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ARE THERMAL DOMES HEATED BY CO_2-RICH FLUIDS FROM THE MANTLE?

R.D. SCHUILING and R. KREULEN

Vening Meinesz Laboratory, Department of Geochemistry, University of Utrecht, Utrecht (The Netherlands)

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A large part of the fluid present in the thermal dome at Naxos, Greece, during the main stage of metamorphism was CO_2-rich and of deep-seated origin. Samples of this pervasive fluid were trapped in fluid inclusions, which are particularly abundant in syn-metamorphic quartz segregations. These quartz segregations are considered to represent the main passageways of the escaping fluids. Mass-balance calculations based on $\delta^{13}C$ values of fluids and rocks indicate that most fluid/rock mass ratios are between 0.06 and 0.8. The heat added to the metamorphic system by the cooling of these fluids may have been the prime cause of metamorphism and updoming.

1. Introduction

Thermal domes are a common feature in many metamorphic areas, and have been described from many parts of the world [1–3]. They occur within low-grade regional metamorphic rocks, and show a rapid succession of metamorphic zones. These zones, of increasing metamorphic grade, are wrapped around an anatectic or granitoid core. The low-grade rocks away from the domes display no pronounced metamorphic gradients.

It is apparent, therefore, that a well-focussed heat-source must have been responsible for their formation, and it is the aim of this paper to show that hot fluids of deep-seated origin could represent such a focussed heat-source.

Large fluid/rock ratios are well-known intrusions where water, often of meteoric origin, has been set in convective motion due to the temperature disturbance caused by the intrusion [4]. Not only in contact metamorphism but also in regional metamorphic rocks the $\delta^{18}O$ systematics indicate interaction with large amounts of fluids [5–7]. Fluid-inclusion studies in several metamorphic terranes have demonstrated the presence of large amounts of CO_2, possibly originating in the upper mantle [8–12].

In the following the thermal dome of Naxos will be used as an example, and the thermal effect of hot fluids passing through a column of rocks will be calculated using data from Rye et al. [7], Kreulen [12] and Jansen and Schuiling [13].

2. The geology of Naxos

Naxos is the largest island of the Cyclads, Greece, and consists mainly of a regional metamorphic complex of schists and marbles, wrapped around a central core of migmatites. Mineral assemblages and stable isotope fractionations in widely varying rock types indicate temperatures of 700°C in the central part to less than 400°C in the lowest-grade metamorphics [7, 13]. The temperature drop of 300°C occurs smoothly over a horizontal distance of 15 km, representing a stratigraphic thickness of the order of 5 km. The pressure of metamorphism was of the order of 5–7 kbar. The phase of metamorphism accompanying the formation of the dome was designated as the M_2-phase, and dated at 20–25 Ma [14]. It was preceded by a M_1-phase of the high-pressure/low-temperature type with temperatures around 500°C and pressures of 7–9 kbar; this earlier phase came to a close about 40 Ma ago [14]. This high-pressure metamorphism was of regional extent and has been recognized in the greater part of the Cycladic area, whereas the thermal dome structure of Naxos is a local feature.

3. Data

In order to predict the thermal effect of a certain amount of hot fluids passing through a column of rocks, we need data on the following points: (1) composition and thermal properties of the fluid, (2) thermal properties of the rocks, (3) fluid/rock ratios, and (4) approximate time scale of the process.

3.1. Composition and thermal properties of the fluid

Several of the metamorphic minerals from Naxos contain fluid inclusions. By far the most abundant type of inclusion contains liquid CO_2 as the major phase; in addition these inclusions contain water and some of them a gas bubble. The most common fluid composition is 50–80 mol.% CO_2. For a detailed description of the inclusions the reader is referred to Kreulen [12]. Metamorphic reactions in an area of pelitic and carbonate rocks tend to produce water-rich fluids at low temperatures and CO_2-rich fluids at higher temperatures. At Naxos, however, the composition of the fluid inclusions is independent of the local lithology and metamorphic grade. This suggests that most of the fluid is not of local origin but pervasive. From a study of the stable carbon isotopes of CO_2 from the inclusions [12] it appears that locally derived decarbonation CO_2 (with $\delta^{13}C$ values of +2 to +5‰) is indeed scarce; quantitatively, the amount of metamorphic Ca-Mg silicates in the marbles is negligeable. There is a number of inclusions with low $\delta^{13}C$ values (−8 to −16‰), but these are restricted to a zone with graphite quartzites, and they owe their isotopic composition to the oxidation of organic carbon. The large majority of inclusions, however, fall in the range of −1 to −5‰, which is somewhat higher than the values around −6‰ commonly accepted for deep-seated CO_2 [15].

For this reason we assume that the CO_2 in the metamorphic fluids of Naxos is a mixture of 2/3 deep-seated CO_2 and 1/3 decarbonation CO_2, produced by mineral reactions below the presently exposed level. Mixing probably took place also below the presently exposed rocks. A deep-seated origin of the fluids present during metamorphism was also indicated by Rye et al. [7], who found that $\delta^{18}O$ and δD values of metamorphic minerals and δD of water from fluid inclusions approached typical magmatic values in the higher-grade rocks of Naxos. The initial temperature of the fluid, as it entered the metamorphic system must have been around 1000°C; even now, 20 million years after the peak of metamorphism, the top of the mantle at a depth of 26 km is still at 850°C, and temperatures of 1000°C are reached already at a depth of 50 km [16]. Moreover, in order to provoke dissociation of carbonates and OH-bearing silicates in the upper mantle, temperatures around 1000°C are needed [17,18]. The temperature at which the fluids left the metamorphic system will be set at 400°C, the lowest metamorphic temperature associated with the M_2-phase of metamorphism. This temperature estimate is corroborated by the fact that during the preceding M_1-phase temperatures of 500°C were reached at pressures of approximately 8 kbar, corresponding to a geothermal gradient of about 17°/km. At the beginning of the M_2-phase, the pressure had dropped to 6 kbar, corresponding to a depth of 20 km. If the geothermal gradient had not yet increased much, this would correspond to a temperature of 400°C.

We will therefore consider the thermal properties of a fluid with a molar CO_2/H_2O ratio of 1 between the temperatures of 1000 and 400°C at a constant pressure of 6 kbar. As it will be shown that the fluid/rock ratio is by far the largest uncertainty in the model, deviations from ideality can safely be neglected. For a fluid with the above composition we arrive at an average specific heat in the temperature range between 400 and 1000°C of 0.365 cal g^{-1} $°C^{-1}$ [19]. Because only 2/3 of this fluid is considered to be of deep-seated origin, only 2/3 of the heat lost by this fluid by cooling from 1000 to 400°C will be considered as "added" to the metamorphic system.

3.2. Thermal properties of the rocks

Although not many data are known about the thermal properties of rocks at higher temperatures, the thermal properties of most of the common rock-forming minerals are sufficiently similar that an average specific heat of 0.3 cal g^{-1} $°C^{-1}$ can be used [20]. This is somewhat above the average value at room temperature, as the specific heat of rocks slightly increases with increasing temperature.

As far as other heat losses to the metamorphic system are concerned, it should be stressed that the system had already undergone an earlier (M_1-phase) of metamorphism, so that many of the energy-consuming dehydration reactions had already gone to completion, and most of the pore-waters had already been removed. Anatexis, however, is definitely restricted to the M_2-phase of metamorphism and will be considered in the section on the thermal effects.

3.3. Fluid/rock ratios

Several lines of evidence lead to the conclusion that fluid/rock ratios during the M_2-phase of metamorphism were high.

(1) The observation that CO_2/H_2O ratios in the fluid inclusions are largely independent of lithology and metamorphic grade indicates that much more fluid migrated through the rocks than was produced by dehydration and decarbonation reactions of the rocks proper.

(2) $\delta^{18}O$ values of the schists and quartz segregations decrease regularly from about 18‰ in the least metamorphosed rocks to about 10‰ in the migmatite [7]. A tendency of $\delta^{18}O$ values in high-grade rocks to approach igneous values has been observed in many regionally metamorphosed arèas, and is generally attributed to isotope exchange with fluids from a deep-seated source [5–7]. Mass-balance calculations provide a means of estimating fluid/rock ratios. In order to bring the presently exposed rock section from a $\delta^{18}O$ of 18‰ to an average value of 14‰ (half way between the least metamorphosed rocks and the migmatite), a mass of fluid about equal to the rock mass is required, assuming that the oxygen of this fluid was in isotopic equilibrium with the migmatite.

(3) Independently, fluid/rock ratios have been estimated by means of the carbon isotopic composition of calcite in schists [12]. During metamorphism the $\delta^{13}C$ of these calcites attained lower values as a result of isotope exchange with CO_2-rich fluids. In order to produce the measured $\delta^{13}C$ of the calcites, masses of fluids between 0.06 and 0.8 times the mass of the rocks must have passed. It should be stressed that the mass balance calculations based on isotope exchange in general yield minimum fluid/rock ratios; once fluids have equilibrated with the rock, they can no longer be observed by this method, and, therefore, the real fluid/rock ratios may have been larger.

(4) From the fact that the ubiquitous quartz segregations contain almost exclusively samples of a pervasive fluid of deep-seated origin, one may conclude that the quartz mostly has precipitated from this fluid. The solubility of quartz in water at p_{H_2O} = 3 kbar decreases from 1.4 wt.% at 700°C to 0.3 wt.% at 400°C [21,22]. 700–400°C is the range of metamorphic temperatures in the exposed part of the metamorphic rocks at Naxos. Although it is hard to quantify the rather variable amount of quartz segregations in the metamorphic series, even 0.1% of quartz occurring as segregations in the rock (and this estimate is certainly too low) would suggest already a fluid/rock mass ratio of 0.1.

3.4. Approximate time scale of the process

For metamorphic systems of the size of thermal domes as at Naxos and other areas, usually of ellipsoidal shape and horizontal dimensions of ten to several tens of kilometers, heat conduction becomes important at time scales of a few tens of million years. From the geochronological history of the M_2-phase at Naxos [14], it is evident that the formation of the dome took less than 10 Ma, and we may conclude that, although a detailed thermal model would require some corrections for heat losses by conduction, such corrections can safely be neglected in an order of magnitude approximation as used here.

4. Thermal effects

With the data given above, the thermal effects can be calculated. In the preceding section it was found that the fluid/rock mass ratio was probably between 0.06 (which we will call the "minimum model") and 0.8 or even more (the "maximum model").

By using the thermal data on the fluid and rock as given above, and taking into account the fact that only 2/3 of the fluid is considered to have entered the system from below, the mean temperature of the rocks for a fluid/rock ratio of 0.06 will increase by:

$$\frac{0.06 \times 2/3 \times 0.365 \times 600 \text{ cal g}^{-1}}{0.3 \text{ cal g}^{-1}\,{}^{\circ}\text{C}^{-1}} = 29.2^{\circ}\text{C}$$

In the maximum model, with a fluid/rock ratio of 0.8, the resulting rise in mean temperature is 390°C. If the top of the section remains at 400°C, and a linear temperature distribution is assumed, the temperature of the bottom part will increase by 58°C, whereas in the maximum model there is a large excess of heat over the amount required for simple heating to 700°C. This excess heat must have caused the large-scale partial melting (anatexis) observed in the central part of the metamorphic system. It may be concluded that heating by deep-seated fluids contributed at least significantly to the formation of the thermal dome, and may in fact have been its sole cause.

5. Release of CO_2-rich fluids from the mantle

Quite substantial amounts of CO_2 may be stored as carbonates in the mantle, where carbonates and OH-bearing silicates can be stable at temperatures around 1000°C at pressures of 15 kbar and higher [17,18,23]. A pressure drop will cause the breakdown of these carbonates and hydrous silicates. The presence of a mantle plume underneath the Cycladic area has been postulated by several authors [16,24]. In a mantle plume the condition of decreasing pressure, under which CO_2 and H_2O are released, is fulfilled. It is postulated here that thermal domes in the crust may be generated over the apical points of mantle plumes, where released fluids can escape most readily. These fluids, with initial temperatures of about 1000°C (at significantly lower temperatures the carbonates and hydroxyl-silicates remain stable), provide an effective and localized means of heat transfer. Convection of heat by fluids through particular zones may lead to the sharply contrasting thermal regimes over fairly small horizontal distances, characteristic of thermal domes. Simple conduction of heat over a mantle plume is too slow a process, and will not lead to locally higher geothermal gradients. Intrusions, which are often mentioned to explain the steeper geothermal gradients, took place at Naxos after the formation of the thermal dome; they are considered to be the result of the upward movement of hot fluids and not the prime cause of thermal dome formation.

6. Conclusions

During the formation of the thermal dome of Naxos large amounts of fluids of deep-seated origin have passed through the metamorphic rocks. The heat carried upwards by these fluids seems adequate to cause metamorphism and anatexis. Heat transport by hot fluids from the mantle, focussed in small areas, may act more rapidly and less diffusely than heat conduction, and explains the large variation of the geothermal gradients over small horizontal distances.

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