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THE EFFECTS OF REHEATING OF THE CRUST ON RADIOGENIC SYSTEMS IN THE RHODOPE COMPLEX, BULGARIA

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ABSTRACT

Subsequent to the regional metamorphism which produced high-grade metamorphic rocks of the Rhodope area of Southern Bulgaria, the metamorphic complex was subjected to reheating resulting from major magmatic episodes. Such magmatism took place in Laramide (Late Cretaceous) times with the emplacement of granites and related plutonic rocks, and in Palaeogene times, notably during the Upper Eocene and Oligocene Epochs, when large volumes of volcanic rocks, ranging from intermediate lavas to salic tuffs, were erupted. Palaeogene activity was accompanied by Pb/Zn polymetallic mineralisation. Studies of a metabasite from the Rhodope Complex (Rhodopian Supergroup) in the Asenovgrad area, and a basic sheet in migmatites belonging to the Prerhodopian Supergroup in the region of the Madan-Davidkovo Dome, show consistent differences between K-Ar hornblende and biotite ages, from which uplift rates of between 0.28-0.55 mm yr^{-1} are calculated for the region between 55 Ma and 40 Ma. Determination of a quality Sm-Nd isochron is hindered by the proximity of the Sm/Nd ratios of both amphibole and garnet. This work contributes to the assessment of the significance of radiometric age determinations in understanding the structural history of the Rhodope Complex.

1. INTRODUCTION

The Rhodope Mountains lie in the southern part of Bulgaria, south of the Srednogorie Zone and the Plain of Thrace and to the east of the Pirin and Rila Mountains (Fig. 1). The main geological features of the area include a basement of medium- to high-grade metamorphic rocks, here referred to as the Rhodope Basement Complex, covered in places by Triassic sediments and disrupted by block faulting initiated in Palaeocene times to form extensive basins filled with Palaeogene sediment. The Rhodope Complex extends into neighbouring Greece. Basin evolution was controlled by heterogeneous extensional faulting of Eocene-Oligocene age which had a major effect on basin shape, the location of sub-volcanic intrusive complexes, and the widespread mineralization of the Rhodope region. Basement rocks were involved in this extension, with major fracture zones controlling the segmentation and

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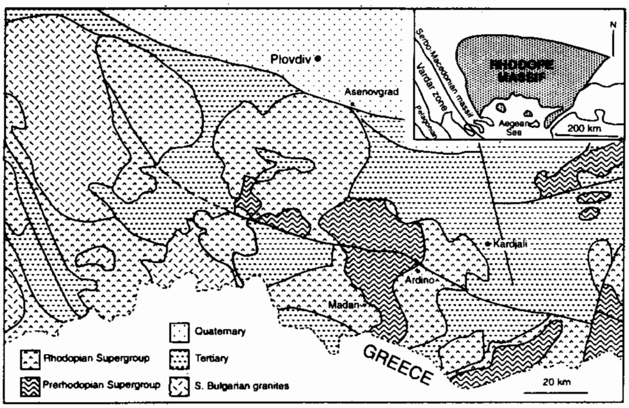

Fig. 1: Geological sketch map of Southern Bulgaria

mineralization of the Rhodope massif. Igneous activity has expressed itself in the formation of Cretaceous (Laramide) granite intrusions and Palaeogene volcansim, which led to extensive eruptions of lava and tuffs varying in composition from basalt to andesite and latite. Polymetallic ore deposits were formed at this time, notably in the Madan area around the Madan-Davidkovo granite-gneiss basement dome. Strata-bound base-metal mineralization associated with basic and ultrabasic basement rocks has important economic significance (Billett & Nesbitt 1986).

A considerable amount of work has been done on the continuation of the Rhodope Complex into Greek territory, notably on the metamorphism (Mposkos 1993, Mposkos et al. 1990, Del Moro et al. 1990) and structural geology (Kilias & Mountrakis 1990). The unpublished report by Mposkos (1993) provides an excellent summary of the tectonic structure, metamorphic evolution and controversies surrounding the age of the complex.

The Rhodope Complex is considered by Dinter & Royden (1993) to be a metamorphic core complex associated with middle Miocene to early Pliocene extension, accompanied by a major detachment. Sokoutis et al. (1993) and Burg et al. (1990) view the Rhodope Complex as a crystalline part of the Alpine belt and not a remnant of some ancient continental fragment. Furthermore, Arnaudov et al. (1990) use U-Pb model ages from K-feldspars and U-Pb ages from zircons to propose that the metamorphism responsible for the earliest episode of migmatisation in the Rhodope Basement Complex took place in the Tertiary. Our geological observations and modelling work contradict this latter view.

2. THE BASEMENT COMPLEX

The rocks of the Rhodopian and Prerhodopian Supergroups have been the subject of detailed mapping carried out by members of the Bulgarian Academy of Sciences, notably D. Kozhukharov and many others (Kozhukharov 1984, 1986, 1992). From detailed mapping an accurate picture of the outcrop distribution of mappable units of varied lithologies has been determined for much of the area. This has been interpreted by Kozhukharov to be a stratigraphical sequence which can be divided into two major successions, an older Prerhodopian Supergroup (also referred to as the Ograzhdenian Supergroup after the locality of Ograzhden in the western Rhodope region), and lying unconformably on top of it, the Rhodopian Supergroup. Each of these is further sub-divided into a series of groups and formations (Table 1). Zagorchev (1976) offers a comprehensive summary of the status and definitions of "Ograzhdenian Complex" and "Rhodopian Complex", names used initially to designate informal lithostratigraphic units.

Table 1: Stratigraphic units in the Rhodope Complex (Kozhukharov 1986)

Supergroup	**Group**	**Formation**
Rhodopian	Asenovgrad	Belashtitsa Calc-silicates Dobrostan Marble
	Sitovo	Lukovitsa Gneiss Bachkovo Leptinite Boikovo Gneiss
	Rupchos	Vacha Variegated Fm Bogutevo Gneiss Chepelare Variegated Fm
Prerhodopian (Ograzhdenian)	Arda	Lyubinovo Gneiss Vishnevo Gneiss Madan Granite-gneiss Vyrlidol Granite-gneiss Alamovo Leuco-gneiss
	Sakar	Lisovo Amphibolite Mladinovo Variegated Fm Konstantinovo Metaconglomerate
	Yuruklerska	Pynovo Migmatite-gneiss Gornoyursko Leptite Kartalbunar Gneiss

The Prerhodopian Supergroup as defined above consists predominantly of migmatitic gneisses varying in composition from acid gneiss to amphibolite with occasional marbles and Al-rich paragneisses. The Rhodopian Supergroup by contrast includes alternating sequences of gneisses, petrographically rather similar to those of the Prerhodopian Supergroup, and the much more varied sequences of rocks which in addition to the lithologies described above include schists, serpentine, marble, calc-silicate rocks, quartzites and high-grade aluminous gneisses, giving the general impression of a sequence of metasediments within which ophiolitic rock associations alternate with orthogneiss.

3. THE AGE OF THE RHODOPE COMPLEX

Although at the time of writing, the primary geological ages of the Rhodopian and Prerhodopian Supergroups have not been accurately determined, there are stratigraphical pointers which impose significant constraints on how old or young they can be. Reported Mesozoic fossil finds (Ivanov et al. 1988) were disputed, and Kozhukharova & Ichev (1989) demonstrated convincingly that high ductile strain in shear belts affecting marbles produced textural effects in mylonites where rotated and recrystallized metamorphic clasts could superficially be mistaken for fossils. Considerable controversy surrounds the absolute age of the complex. The current situation is wellillustrated in a contribution by Arnaudova et al. (1990) who argue for an Alpine age. This is refuted by Ichev (1993), and readers are referred to the ensuing correspondence in the discussion after Ichev's remarks. Kozhukharov (in Kozhukharov et al. 1988) and Boyadjiev & Lilov (1976) quote K-Ar ages for biotite from biotite gensses and migmatites in the Madan region of 26, 35, 40 and 48 Ma, and 69 Ma at a locality 5 km south of the Devil's Bridge (Shatanköprö) near Ardino, where the Egri Dere river flows into the Arda river.

3.1 Palaeogene Basins

Throughout the area of Southern Bulgaria the crystalline basement has been affected by extensive block faulting since Palaeogene time, which has produced extensive sedimentary basins. The sediments in these basins rest on the faulted margins of both Rhodopian and Prerhodopian rocks and many of the coarser clastic deposits, ranging in age from Palaeocene to Oligocene, contain boulders clearly derived from the basement complex.

During Palaeogene times, fault-controlled synsedimentary basin formation was accompanied by volcanic activity, especially during the Oligocene, when great volumes of extruded material, varying in composition from basalt to andesite and latite, and large volumes of rhyolitic ash, were erupted covering large areas of the basement as well as occurring within the limits of the basins.

3.2 Permo-Carboniferous conglomerates

Late Palaeozoic conglomerates lying to the NE of the Rhodope massif contain basement gneiss clasts and lower Palaeozoic granites which, from petrographic evidence and palaeocurrent indicators, were derived from the Rhodope Complex rocks. K-Ar ages on these clasts yield 395 Ma from an aplite, 320 Ma from a muscovite gneiss, and 214 Ma from a granite (Kozhukharov et al. 1980, 1988). Conglomerate clasts are believed to retain evidence of repeated tectonothermal events, whereas generally their analogues from outcrops in the massif retain a memory of only the latest event.

3.3 Evidence from microfossils in the Asenovgrad Group

Microfossil finds have been reported from the Rhodopian Supergroup (Tchoumatchenco & Sapunov 1989 [*Aspidella terranovica* from mables at the Asenovgrad Fortress], Kozhukharov & Timofeyev 1989 [*Protosphaeridium* etc.]) that purport to demonstrate an Early Proterozoic age for the Rupchos and Sitovo Groups (Table 1) and a Riphean age for the Dobrostan Marble and Belashtitsa calc-silicates in the Asenovgrad Group. Microphotographs published by these authors do not appear to be completely convincing.

3.4 Summary of Evidence for age of Rhodope Complex

From the above it can clearly be seen that the origin of the Rhodope Complex, including both the Rhodopian and Prerhodopian Supergroups, is pre-Mesozoic and possibly as old as Precambrian. Suggestions that the protolith is of Mesozoic or later origin are clearly not sustainable on geological evidence, as argued convincingly by Zagorchev (1991). Arnaudov et al. (1990) maintain that the metamorphic event was Tertiary in age, but the discovery of gneiss clasts in Permo-Carboniferous conglomerates clearly establishes the migmatisation (i.e. the metamorphism) as being pre-Permo-Carboniferous. It is difficult to assess the U-Pb data of Arnaudov at al. (1990), as complete analytical details such as errors and blank atomic ratios (including $^{207}Pb/^{206}Pb$) are not given. Nonetheless, the data do seem to suggest that either the majority of zircon growth in the migmatitic gneisses of the Ardino Group took place during the Tertiary, or that the analysed zircons experienced significant Pb loss at this time, which we infer (from our K-Ar work) was a time of significant uplift. Indeed, Gebauer and Grünenfelder (1979) have suggested that zircons may lose Pb due to pressure release during uplift. Without being able to assess the results more fully, it is not clear whether or not the data could also be consistent with substantial recent Pb loss from older grains. The broad agreement between the thorogenic model ages for K-feldspars from migmatites (62-30 Ma) and the U-Pb zircon ages ($^{206}Pb/^{238}U$ ages = 42-33 Ma) may be fortuitous in view of the potential uncertainty of the U-Pb data and of the model dependence of such thorogenic ages.

4. RADIOMETRIC EVIDENCE FOR THE AGE OF THE RHODOPE COMPLEX

The mineralogy of the crystalline basement rocks provides, on the face of it, wide scope for the radiometric dating of the rocks using a variety of techniques. The practical application of such techniques is, however, fraught with difficulty due to the history of major thermal events which have led to the eruption of extensive extrusive igneous rocks during Oligocene times with accompanying plutonic activity. Cretaceous (Laramide) plutonic magmatism, resulting in the emplacement of major granites and related rocks, and older events from Palaeozoic or older times, which express themselves in the numerous pegmatites and veins which cut the gneisses of the basement, also produced regional heating events.

4.1 Sampling

Two samples of metabasites were analysed, from Egri Dere and from Asenovrad, the localities being 50 km apart (Fig. 1). The sample from Egri Dere (7B) is a dyke in the Prerhodopian complex, emplaced into banded leucocratic migmatitic gneisses, and that from Asenovgrad (2B) is a metabasite (a plug, part of a possible volcanic structure) in the Rhodopian Supergroup (Kozhukharova 1972). The latter is therefore structurally much higher. Brief petrographic descriptions follow.

B89-2B is a fresh, unweathered metabasite from the Ruen volcanic region, Lukavitsa River, Asenovgrad, from near the northern edge of the Rhodope Complex but clear of any obvious shear zones. It is a metamorphosed high-alumina gabbro-diabase intersecting the "leptinites" (highly-sheared fine-grained quartzo-feldspathic gneiss) of the Rhodopian Bachkovo Formation (Table 1). Weakly foliated, medium-grained, amphibole-rich, with biotite, ore minerals and large epidote grains; some fine-grained granular aggregates of amphibole intergrown with quartz and feldspar; feldspars fresh, showing no signs of sericitisation.

B89-7B is a strongly foliated basic sheet in the Lyubinovo Formation, Prerhodopian Supergroup, Egri Dere river, Ardino, part of the Madan-Davidkovo Dome. Nearly conformable with the foliation of the host gneisses. Egri Dere is a deeply incised gorge and good clean three-dimensional exposures are abundant in the stream bed. Fresh, unweathered rock, practically unbanded. Unstrained biotite 1-2 mm, amphibole 1 mm, plagioclase with albite twinning <1 mm, quartz 0.5 mm with sutured grain boundaries; accessory sphene and apatite. Not near any major intrusions.

4.2 Results

The results of the K-Ar dating are given in Table 2. Hornblende from the

Egri Dere sample (7B) gives an age of 55±3 Ma, whereas biotite has an age of 40±2 Ma. The hornblende and biotite from Asenovgrad (2B) yield ages of 64±16 Ma and 40±1 Ma respectively. The biotite ages are identical. The age of the hornblende from sample 2B has a relatively poor precision, but is within error of the hornblende age from sample 7B. This higher error may be due to the low K content of the amphibole from 7B which in turn has resulted in only limited production of radiogenic ^{40}Ar. We consider the hornblende age of 55 Ma from Egri Dere to be the more reliable.

Table 2: K-Ar dates from Rhodopian and Prerhodopian rocks

Sample	Mineral	K (%)	Radiogenic ^{40}Ar ($x10^{-10}$ moles gm^{-1})	Age (Ma)
B89-7B	Hornblende	1.90	1.828	54.6 ± 3.4
B89-7B	Biotite	5.27	3.710	40.1 ±1.5
B89-2B	Hornblende	0.27	0.308	63.9 ± 16.4
B89-2B	Biotite	5.86	4.055	39.5 ± 1.1

4.3 Modelling

The K-Ar biotite ages from 7B and 2B are identical within error at ~40 Ma. Both samples appear to have been unaffected by the well-documented, widespread later Oligocene (~30 Ma, Dabovski et al. 1991, Lilov et al. 1987) magmatic event. This, coupled with the fact that the Oligocene magmatic products unconformably overlie the basement amphibolites, suggests that the latter had already been uplifted prior to the magmatism, and therefore that these ages may plausibly reflect this earlier uplift.

In order to determine the rate of this uplift event we can utilise the differences in K-Ar ages between the hornblendes and biotites, coupled with the theory of closure temperatures (Dodson 1973). The most widely accepted closure temperature for K-Ar in hornblende is 550°C, whereas for biotite it is 300°C (Dempster 1985). This assumes that there was no fluid alteration or recrystallisation of the amphibole which would tend to lower the apparent closure temperature (Miller et al. 1991).

Zagorchev (1991) has used Rb-Sr geochronology and geological arguments to estimate the uplift rates of the Rhodope Massif. He concludes that rates of the order of 0.2-0.3 mm yr^{-1} appear to be reasonable.

From the K-Ar data and the closure temperature estimates it appears that there was a decrease in temperature of 250°C during an interval of 15 Ma; this represents a cooling rate of ~17°C Ma^{-1}. If the geothermal gradient were considered to be (a) 30°C km^{-1} (typical continental geotherm), or (b) 60°C km^{-1} (suggested by Zagorchev 1991), then calculated uplift rates from our data are ~0.55 mm yr^{-1} and 0.28 mm yr^{-1} respectively. These values represent the average uplift rate during the 15 Ma time interval. The latter value is consistent with Zagorchev's (1991) independently estimated uplift rate.

4.4 Assessment of pre-Tertiary events

In view of the fact that both Rb-Sr and K-Ar biotite and K-Ar hornblende isotope systematics reflect Palaeogene uplift events, attempts to assess the timing of pre-uplift events in the basement complex must be based on geochronological systems which have higher closure temperatures than that of K-Ar in hornblende (*c*. 550°C; Dempster 1985). To this extent we analysed a garnet amphibolite from Asenovgrad, an area which has apparently suffered a minimal amount of Rhodopian and later tectono-thermal activity, using Sm-Nd techniques on garnet, amphibole and whole-rock. The closure temperature of garnets is controversial, with estimates ranging from 500°C-900°C (Humphries & Cliff 1982; Cohen et al. 1988); more recently Mezger et al. (1992) have proposed a closure temperature of 600°C. It appears that the closure temperature for garnet is likely to be at least 600°C, which is significantly greater than that for K-Ar in hornblende (see above); consequently we believed that Sm-Nd work on this garnet amphibolite could yield information about the age of the Prerhodopian.

Preliminary attempts to obtain an isochron from whole-rock, amphibole and garnet measurements have so far proved unsuccessful. Results indicate that (a) the Sm and Nd concentrations of both garnet and amphibole are low, markedly so in the case of the garnet: amphibole Sm = 0.908 ppm and Nd = 2.121 ppm; garnet Sm = 0.222 ppm and Nd = 0.536 ppm), and (b) the Sm/Nd ratios of both phases are very close together (0.428 and 0.414 for amphibole and garnet respectively). The proximity of the Sm/Nd ratios results in a distinctly compressed isochron, which is obviously unsatisfactory.

As a second strategy of approaching this problem, we are also performing U-Pb analyses on zircons from a granitic leucosome from a migmatitic gneiss immediately adjacent to the Egri Dere metabasite (7B). We are separating high-integrity zircon needles which are devoid of cores, and which we consider crystallised from the granitic melt. Hence, due to the high U-Pb retentivity of high-integrity zircon crystals, these needles may provide information relating to the timing of earlier igneous and metamorphic activity within the Rhodope massif.

5. DISCUSSION

The age of the Rhodope complex is clearly controversial, reflecting the very complicated, multi-episodic history of the region. Currently we have geological information which gives some clues to the relative age (metamorphic clasts in conglomerates, etc.), but as yet we have no reliable, high-quality isotopic data. However, recent work has begun to unravel at least some of the history (Zagorchev's and our K-Ar data), and the main aim of our investigations is to produce an absolute age for the Prerhodopian Supergroup, hopefully using the zircon technique.

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