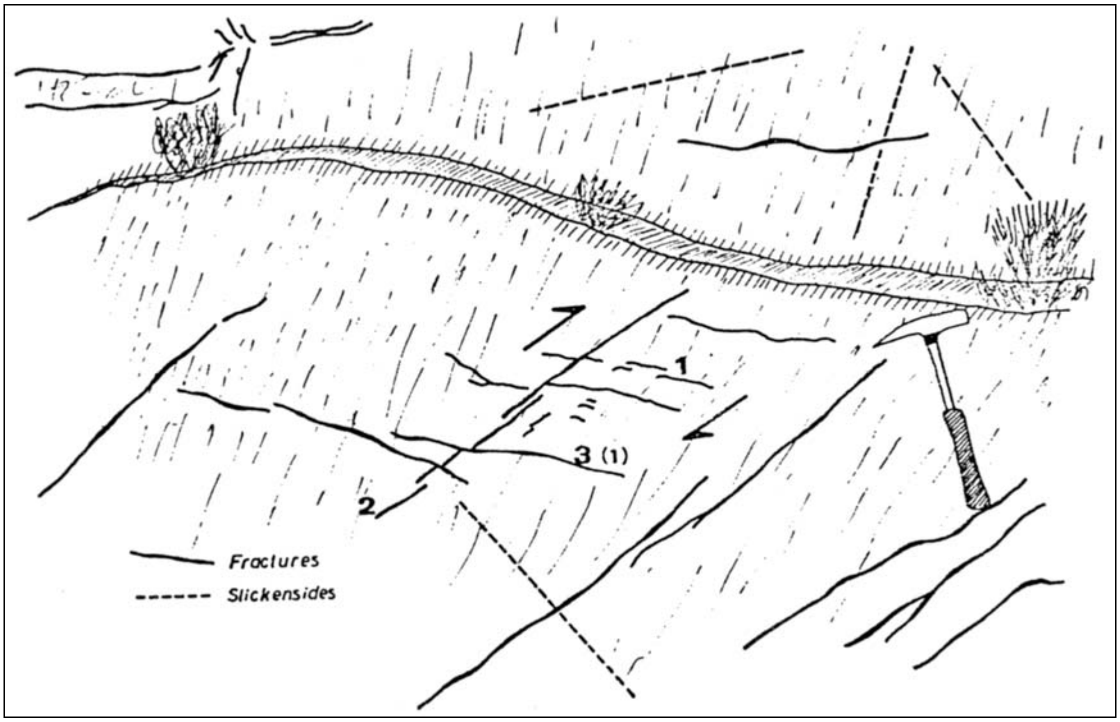

Fig. 9 The relative age of some fracture sets and micro-faults.

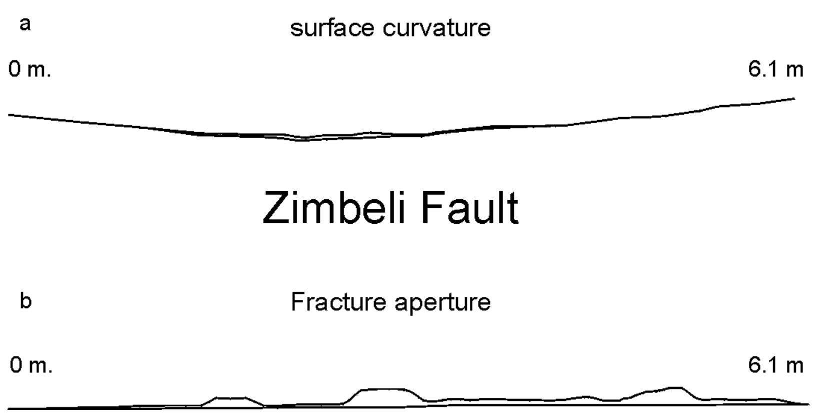

Fig. 10 (a) Curvature and displacement magnitude along Zimbeli fault plane – section is normal to fault surface, (b) fracture aperture along the fault plane – section is parallel to fault surface (After MARIOLAKOS et al. 1987a).

DYNAMIC OF DEFORMATION - DISCUSSION AND CONCLUSIONS¶

Following the geometrical and kinematic analysis of the structures that have been presented at the previous paragraphs we tried to approach the deformation of this small area, from the dynamic point of view.

The interesting of the Zimbeli fault surface is based on the fact that not only the tectonic evolution of this surface, but also its deformation by the younger phases of the neotectonic period, has been printed on it.

By all above mentioned the following conclusions can be done:

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- The presence, of successive tectonic breccias and of various striations, which plunge in different directions prove repeated reactivations of the fault. Some of them have certainly taken place during the neotectonic period.
- The presence of almost everywhere horizontal or obliquely plunging striations proves that the participation of the horizontal component is very important although this fault surface represents a typical normal fault. In one case this "normal" fault has been reactivated as a strike slip fault.
- The horizontal component of the movement is presented as right or as left lateral.
- The younger micro-faults, which intersect the Zimbeli fault surface are considered as normal but:
  - (i) The en echelon arrangement
  - (ii) The gradual increase of the displacement along the micro-faults
  - (iii) The small curving of anticlinal type that is observed at all the uplifting micro-blocks
  - (iv) The very small but constant rotation of the micro-blocks around an NE-SW axis, which is parallel to the fractures and micro-faults strike (**Fig. 11**), prove that these structures (younger micro-faults) although they look like as normal type faults - they are structures that are not connected with a pure extensional, but with a more complicated stress field.

So we accept that a stress field of coupling or torsion character, the result of which is the creation of local compressional stress fields, must create these structures.

So the "curving" of the Zimbeli fault surface itself, as well as the "curving" of the micro-blocks in which is intersected the fault surface because of the younger deformation prove (**Fig.12**) that:

(i) Both of them must be created by the participation of a compressional stress field and

(ii) The deformation is not of brittle but also of ductile type.

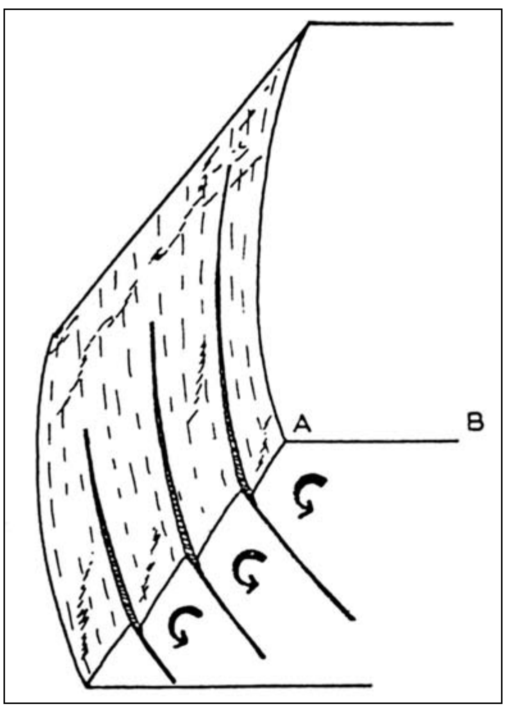

Fig. 11 Schematic cross section (A-B) perpendicular to the strike of Zimbeli fault surface showing the younger small faults and the kinematics of the microblocks.

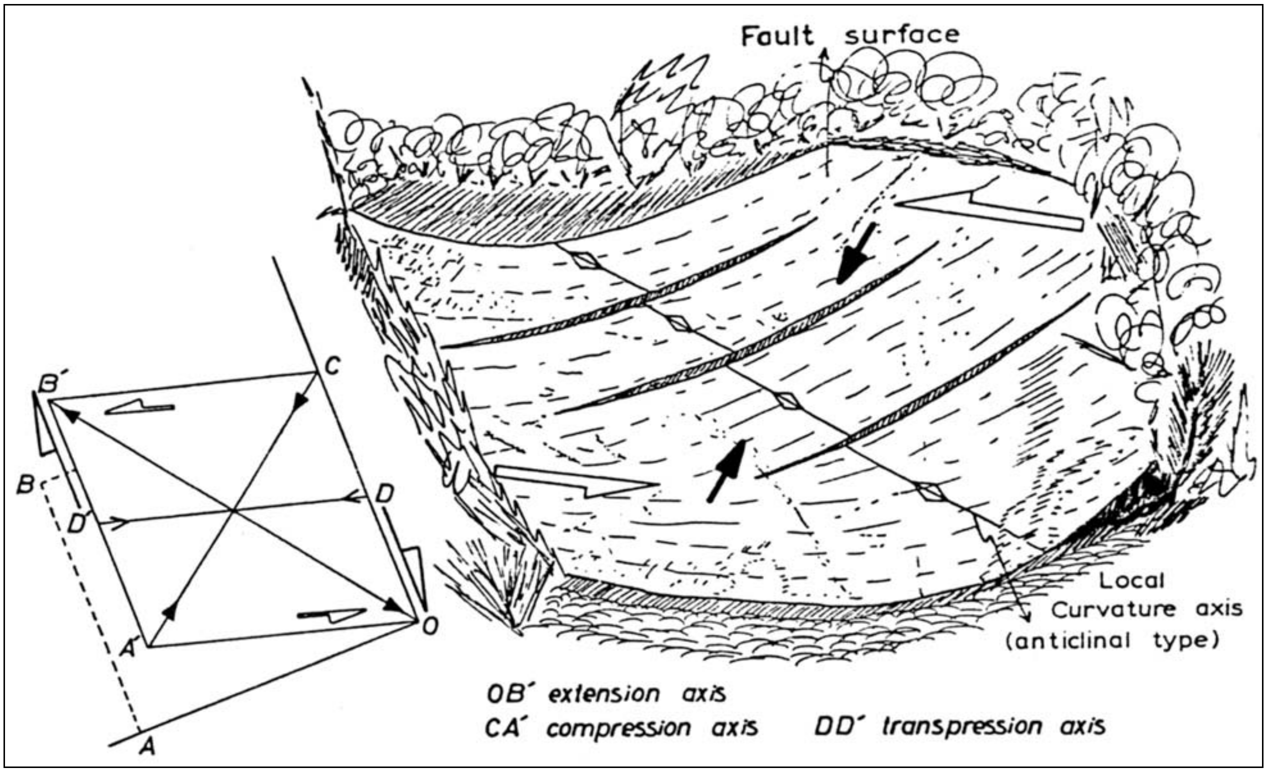

Fig. 12 A proposed model for the kinematic and dynamic interpretation of the "brittle-ductile" type deformation. The stress field is a combination of "coupling", "compression" and "rotation".

Consequently all these structures are connected with a "brittle - ductile" type of deformation and more especially the deformation of the geological body (blocks) must have started as ductile and then neotectonic developed as brittle. But "curving" can not be created by a pure extensional stress field, since this "curving" is connected with shortening in a direction perpendicular to the axis of the curved surface. In this case parallel to the micro-faults surfaces the shortening is estimated to 2-3%.

The general conclusions of the above analysis are that:

(1) The normal faults and consequently the neotectonic normal faults are not only connected with an extensional stress field but with coupling and torsion and even with a regional compressional stress field as well, and

(2) The neotectonic deformation is not only of "brittle" type but also of "ductile - brittle" type. This small amount of plastic deformation before rupture, which is the main reason of the observed embryonic folding could be the result of the creep, in other words this plastic strain which proceeded faulting could ascribed to the long time acting of compressional stresses on the rock body.

With the deformation mechanism described above many minor and major neotectonic macrostructures of Aegean Arc, which have been considered so far as the result of an extensional tectonics e.g. the neotectonic evolution of the Corinth Isthmus area (B.v. FREYBERG, 1973) and the creation of the Corinthian Gulf (MARIOLAKOS and STIROS, 1988).

English version

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