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FLOW PARTITIONING DURING NAPPE MOTION IN THE AGIA MARBLE, THESSALY, GREECE

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ABSTRACT

During the Eocene the Agia marble was incorporated in the nappe motion in East Thessaly. During this motion these marbles suffered normal layer and parallel layer shortening. Boudinage analysis shows a layer normal shortening of 30% and the style of folding shows layer parallel shortening balanced from zero to over than 50%. A partitioning of deformation is expressed by closely spaced flow domains over the sole thrust and wide spaced flow domains in the upper stratigraphic level. A mechanism of more rigid parts trailing over more viscous domains is the prefered style of nappe motion.

ΣΥΝΟΨΗ

Τα μάρμαρα Αγιάς κατά τη διάρκεια του Ηωκαίνου συμπερι-λήφθηκαν στην κίνηση των καλυμμάτων που έλαβε χώρα στην Ανατολική Θεσσαλία. Η κίνηση αυτή παραμόρφωσε κατά την οριζόντιο και κατά την κατακόρυφο τα μάρμαρα Αγιάς. Η κατακόρυφη βράχυνση με βάση την ανάλυση απο Boudinages ήταν 30% και η οριζόντια με βάση το στυλ της πτύχωσης από 0 έως 50%. Η διαφοροποίηση αυτή είχε σαν αποτέλεσμα την δημιουργία ρευστικών περιοχών που διατάσσονται πυκνότερες στην περιοχή της βασικής επώθησης και αραιότερες στα ανώτερα τμήματα της ακολουθίας. Η συνολική κίνηση του καλύμματος έγινε με κίνηση πιό άκαμπτων πετρωμάτων πάνω σε πλαστικά πετρώματα.

INTRODUCTION

Lithological variations in layered systems are accompanied by strain differentiations during the deformation of these rocks. Such differentiations are based on the competence contrast and on the preexisting planar anisotropy which is produced by the bedding planes or the foliation planes.

Normal layer or parallel layer deformation of rocks can be analysed by the boudinage-analysis and the style of folding respectively.

Several experimental works with rock analogous (SOWERS, 1973, LLOYD & FERGUSON, 1981, and WOLDEKIDAN, 1982) have been carried out during the last years. These works have shown that the initial geometrical characteristics and the material properties of layered systems is of great importance for the development of the boudinages. Such differentiation in strain is cleavage refraction (RAMSAY, 1967, TREAGUS, 1983, 1988), amplification of boudinage formation, fold propagation PRICE & COSGROVE (1990), and strain hardening or softening WOJTAL & MITRA (1986).

It was shown by COBBOLD (1983) that such strain differentiations are taking part along the interfaces which are characterized by several properties.

LISTER & WILLIAMS (1983) compared flow partitioning phenomena with the

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preexisting structure of rock and the reflexion of this partitioning in the strain pattern.

JAEGER (1969) has shown in a mathematical point of view the equations of materials under strain in response to their properties.

This work is focused on the description of boudinage development and fold propagation in order to interprate the mechanism of nappe transportation.

GEOLOGICAL SETTING

The area under investigation is a part of the Pelagonian zone. Agia marble of U. Cretaceous age, (MIGIROS & KATSIKATSOS 1980) (Fig. 1) corresponds to a part of the complex "Eohellenic nappe" of DOUTSOS et al. (1993), JACOBSHAGEN et al. (1978).

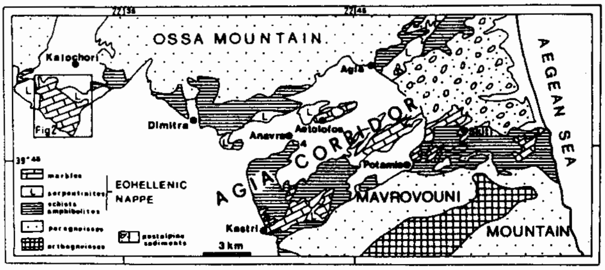

Fig. 1: Geological map of Agia corridor based on the IGME maps sheet Platycambos KATSIKATSOS et al. (1981) and Agia-Panagia MIGIROS & VIDAKIS (1984).

Σχ. 1: Γεωλογικός χάρτης του "διαδρόμου Αγιάς" βασισμένος στούς γεωλογικούς χάρτες του ΙΓΜΕ φύλλα Πλατύκαμπος ΚΑΤΣΙΚΑΤΣΟΣ κ αλ. (1981) και Αγιά-Παναγιά ΜΙΓΚΙΡΟΣ & ΒΙΔΑΚΗΣ (1984).

The Agia marble is part of a complex lithotectonic unit called here Agia-Anavra unit consisting of schists, greenschists, amphibolites, serpentinites and marbles. These marbles are analysed as the key exposures in order to describe the deformation proceses in this unit.

The main tectonic element of the area is the NE - SW trending Agia corridor (DOUTSOS et al., 1993) defining the "basement" for the eastward nappe motion.

These marbles are separated into two subunits, the lower one, with platy black horizons, and scarce intercalations of schist layers, passing gradually to the upper one with massive white recrystallized marbles. The thickness of the layers in the lower subunit ranges from 5 cm to 80 cm whilst the thickness of the layers of the upper subunit ranges from 20 cm to 3 m, with a total thickness of this marble of 250 m.

The existence of granitic pebbles in these marbles with size of 5 x 8 cm, compined with the finding of Rudistids GODFRIAUX (1968) indicates that these rocks are deformed reef limestones.

The structural analysis of this area has been carried out by DOUTSOS (1984).

NAPPE MOTION

The nappe motion during the Eocene in East Thessaly depends on the existence of obstacles and corridors DOUTSOS et al. (1993). Thence it is characterized by a scattering of the mass transportation, from NE to SE direction with predominance of the eastward direction.

The marble of Hassambali is gliding over its footwall (ophiolithic basement) in a brittle-ductile condition following passively the basement morphology (Fig. 2 cross section). During this motion the lower parts of the nappe are more deformed and the upper part is transported easily.

This work is dealing with the analysis of the two components of the nappe motion; the layer normal and the layer parallel shortening.

Four sites with excellent outcrops are analyzed parallel to the (XZ) plane and perpendicular (YZ) plane to the stretching lineation (L2) of DOUTSOS

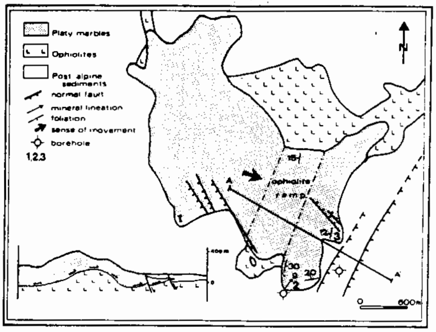

Fig. 2: Geological map of Hassambali area modified from the Igme map sheet Platykampos.

Σχ. 2: Γεωλογικός χάρτης της περιοχής Χασσάμπαλι τροποποιημένος απο το χάρτη του ΙΓΜΕ φύλλο Πλατύκαμπος.

(1984).

In these sites the collected data include boudinage shape ratio, amount of shortening, line element rotation and interface descriptions.

NORMAL LAYER SHORTENING

The detailed observations of the Hassambali marbles indicate that the lithological variations are giving rise to viscosity contrast through the rock. Fractures and later boudinages are produced by such instabilities in layered systems SOWERS (1973).

Experimental works have formulated that in such systems the competence contrast and the strain rate determine the shape of the boudinages (LLOYD & FERGUSON, 1981). Four groups of experiments, as are reviewed by PRICE & COSGROVE (1990), are related to the study of boudinage formation but the most important type of experiments is using rock analogues.

In the area of Hassambali detailed observations of 210 boudinages indicate that they are mainly (150 objects) lenticular or barrel shaped, with sharp boundaries. The statistical analysis of these boudinages (Fig. 3a) indicates an optimum aspect ratio a/b = 3.062. The prepared histogramm (Fig. 3a) is quite similar with the experimentally produced histogramm by WOLDEKIDAN (1982).

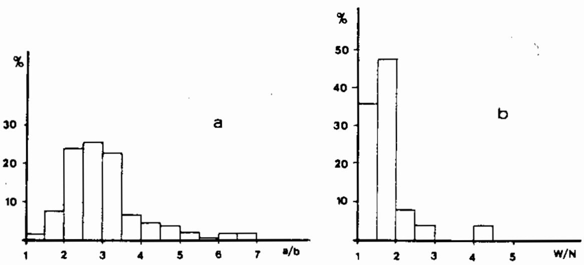

Fig. 3: a.Statistic analysis of a/b ratios of 150 objects in the area of Fig.2. b.Statistic analysis showing the W/N (wide/narrow) ratios for 25 subdivided boudinages under progressive deformation.

Σχ. 3: α.Στατιστική ανάλυση του λόγου a/b για 150 boudinages στην περιοχή του Σχ. 2. β.Στατιστική ανάλυση του λόγου της διαίρεσης μεγάλων boudinages στην διάρκεια προοδευτικής παραμόρφωσης.

The least boudinages (60 objects) are subdivided in two classes. The firts class (24 objects) are boudinages with one main body and one or two secondary bodies. The second class (36 objects) is characterized by variable territories with embayments or apophyses in the matrix.

This subdivision is produced during the progressive deformation of the marble. Field observations and statistical analysis (24 objects Fig. 3b) show that the majority of these boudinages are divided by a ratio (Wide/Narrow) W/N = 1.5.

Otherwise the boudinages are incorporated into the folding during progressive simple shear. The critical dimensions are a = 12 cm and b = 7 cm, boudinages with smaller a,b number are folded while bigger boudinages are acting as rigid bodies.

These observations show that normal layer shortening is taking part during the first stages of the nappe gliding. The normal layer shortening of the sucession is estimated to the amount of 30%. The marbles deformed under a

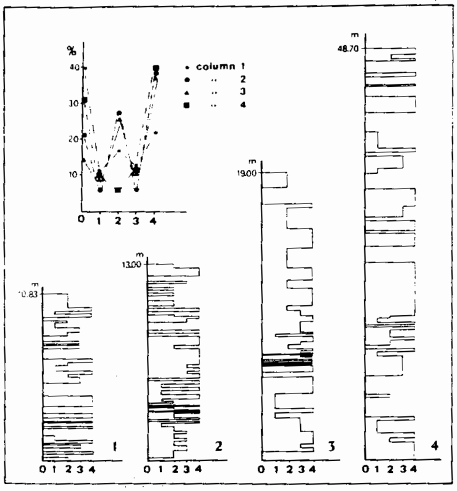

Fig. 4: Vertical structural profiles, in the area of Hassambali columns 1,2 and 3 and in the Anavra village column 4. Horizontal axis represents flow domains (not in scale). At the upper left corner it is graphically represented the percentage of the column which belongs to each flow class.

Σχ. 4: Κατακόρυφες τεκτονικές τομές, στην περιοχή Χασσάμπαλι κολώνες 1,2, και 3 και στο χωριό Ανάβρα κολώνα 4. Ο οριζόντιος άξονας αντιστοιχεί στις κατηγορίες παρα- μόρφωσης 0, 1, 2, 3 και 4 . Στην ανω αριστερή γωνία του σχήματος παρουσιάζεται υπο μορφή γραφικής παράστασης το ποσοστό κάθε κατηγορίας παραμόρφωσης σε κάθε στήλη.

homogenous progressive deformation as indicated by the continous separation of the boudinages. The amplification of boudinage formation observed in parts of rock with thickness 30 cm and rapid lithological alternation. The existence of barrel shaped boudinages indicates that the boudinage bearing layers possess the same competence.

PARALLEL LAYER SHORTENING

The movement of the marble nappes in the study area is accomplished by the deformation of the rocks in a variable degree as it is expected in multilayer systems (TREAGUS 1988). In such multilayers the deformations are balanced, from layer to layer, from zero up to a maximum in relation to the competence contrast.

The following data come from well exposed sections in the area of Hassambali (Fig.2, sites 1,2,3), and Anavra village (Fig.1 site 4). The composite structural profiles (Fig.4 and Table I) are reconstructed 20-50 m above the sole thrust which is exposed in the contact zone between the marble and the basement. This sole thrust is defined as an intensely deformed of 15 m thickness, into the marble.

In the area of Hassambali mesoscopic analysis (Fig.4 columns 1,2,3) indicates that the whole rock is separated in flow domains which are defined as lithotectonic successions.

The detailed observations of these cross sections define five flow classes, each one expressing the following elements.

Flow domain 0 : A lithological succession consisted of thick bedded marble horizons with dark grey colour. The parallel layer shortening is zero.

Flow domain 1 : A lithological succession consited of dark grey horizons alternated with light grey marble horizons. The thickness of the dark and light marbles is equal to each other.

The parallel layer shortening of this category is estimated to the price of the 5% according to the HANDIN et al. (1972). The boudinages in these domains are totally undeformed.

Flow domain 2 : A lithological succession quite similar with the domain 1, deferentiated in that the light and dark horizons are not of equal thickness.

The parallel layer shortening of these domains are estimated at about of 10-15%. The boudinages in these domains are slightly folded.

Flow domain 3 : A lithological succession consisted of rapid alternations of dark and light grey marble horizons and scarse intercallations of schist horizons.

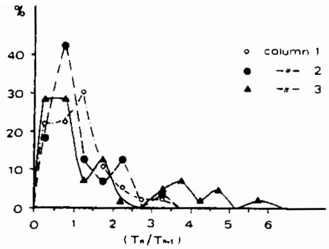

Fig. 5: Graphical representation of the ratio (Tn/Tn-1) (Thickness of the overlain domain/ thickness of the underlain domain). This presentation is expressing the produced separation during the flow - partitioning.

Σχ. 5: Στατιστική ανάλυση του λόγου (Tn/Tn-1) (πάχος υπερκειμένου/ πάχος υποκειμένου). Η ανάλυση αυτή παρουσιάζει τον αναλογία των ρευστικών περιοχών κατά πάχος.

The parallel layer shortening according to the method of RAMSAY (1967) is estimated at about 40%. The vergence which is indicated by the short limbs of the observed folds is SE ward. The boudinages in these domains are partly deformed depending on the a,b dimensions of each boudinage.

Flow domain 4 : A lithological succession consisted of rapid compositional alternations as the domain 3.

The parallel layer shortening is estimated to over than 50%. The style of folding in these domains indicates that the majority of these folds are developed as sheath folds. Fold analysis shows a southeastward sence of movement although some scarse observations display a northwestward sence of movement (site 1, Fig.2). Boudinages observed in these domains are intensively deformed.

Ratio (Tn/Tn-1) (thickness of overlain/thickness of under-lain) (Fig. 5) in the sites 1,2 and 3 shows that the deformation tends to separate the moving mass in domains of equal thickness.

From the detailed analysis and the above description it is observed that the more inhomogenous the lithology the most intensive the deformation.

INTERFACE DESCRIPTION

Each flow domain is separated by singular surfaces or by material surfaces according to the nomenclature presented in COBBOLD (1983). Such boundaries between the overlain and the underlain flow domain is a zone of strain transition. Through this zone is taking part a "jump" in the amount of shortening according to the theoretical prediction by COBBOLD (1983).

Four types of transition zones are observed:

The **type 1** transition zone is compined with thin cataclasites parallel to the bedding planes.

The **type 2** transition zone is taking part on phyllosilicate rich horizons. In these types of transition finally the phyllosilicate rich horizons are separated in lenticular bodies with C and S surfaces.

The **type 3** transition zone is expresed by one singular surface. Typically this surface is exposed as a plane truncating the internal structure of both domains.

The **type 4** transition zone is characterized as a complex zone defined by 3 to 15 singular surfaces. These surfaces are symmetrically arranged around a main surface with a maximum thickness of 20 cm. Typically such zones are defined by 3 to 5 surfaces lumbricated by philosilicates. Detailed observations in the four sites (Fig.4) indicates that the most complex transition zones are observed in sites with abrupt transition in the amount of shortening.

Finally these material surfaces are incorporated in the folding of the whole rock during the climping up of the nappe or interlocked of the horizontal shear zones (called here flow domain 4).

STATISTICAL DATA FOR THE ANALYSED STRUCTURAL PROFILES

flow domain	Σx(cm)	x	n	%	Σx	x	n	%	Σx	x	n	%	Σx	x	n	%
0	428	35.7	12	39.8	278	19.8	14	21.1	260	32.5	8	13.7	1525	125	13	31.2
1	114	28.5	4	10.6	84	21	4	6.3	214	53.5	4	11.2	546	109	5	11.2
2	179	29.8	6	16.6	362	25.8	14	27.5	488	81.3	6	25.6	313	53	6	6.4
3	127	25.4	5	11.8	78	19.5	4	5.9	219	31.2	7	11.5	506	168	3	10.4
4	226	25.1	9	21	511	26.8	19	38.9	711	39.5	18	37.5	1980	111	17	40.7
	1074	28.9	36	99.8	1313	22.5	55	99.7	1892	47.6	43	99.5	4870	113	44	99.9

Table 1: Statistical parameters for the columns refered in the Fig. 4. Óx= sum thickness of all mesured flow domains. X= mean thickness for each flow domain. n= sample size (number of separate flow domains). %= percent against to the total thickness.

Πίν. 1: Στατιστική ανάλυση των παραμέτρων παραμόρφωσης κάθε τεκτονικής στήλης που αναφέρεται στο Σχ. 4. Σχ= άθροισμα του πάχους των περιοχών όμοιας παραμόρφωσης. χ= μέσο πάχος κάθε περιοχής κατά κατηγορία. n= αριθμός των διακρητών περιοχών κάθε κατηγορίας. %= εκατοστιαία αναλογία κατά στήλη και κατηγορία παραμόρφωσης.

CONCLUDING REMARKS

In the study area several separated outcrops of platy dark grey to light grey marbles are considered to be the most representative rock types in order to analyse the deformation of the upper part of the Eohellenic nappe. Pure shear and simple shear deformation is taking part during this nappe motion. The pure shear deformation is producing boudinages during a normal layer shortening of 30%. The simple shear deformation is remarked by the existence of flow domains with variable degree of deformation. The boundaries defining each flow domain are acting as interfaces and later are incorporated in the folding of the marble unit.

The most intensive shear deformation is taking part in the flow domain 4 defined by sheath folding. In these flow domains the outer part of the domain is described as a shear zone while the inner one is deformed by rotational or pure shear deformation. Detailed observations shows that :

1) The most rapid alternation of thin highly deformed domains are exposed closer to the sole thrust while intensively deformed domains are wide spaced in upper stratigraphical positions.

2) Pure shear and simple shear mechanisms of deformation are spatially linked with the ability of the mass to glide above ramps. So the pure shear is observed as more intensive in areas easy to move while the simple shear is the prominant mechanism before the ramp.

3) Based on the above analysis, more rigid parts of rock are trailing over more viscous flow domains lumbricated by phylosilicates.

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