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THE ORIGIN AND EMPLACEMENT OF THE VRONDOU GRANITE, SERRES, N. E. GREECE

C. Kolocotroni* and J. E. Dixon*

ABSTRACT

The Vrondou Granitoid, NE Greece is an Oligocene I-type pluton consisting mainly of quartz-monzonite, but with subsidiary more acid and basic components. It was emplaced in the Lower Tectonic Unit of the Western Rhodope Massif, adjacent to its western boundary, and borders the Strimon and Serres basins to the west and south.

The southern and eastern contacts are strikingly different in character. The east and north-east contacts are apparently undeformed, with the granitoid there having a variable pre-full-crystallisation fabric. High-grade hornfelses are developed in a limited zone within the pelitic country-rock. The southern contact is a wide mylonitic shear-zone, dipping moderately to steeply to the SSE, with a gently SW-plunging stretching lineation and top-to-SW sense of shear. It affects both country rock and granitoid, and importantly, is cut by late melts which are also sheared, implying active deformation during emplacement. The shear zone shallows in dip northwards, but steepens southwards into the major normal fault bounding the Serres basin. Immediately to the south of this fault and the main Vrondou body, the roof of the Elaion granitoid is exposed as a flat mylonite zone overlain by a highly deformed, stretched cover of Rhodope marble, in places as disrupted boudins, and bearing a striking similarity to aspects of Western USA metamorphic core-complexes. The emplacement of the body has occurred during WSW-directed extension, probably between WSW-ENE bounding strike-slip faults. One of these faults later served as the bounding fault for the Serres Basin.

The geochemistry of the granitoid is consistent with generation by crystal fractionation of a single basic magma source from subduction-modified mantle, with minor crustal input. Initial Sr and Nd isotope ratios for gabbro, enclaves and granitoids are all closely grouped between 0.7052-0.7072 and 0.5124-0.5126 respectively, with enclaves close to host granitoid values.

The extensional setting of emplacement raises the possibility that granitoid generation itself was driven by extensional melting of subduction-modified lithosphere.

ΣΥΝΟΨΗ

Ο πλουτωνιτης της Βροντου, Β των Σερρων, ειναι ενας Ολιγοκαινικης ηλικιας χαλαζιακος μονζονιτης, με δευτερευοντα πιο οξινα και πιο βασικα μελη και "I-type" χαρακτηρα. Εχει τοποθετηθει στην Κατωτερη Τεκτονικη Ενοτητα (Παγγαιο) της Ροδοπης, κοντα στο δυτικο οριο της μαζας με την Σερβομακεδονικη,και συνορευει με τις λεκανες του Στρυμωνα και των Σερρων, Δ και Ν, αντιστοιχα.

Οι νοτιες και ανατολικες επαφες του πλουτωνιτη με τα περιβαλλοντα πετρωματα εμφανιζονται με σαφως διαφορετικο χαρακτηρα. Οι ανατολικες και βορειοανατολικες επαφες ειναι φαινομενικα απαραμορφωτες και ο γρανιτης εκει εχει δομες "προ-πληρους κρυσταλλωσης". Κερατιτες υψηλου βαθμου αναπτυσσονται σε μια περιορισμενη ζωνη στο πηλιτικο περιβαλλον πετρωμα. Η νοτια επαφη αντιπροσωπευεται απο μια πλατεια ζωνη παραμορφωσης (διατμησης), με μεσες ως μεγαλες κλισεις προς τα ΝΝΑ και μια χαρακτηριστικη ΝΔ-βυθιζομενη υπο-οριζοντια

*Department of Geology and Geophysics, University of Edinburgh, Grant Institute, West Mains Road, EDINBURGH EH9 3JW., Scotland.

ορυκτολογικη γραμμωση και "επανω-προς-ΝΔ" εννοια κινησης. Αυτη η ζωνη παραμορφωσης επηρεαζει και το περιβαλλον πετρωμα και πιο σημαντικα. διασχιζεται απο μαγματικο υλικο που εχει επισης παραμορφωθει, αλλα σε μικροτερο βαθμο, υποδηλωνοντας ενεργη παραμορφωση κατα την τοποθετηση του πλουτωνιτη. Οι κλισεις στη ζωνη διατμησης μειωνονται σταδιακα προς το Β, αλλα προς το Ν η ζωνη βυθιζεται με μεγαλες κλισεις προς το ρηγμα που οριοθετει την λεκανη των Σερρων. Αμεσως Ν αυτου του ρηγματος και του κυριως σωματος του πλουτωνιτη της Βροντου, εμφανιζεται η οροφη του γρανιτη του Ελαιωνα με τη μορφη μιας οριζοντιας ζωνης μυλονιτιωσης που βρισκεται κατω απο τα εντονα παραμορφωμενα, λογω εφελκυσμου, περιβαλλοντα μαρμαρα, που εμφανιζονται τοπικα σαν "διαμελισμενα boudins", θυμιζοντας εντονα αποψεις των "metamorphic core-complexes" των Δυτικων Η.Π.Α.. Η τοποθετηση του πλουτωνιου σωματος ελαβε χωρα κατα τη διαρκεια ΔΝΔ εφελκυσμου, πιθανα αναμεσα σε ΔΝΔ-ΑΒΑ περιθωριακα ρηγματα οριζοντιας συστροφικης μετατοπισης. Ενα απο αυτα τα ρηγματα αποτελεσε αργοτερα οριακο ρηγμα της λεκανης των Σερρων.

Η γεωχημεια του γρανιτη υποδηλωνει δημιουργια του μαγματος λογω κλασματικης κρυσταλλωσης ενος μονο βασικου μαγματος προερχομενου απο μανδυακο υλικο επηρεασμενο απο χαρακτηριστικα ζωνης υποβυθισης, με δευτερευσα συμμετοχη απο το φλοιο. Οι τιμες των αρχικων ισοτοπικων λογων Sr και Nd για γαββρο, γρανιτοειδη και βασικα μαγματικα εγκλεισματα, κυμαινονται σε σχετικα περιορισμενα ορια, μεταξυ 0.7052–0.7072 και 0.5124–0.5126 αντιστοιχα, με τις τιμες των εγκλεισματων παρομοιες με αυτες του περιβαλλοντος τους.

Το εφελκυστικο περιβαλλον τοποθετησης υποδεικνυει την πιθανοτητα δημιουργιας του μαγματος σαν αποτελεσμα τηξης λογω εφελκυσμου, λιθοσφαιρας με χαρακτηρες υποβυθισης.

INTRODUCTION

The Vrondou or Serres-Drama granitoid complex is an Oligocene I-type composite pluton (Marakis, 1969; Theodorikas, 1982), intruded in marbles and schists of the Western Rhodope Massif, adjacent to its western boundary with the Serbomacedonian Massif. It borders the Strimon and Serres basins to the West and South, respectively, (Fig. 1).

Topographically (Fig. 2), the area under consideration can be divided into two sub-areas, either side of the Serres basin bounding fault: high ground to the north, and low ground to the south of the fault. Granite *s.l.* crops out in both areas (Vrondou to the N, Elaion to the S), together with its envelope. In the high ground, alternations of schists, amphibolites, marbles and gneisses prevail (the Transitional Zone, according to Chatzipanagis, IGME, pers.comm.), whereas in the low ground the envelope is represented by the Menikio marbles.

The contact is only well exposed along the southern and eastern borders and marked differences exist between the two. The east and north-east contacts are apparently devoid of deformation, and the monzonite there exhibits a variable pre-full crystallisation fabric in the sense of Hutton, (1988). Locally it shows a knife-sharp contact between medium-grained unsheared monzonite and a hornfelsed zone of country-rock. The southern contact, in contrast, is deformed by a flat-lying shear system, which produced mylonitic foliations and a shallow, constantly SW-plunging stretching lineation. Near the margin, a wrench-type shear-system steepens and folds the flat-lying fabrics. The key observation is that the folded mylonites are intruded by later melts, implying that the deformation was syn-intrusional.

Immediately to the South of the main Vrondou body, the roof of the Elaion granitoid is exposed as a flat-lying mylonitic zone overlain by a highly deformed, stretched cover of the Menikio marbles, in places as disrupted blocks and boudins.

This paper will consider the observed deformation in relation to : 1) the intrusion history and 2) the basin boundary faults.

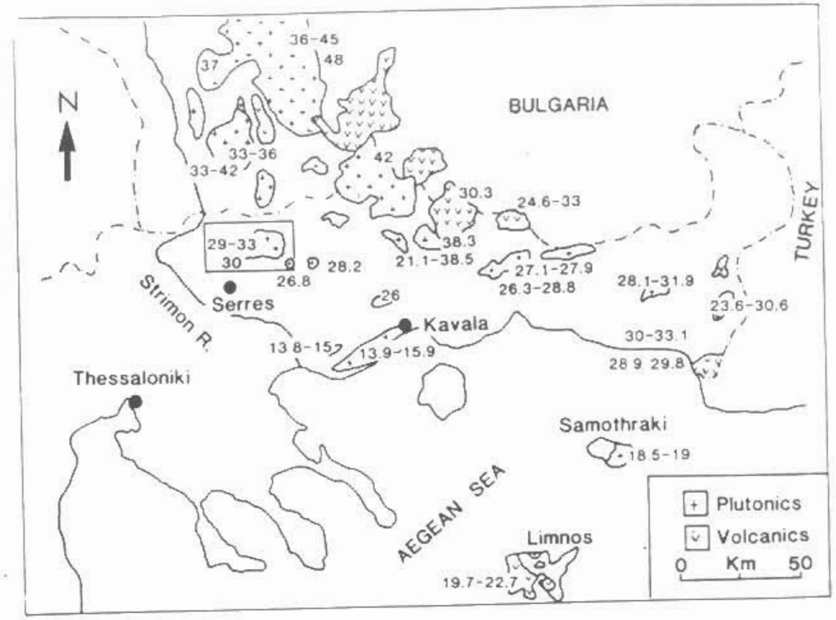

Fig.1 : Age data on Tertiary magmatism in the Rhodope area, from a map compiled by Kyriakopoulos (1987, fig.59, p.268), with modifications. For details, see the original sources: Dürr et al. (1978); Eleftheriadis & Lippolt (1984); Fytikas et al. (1979); Kyriakopoulos (1987); Marakis (1969); Palsin et al (1978); Sklavounos (1981); Yordanov et al (1962).

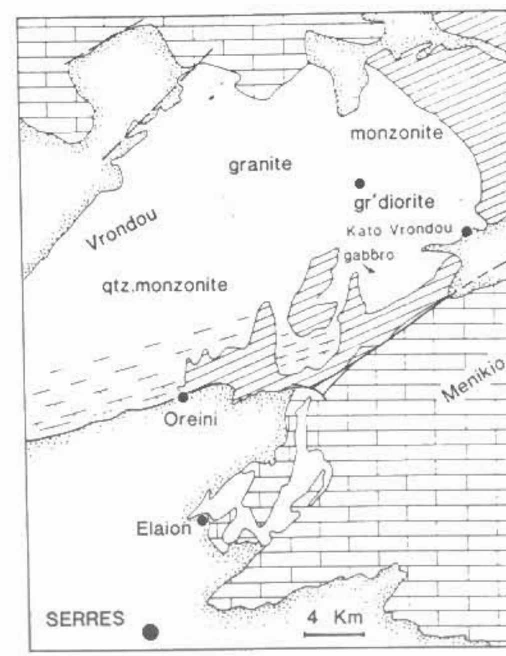

Fig.2 : Schematic geological map of the area of the Vrondou granite, modified after Theodorikas (1982) and IGME 1:50,000 Geological maps, "Serres" (1985) and "Achladochori" (1987). The pelites, amphibolites and gneisses of the Rhodope Transitional Unit are shown with diagonal ruling. Tertiary sedimentary basins have dotted boundaries.

PETROLOGY-GEOCHEMISTRY

The petrography and geochemistry of the Vrondou granitoid pluton have been described in three Ph.D. theses (Papadakis, 1965; Coucoulis, 1982; Theodorikas, 1982) and are therefore generally well established.

The pluton consists mainly of quartz-monzonite, which occupies two thirds of the exposed area, and has gradational contacts with the more acid members, granodiorite and granite *s.s.*, and obscured contacts with the basic members, monzonite (in the north-east of the body) and gabbro. Microdioritic enclaves are observed in all rock-types except the gabbro.

The petrology and geochemistry of the granitoid are consistent with it being a composite I-type pluton, resulting most probably from fractional crystallisation of a single basic magma source from a subduction-modified mantle, as proposed by Theodorikas, (1982) and Kotopouli and Pe-Piper, (1989). Our own major and trace element data are consistent with this hypothesis, as shown in Figs. 3 & 4, the Fe2O3t v SiO2 variation diagram and the trace element spider diagram, representative of a comprehensive data set which will be published elsewhere. The rocks appear to behave as a coherent suite, with an increase of incompatible elements with differentiation. The compositions of the youngest leucocratic sheets are consistent with late apatite fractionation and show moderate LREE depletion. The gabbro exhibits a distinctive relative Nb depletion, compared to MORB, consistent with a subduction signature. Coucoulis (1982) stressed the K enrichment of the monzonitic member in particular and therefore classified it as a *subalkaline potassic* (calc-alkaline) complex.

Sr and Nd isotope results (Kolocotroni, unpublished) from gabbro, granitoids and microdioritic enclaves, show initial $^{87}Sr/^{86}Sr$ ratios (age corrected for 29 Ma) in the region of 0.7052-0.7072 and $^{143}Nd/^{144}Nd$ ratios in the region of 0.5124-0.5126, with enclaves exhibiting equilibration with their hosts. The values imply some crustal input in the genesis of the melts, probably in the form of assimilation during fractional crystallisation processes. The isotopic equilibration of the enclave-host pairs unfortunately means that no specific origin for the microdiorites can thereby be ruled out. The relatively high values of the gabbros may imply an enriched (modified) mantle source.

The rocks from the deformed south contact of the main body and from the Elaion granitoid, south of the bounding fault show a close geochemical overlap with the main Vrondou body itself, as can be shown by their similar behaviour in the variation diagrams (Fig. 3) and also, by the REE normalised patterns (Fig. 5). Generally, it seems that deformation has not altered the chemistry of the rocks significantly. However, bulk assimilation processes at the time of emplacement appear to have affected the first (more deformed) melts to be emplaced, resulting in generally elevated SiO_2 contents relative to the main quartz-monzonite mass and higher Sr initial ratios (0.7079-0.7080). The Elaion granitoid south of the fault is compositionally indistinguishable from the Vrondou body to the north and is regarded as being derived from the same magma source at the same time.

EMPLACEMENT

As was mentioned above, the contacts of the pluton with its envelope have a markedly different character in different places.

Eastern contact

At the Eastern contact (Fig. 2), near Kato Vrondou village, the granitoid is apparently devoid of shearing. It is porphyroidal with an undeformed isotropic matrix

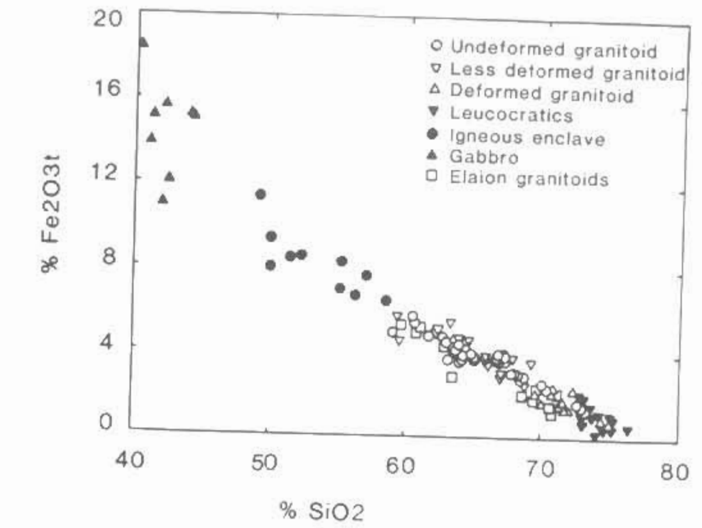

Fig.3 : Fe_2O_3t v SiO_2 variation diagram, exemplifying the systematic major element variation in the Vrondou-Elaion suite. Data from unpublished analyses of Kolocotroni

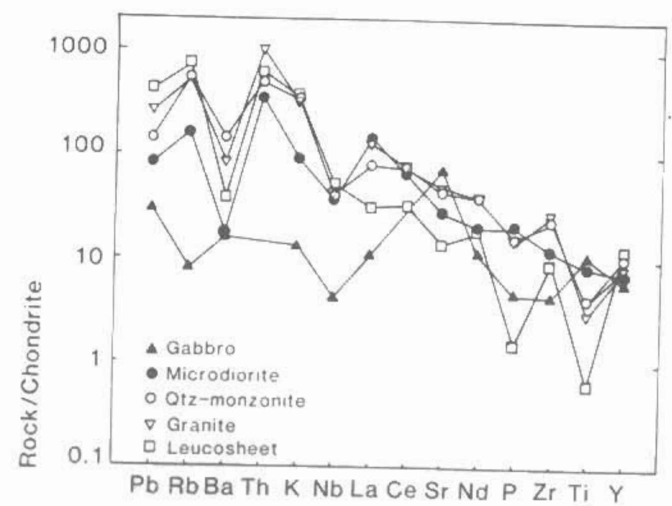

Fig.4 : Trace element spidergram for the Vrondou-Elaion suite. Normalisation values after Thompson (1982). (rock/chondrite, except K, Rb, P for which rock/primordial mantle). Unpublished data of Kolocotroni.

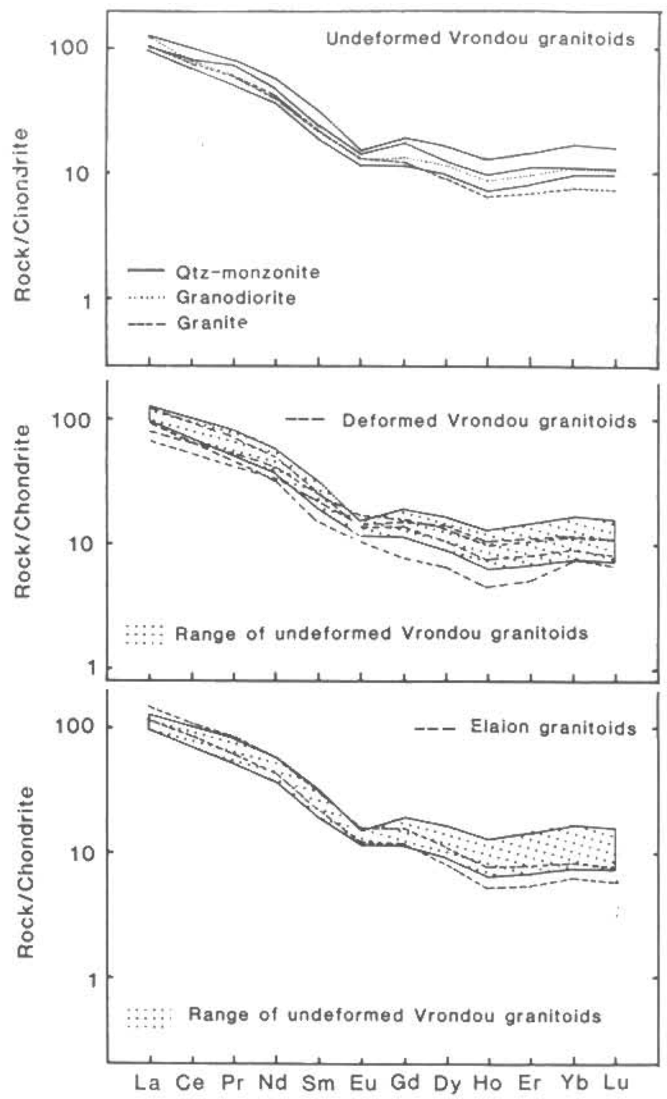

Fig.5 : Chondrite-normalised REE diagrams of undeformed Vrondou, compared with deformed Vrondou and with the Elaion granite. (Normalisation values after Royal Holloway and Bedford New College, London, internal reference set: La 0.33; Ce 1.09; Pr 0.12; Nd 0.63; Sm 0.20; Eu 0.08; Gd 0.27; Dy 0.34; Ho 0.08; Er 0.22; Yb 0.22; Lu 0.0.)

and aligned K-feldspar megacrysts 3 to 4 cms long which indicate some pre-full crystallisation fabric (according to Hutton, 1988), apparently in two directions.

The envelope is represented here mainly by pelites with minor psammitic intercalations. High grade pelitic hornfelses, with andalusite-cordierite-corundum-spinel-Kspar and hints of partial melting in the more psammitic layers are developed in a poorly exposed zone up to c.20m thick. The pressures implied by the hornfels assemblages are no more than 2-3kb. These are consistent with the results of aluminium-in-hornblende geobarometry in the quartz monzonite of the Vrondou body. The contact, where observed, is sharp, dipping steeply to the ESE (under the hornfelses) and the monzonite is undeformed having only a minor chilled margin.

Southern contact

At the Southern margin, near Oreini village (Fig. 2), the picture is altogether different. The envelope here is represented in the high ground by alternations of psammites, amphibolites, schists and marbles, the Transitional Unit of IGME workers, and in the lower ground (Elaion village) by the thick Menikio marbles.

The quartz monzonite here is strongly deformed by a flat-lying shear system, which produces S-C mylonitic foliations, generally dipping to the SE and a strong stretching lineation shallowly plunging to the SW. The sense of shear from porphyroclast tails and S-C intersection sense, is top to the SW. The intensity of the deformation diminishes towards the north (centre of the pluton) where it is represented by a very weak planar fabric.

Near the margin, towards the Serres basin fault, an increase in strain is observed. A steep shear zone affects the granitic mylonites and envelope, developing tight asymmetrical folds, with steep axial surfaces and shallow hinges plunging to the SSW. The asymmetry of the folds is consistent with a dextral sense of motion, with a NW vergence.

The folded mylonites are intruded by later, less deformed melts and leucocratic sheets, implying that the deformation was synchronous with intrusion. These later melts are themselves affected by a flat-lying shear deformation.

This sequence of intrusion-deformation-intrusion is illustrated by the field photographs (Fig. 6) and summarised by a schematic cross-section approximately perpendicular to the SW-plunging stretching lineation at the Vameno stream locality just east of Oreini,(Fig. 7).

The earliest batch of melt appears to have intruded into an active, possibly flat-lying, shear zone, accompanied by minor stoping at the contact, as implied by the numerous mylonitised, stretched amphibolite xenoliths found in it (Fig. 6a). Continuation of the deformation in the cooling contact zone produced a mylonitic foliation in the hybrid contact facies and in the subsequent melts as they were injected and crystallised. The "melt/enclave/leucocratic sheet" facies became progressively flattened and stretched-out (Fig.6b,c,d). Close to what is now the bounding fault, tight asymmetrical folds developed in this sheared hybrid facies in a steep marginal zone, (Fig.6e,7). The folds plunge significantly more steeply than the stretching lineation and imply vergence towards the north-west. The folded mylonites were intruded by later melts and leucocratic sheets, which closely follow axial surfaces.

In the southern hemisphere stereoplot of the observed structures (Fig. 8) from the vicinity of the transect east of Oreini, the consistent stretching lineation shallowly-plunging to the SW, is clear. The SE-dipping planar fabrics become steeper towards the wrench margin. The fold hinges while also shallowly plunging, are steeper than the lineation and more southerly, i.e. oblique to the lineations and consistent with their development as an oblique transpressional feature.

Intensification of the flattening component of strain and the development of folds appears to have occured together. Progressive shear brings the early leucocratic sheets increasingly into sub-parallelism and the planar fabric that results remains an active element in the deformation.

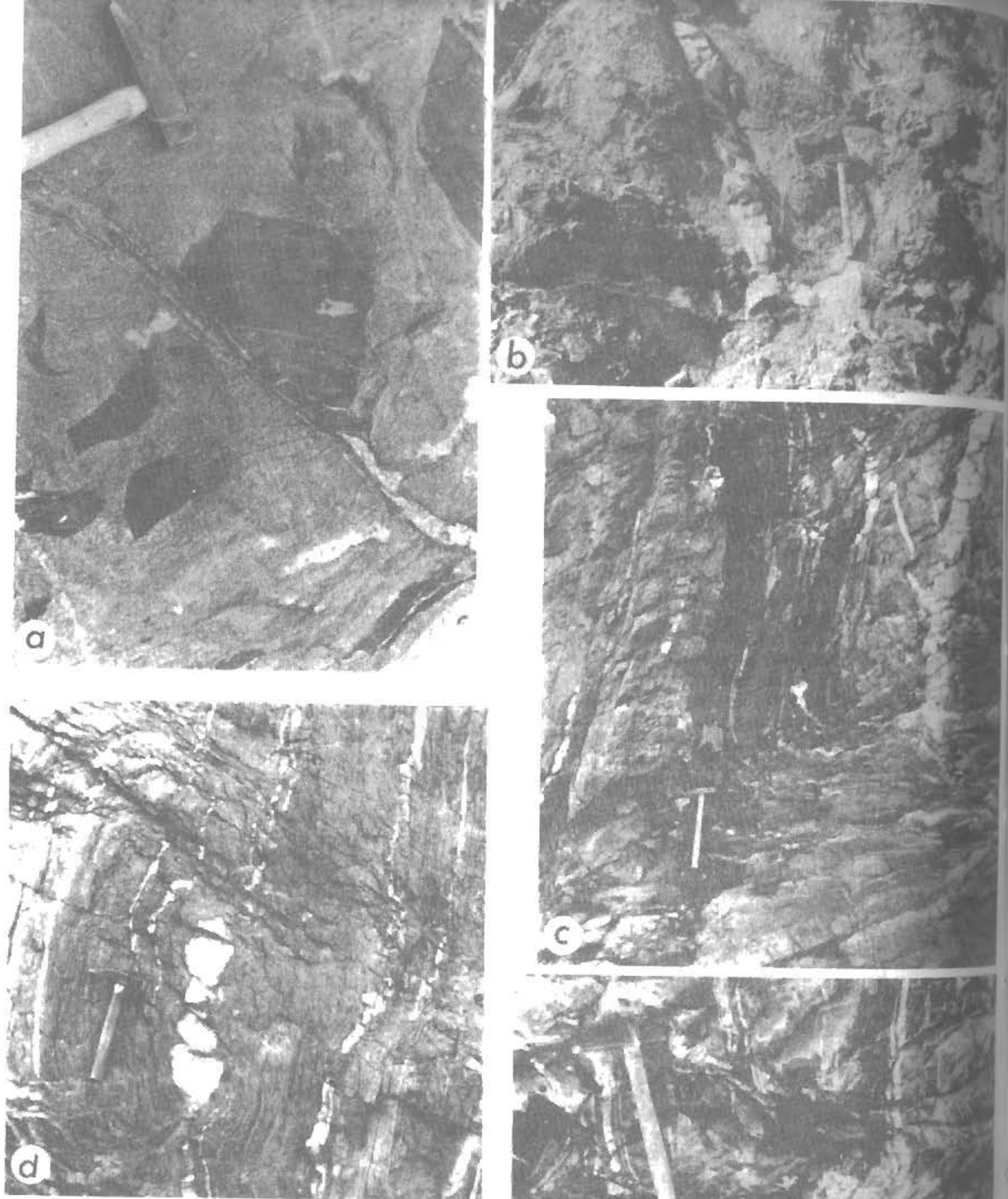


Fig 6 . Field photographs of the marginal facies of the Vrondou body. Vameno Stream section, east of Oreini. a Mylonitised amphibolite xenoliths in hybrid quartz monzonite Some post-solidification strain at lower right b Undeformed late aplitic dykes cutting more mafic, weathered quartz monzonite hybrid with amphibolite xenoliths c Northern edge of the marginal steep shear zone (see Fig.7), c 10m S of b. d Stretched aplite dykes as in c e Folded, stretched aplites in mylonitised hybrid host, with late leucocratic sheet cutting the folds (lower end of the hammer handle).

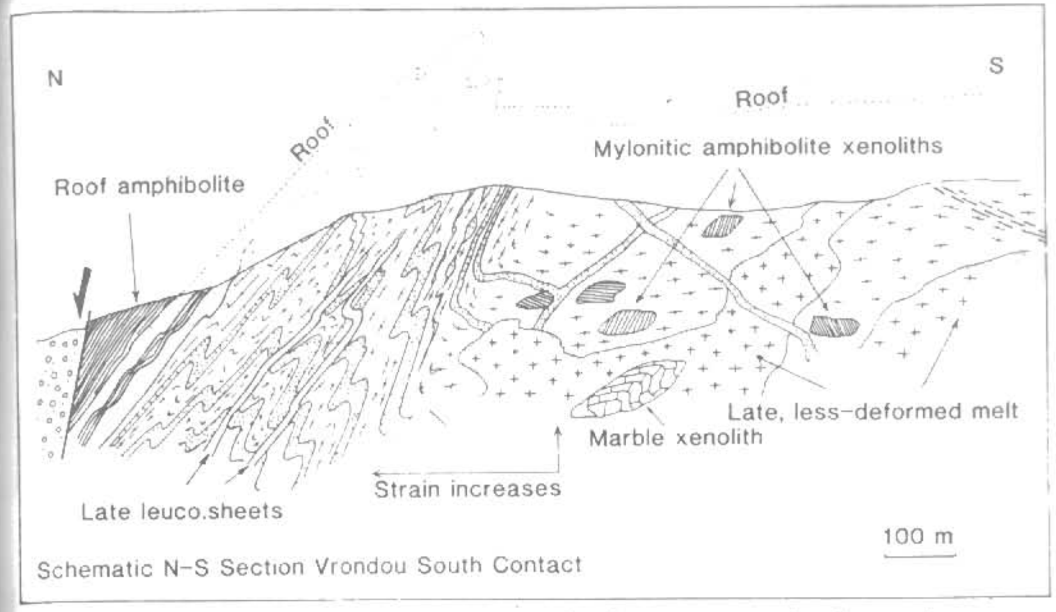

Fig.7 : Schematic N-S cross-section at the Vameno stream locality, as in Fig.6.

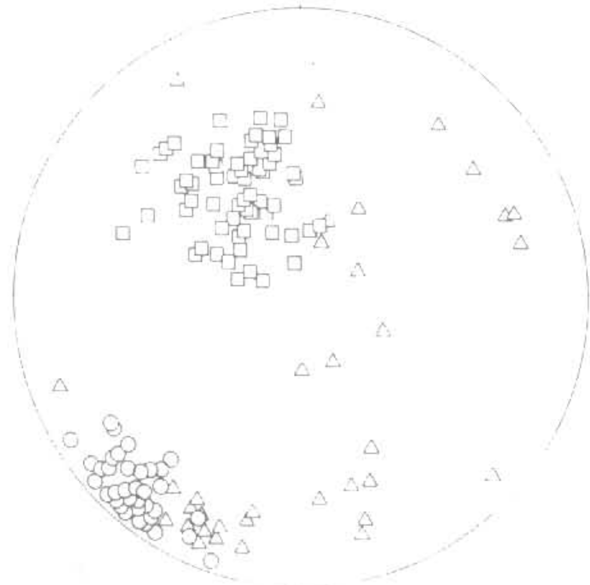

Fig.8 : Southern hemisphere stereoplot of the observed structures at the southern margin. Foliation poles reflect progressive steepening towards the southern contact, effectively rotation about a SW axis close to the stretching lineation direction. Note that fold hinges are more steeply plunging.

The proposed interpretation of the observed sequence of events is one of emplacement of the granitoid in a wrench-shear bounded extensional space (Figs. 9 & 10).

Space for the emplacement was created via a flat-lying shear zone, with top to the SW sense of shear, which aided the relative movement of the envelope blocks, creating a hole behind them. Magma existing at the time, moved to fill the hole. The early batch, caught in the initial stages of deformation, stoped the intensely sheared envelope for a while, preserving the envelope deformation state at the instant of stoping, and was then itself deformed as the marginal facies cooled. The magma away from the roof absorbed the extension while it remained liquid, recording less net post-solidification strain and may well have remained largely undeformed if the locus of shear remained close to the original margins of the space even after it began to be filled.

Continuation of deformation and addition or progressive dominance of a marginal wrench-shear component, folded the earlier fabrics, possibly through the interaction of irregularities along the southern margin. Since magma was still being intruded, the folded mylonites are themselves cut by later melts. This steep, marginal zone later served as the steep basin-bounding fault, so that the present level of exposure reveals a succession of increasingly brittle and steep structures developed as unroofing proceeded.

THE ELAION AREA : SOUTHERN EXTENSION OF THE BODY

The structural evolution of the root of the pluton cannot be followed in the Vrondou body where uplift and erosion has largely removed the record. However it can be examined in the lower ground (south of the Serres basin fault), in the area of the Elaion village (Fig. 2), where down-faulting has preserved the roof.

The Elaion granitoid represents a continuation of the Vrondou body. Near the sub-horizontal contact it is an S-C mylonite, with a flat-lying fabric with the same prominent shallowly-plunging stretching lineation to the SW, and the same sense of shear (top to the SW) as the main Vrondou body at its southern contact.

The roof is represented by the thick Menikio marbles, which thin from c.400m in the Diavolorema ravine 5km east of Elaion, essentially to zero at Elaion itself. At the limit of the marble cover the marble roof has been reduced to isolated marble boudins between which the sediments of the fill (sands and conglomerates with granitic clasts) rest directly on a thin marble cataclasite sheet covering the S-C Elaion granitic mylonite. The isolated blocks are massive and microbrecciated and cut by steep normal faults, dipping to the SW (Fig. 12a,b), consistent with extension in the same direction as implied by the S-C mylonite fabric. A summary diagram of the critical section is shown in Fig.11.

At the base of the boudins, which range in size down to 2m , towards the contact, an unconsolidated fault-gouge is developed (Fig.12c). This lies on top of the actual detachment surface, which consists of a 10-20cm sheet of carbonate ultracataclasite (Fig.12c). The detachment surface is subhorizontal, striking NE-SW, and locally, minor folds are developed in this ultracataclasite sheet.

Immediately underlying the detachment surface is the Elaion S-C mylonite, which has itself undergone cataclasis and pervasive chloritisation and sericitisation near the contact (Fig.12a,c). In the extreme case, where the roof has been completely stretched out to zero, the basin's mainly granitic fill directly overlies the detachment surface and is itself sheared (Fig.12d), implying that continuous deformation had stretched the pluton's marble cover to zero thickness and that this deformation had continued after the pluton had become unroofed elsewhere to the extent that undeformed granite was exposed and transported to this location..

It is noteworthy that the roof contact here has high-level extensional features in the same orientation as the ductile, syn-intrusional ones observed to the north of the Serres basin fault.

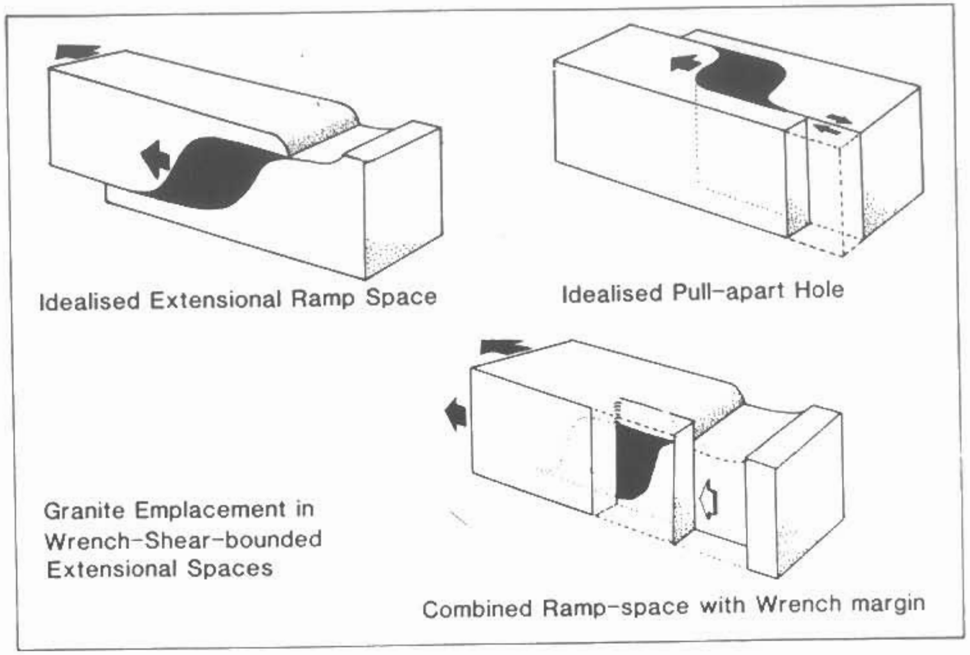

Fig.9 : Proposed idealised model for granitoid emplacement in an active wrench-shear bounded extensional space, giving syn-intrusion deformation at the top and sides but not at the foot-wall contact.

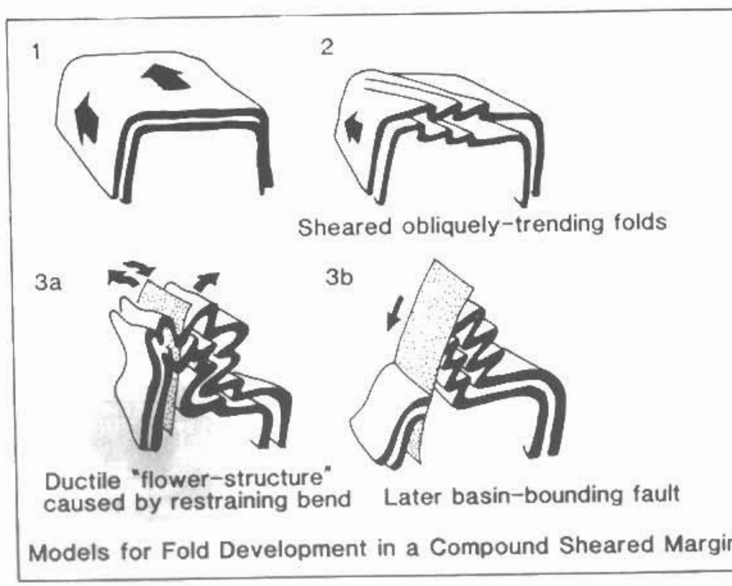

Fig.10 : Models for fold development in a compound sheared margin from the superposition of a wrench-shear component on an active flat-lying shear system. The folded surfaces are a schematic representation of the early shear+flattening fabric. The role of a restraining bend in the marginal shear zone in creating a ductile flower structure and hence the folds, while speculative, is perhaps supported by the offset in the faulted boundary of the granite east of Oreini.

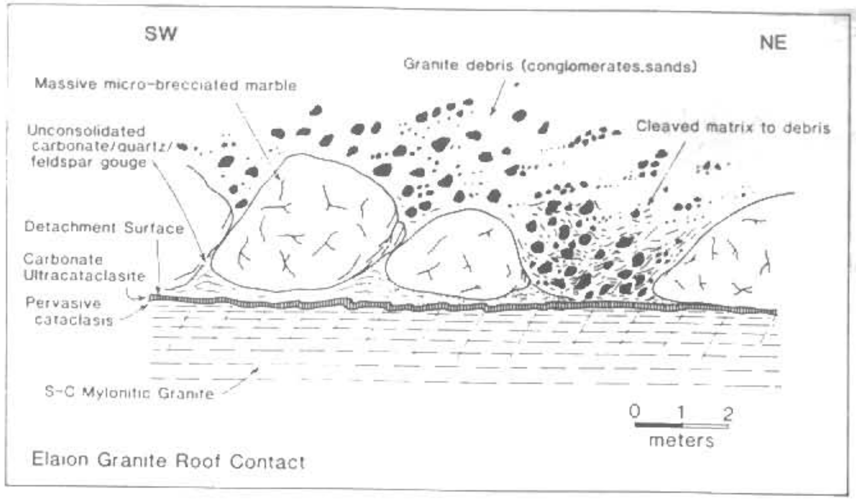

Fig 11 : Summary schematic field section along the extremely stretched granite-marble roof contact at Elaion.

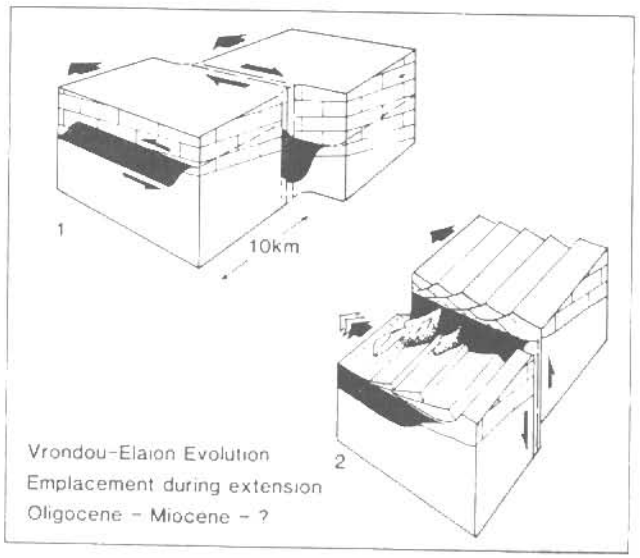

Fig.13 Schematic evolutionary block diagram for the Vrondou/Elaion bodies: 1) Intrusion of granite in an extensional ramp space with the addition of a wrench-shear marginal component, and 2) Activation of the steep boundary as a basin fault, with tectonic unroofing of the Elaion pluton due to extreme stretching of the cover, continuing after solidification of Vrondou to the N.

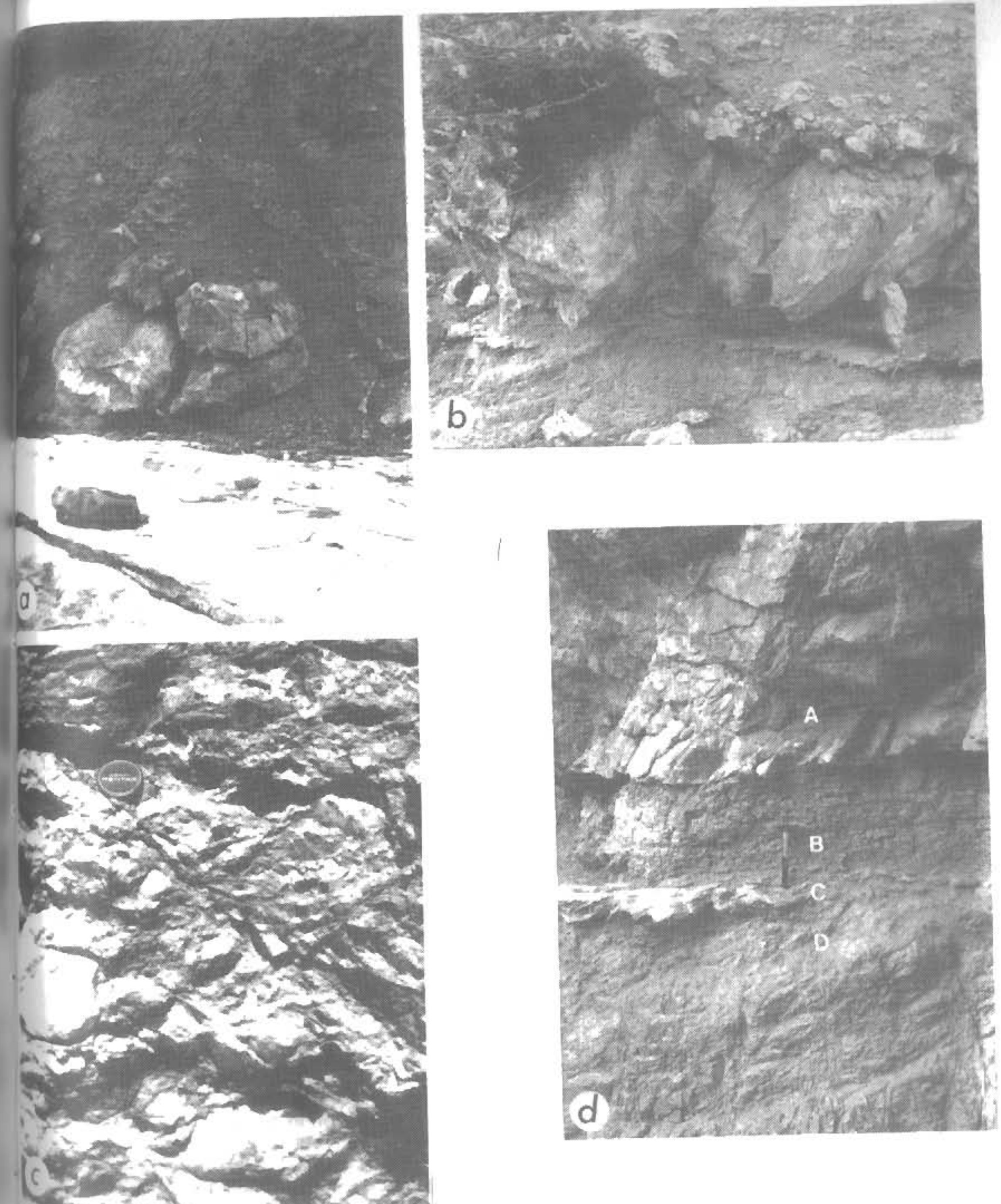

Fig.12 : Field photographs of the Elaion contact illustrated in Fig.11. a: View of the marble ultracataclasite detachment surface (with rucksack); the granite mylonite is seen at the lower left. A small (2m.) marble cataclasite boudin is in the centre, overlain by unconsolidated basin fill. b: View of marble "phacoids" with SW-dipping fractures, resting on the detachment ultracataclasite sheet. c: Close-up of the contact zone;A=marble cataclasite, B=fault gouge, C=marble ultracataclasite sheet, D=S-C mylonitic granite.

The marble bodies, according to their size, record to a greater or lesser extent their previous syn-metamorphic ductile structures. The smallest, a few metres across, are devoid of any visible planar structures and in thin section are entirely cataclastic. Towards the ENE the marble bodies merge into a continuous cover and over 3-400m. the intensity of microbrecciation diminishes, revealing disrupted relict patches of a ductile fabric. Further to the ENE still, high-level brittle deformation is absent. Open, upright, metre-scale folds predating granite intrusion have been deformed in a ductile regime into extremely attenuated isoclines close to sheets of granite *s.l.* interpreted as sub-horizontal off-shoots from the main body below. The granite is converted into an ultramylonite. These features will be described in detail elsewhere.

In summary, the implications of observed high-level structures in the Elaion area are:

1) Tectonic unroofing of the Elaion granitoid was fast and related to high-level extension to the SW.

2) This extensional event is parallel to the syn-intrusional stretching of the Vrondou (=Elaion) granitoid, as they share the shallow-dipping shear system.

3) Extension in the Elaion body has occurred or continued after solidification and exposure of the Vrondou body to the North, as the latter is the obvious source of undeformed clasts.

There are clear parallels of style if not scale, between the structures and intrusive relations described here, and the characteristic features of some Western Cordillera metamorphic core-complexes, for example, the Catalina-Rincon Mountains, Arizona, (Davis, 1987). There Tertiary quartz-monzonite is transformed to S-C mylonite below a detachment marked by a cataclasite ledge, above which is a series of deformed and/or tilted cover rocks. Regionally, there is clear evidence of intrusion synchronous with mylonitisation, (Keith et al., 1980).

CONCLUSIONS

The conclusions of this paper are that the Vrondou-Elaion complex is a calc-alkaline composite pluton emplaced into a space created in a top-to-SW shear system with wrench shear boundaries. There was apparent continuity from ductile (syn-intrusional) deformation through to brittle extension with activation of the steep margin as a basin boundary fault. Tectonic unroofing of the pluton due to high-level extension of the roof resulted in the Elaion marble cover being thinned to zero beneath the Serres basin fill (Fig. 13). If this continuity is real, it suggests that the low angle shear system with extensional ramps, which was exploited by the intruding pluton, may have been developed as a mid- to upper-crustal response to the same regional extension that formed the present Serres and Strimon Basins, and that they were therefore initiated in the Oligocene. Two alternative connections between these events and magma generation on the area can therefore be considered:

Magma was generated by Oligocene subduction (although since K/Ar ages are cooling ages the generation of the magma may have been earlier than Oligocene), with the emplacement being related to extension. In this case, the extensional event could represent a phase of extensional orogenic collapse in the Rhodope and so be directly related to the pervasive mylonite-forming event described by Burg et al (1990).

Alternatively, both the emplacement and the generation of the magma could be related to Oligocene-Miocene-Recent lithospheric extension in a broadly NE-SW direction. In this case, the magma could represent a differentiation product of a basic parent produced by extensional melting of the lithospheric mantle or the thermal boundary layer. The I-type, calc-alkaline character would arise from the thoroughly modified (metasomatised) nature of the mantle in question, following an earlier subduction episode.

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