Timing of rodingitization at the Ronda peridotites (Betic Cordilleras, Spain)

Edad del proceso de rodingitización en las Peridotitas de Ronda (Cordilleras Béticas, España)

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ABSTRACT

This work reports the timing of the rodingitization process of granitic dykes intrusive into the Ronda Peridotites. Representative fission-track ages on zircon and apatite from rodingitized dykes, in combination with cooling rates suggested for the Alpujarride Complex (Monié et al., *1994; Sánchez-Rodríguez, 1998; Sosson* et al., *1998) point to a minimum age of 16.8 ± 1.8 Ma for the rodingitization process. By extrapolating to the timing of formation of the highest stability limit of the serpentine minerals (500°C) we propose that the serpentinization of Ronda peridotites was a continuous process lasting at least for 2.2 Ma, from 19.1 to 16.9 Ma.*

RESUMEN

Este trabajo proporciona la edad del proceso de rodingitización obtenida en el conjunto de diques graníticos intruidos en las peridotitas de Ronda. Las edades relativas obtenidas mediante trazas de fisión en circones y apatitos, en combinación con las diferentes tasas de exhumación calculadas para el complejo Alpujárride (Monié et al., 1994; Sánchez-Rodríguez, 1998; Sosson et al., 1998) proporcionan una edad mínima de 16.8 ± 1.8 Ma para el proceso de rodingitización. La extrapolación de la edad de comienzo de la serpentinización a partir del límite superior de estabilidad de los minerales de la serpentina (500°C), nos hace proponer que la serpentinización en las peridotitas de Ronda, fue un proceso continuo con una duración mínima de 2.2 Ma, desde unos 19.1 Ma. hasta 16.9 Ma.

Key words: *Rodingite, fission track analysis, Cooling ages, Ronda, Betic Cordilleras.*

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Introduction

Rodingites are end products of Ca-metasomatism acting on a great variety of protoliths as a complementary process of serpentinization in nearby ultramafic rocks (e.g. O'Hanley, 1996). The occurrence of rodingites in peridotite massifs reflects the production of Ca-rich fluids owing to the inability of crystal lattices of serpentine minerals to lodge the calcium released from pyroxenes during the serpentinization of peridotites (Schandl *et al.*, 1989, 1990). Other rocks in contact with the ultramafics take in such Ca-rich fluids and are then transformed to assemblages with calcium silicates including hydrogrossular, epidote, idocrase, diopside and pectolite. The first description of rodingites within the Ronda peridotites has been reported by Esteban *et al.* (2001), who recognised pectolite associated with xonotlite and hydrogrossular in granitic dykes intrusive into the Ronda peridotites. Esteban *et al.* (2003), deduced a temperature range between 300° to 350°C as the beginning of the rodingitization process based on the mineral parageneses of the dykes and the surrounded serpentinites. Retrograde alteration at lower temperature conditions has occurred since then, producing aragonite. Thus the rodingitization process has been continuous since the rocks passed through 350°C and continued until near surface temperatures.

Most of the radiometric studies performed on metamorphic rocks of the Alpujarride Complex since the 1980's have yielded evidence for very high cooling rates during Early to Middle Miocene times (Zeck *et al.*, 1989; Monié *et al.*, 1994; Zeck, 1996; Sosson *et al.*, 1998; Sánchez-Rodríguez and Gebauer, 2000). However, the conclusions proposed by these authors disagree in the magnitude of the temperature fall and on the time span required by the cooling process, varying between a cooling rate in the range 100°-350°C/Ma for an age bracket of 20-19 Ma (Monié *et al.*, 1994) and 500°C/Ma within the period 22-17 Ma (Zeck, 1996). A subsequent stage of cooling at lower rates, from below 350°C, has been also detected by some authors (Andriessen and Zeck, 1996; Zeck, 1996; Sosson *et al.*, 1998; Sánchez-Rodríguez, 1998). We report here

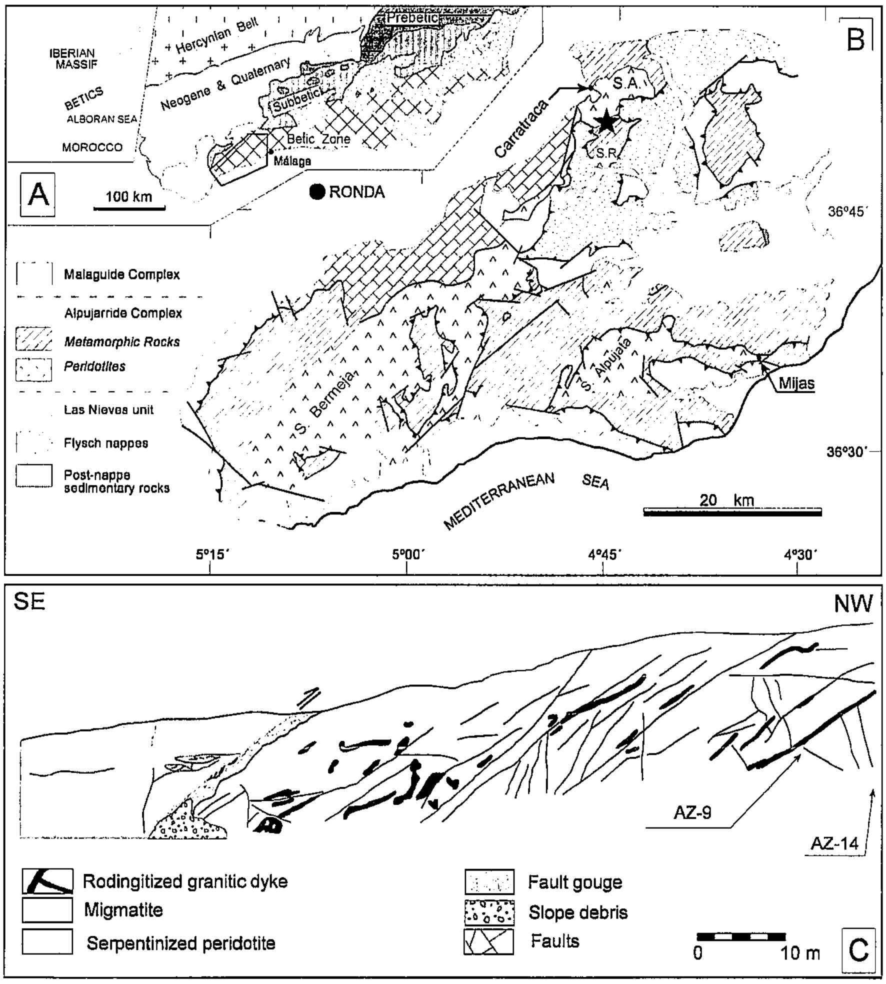

Fig. 1.- A) Location of the study zone in the Betic Cordilleras, west of Málaga. B) Simplified geological map of the western sector of the Betic Cordilleras, showing the main massifs of the Ronda peridotites: Sierra Bermeja, Sierra Alpujata, Mijas and Carratraca (SA: Sierra de Aguas, SR: Sierra de la Robla). (From Tubía, 1994). C) Detailed cross-section of Cerro Tajo Fault (marked by star in B) including the location of the studied samples (AZ-14 is located 200 m. towards the NW from its position).

Fig. 1.- A) Localización del area de estudio dentro de las Cordilleras Béticas al oeste de Málaga. B) Mapa geológico simplificado del sector occidental de las Cordilleras Béticas, con la localización de los principales macizos de peridotitas de Ronda: Sierra Bermeja, Sierra Alpujata, Mijas y Carratraca (SA: Sierra de Aguas, SR: Sierra de la Robla). (Modificado de Tubía, 1994). C) Corte detallado de la falla de Cerro Tajo (señalado con una estrella en la figura 1B) indicando la localización de las muestras estudiadas (La muestra AZ-14 se encuentra situada a 200 m. hacia el NW desde la posición indicada).

new fission track ages on apatite and zircon from two rodingitized granitic dykes located within the Carratraca peridotite massif (Fig. 1). These ages provide the timing of the rodingitization process and hence help to constraint the low-temperature evolution of the Ronda peridotites.

Regional Geology

The Ronda peridotites are the largest mass of orogenic lherzolites in the world. They belong to the Alpujarride Complex of the Internal Zone of the Betic Cordilleras (Fig. 1A & B) and form the lower portion of the highest Alpujarride thrust sheet (Navarro-Vilá and Tubía, 1983; Tubía and Cuevas, 1986). The Ronda peridotites are mainly composed of lherzolite, with subordinate amounts of harzburgite, dunite and mafic layers (Hernández-Pacheco, 1967). The Carratraca Massif is more serpentinized and shows a higher content of granitic dykes than the bigger massifs, Sierra Bermeja and Sierra Alpujata (Fig. 1), of the Ronda peridotites. The dykes are mainly composed of biotite, cordierite, zoned plagioclase ($An_{80} - An_{38}$), and quartz with zircon, apatite and ilmenite as minor components. As outlined above some dykes show the formation of calcium silicates characteristic of rodingitization processes.

Sample location and methodology

The granitic dyke complex in the Carratraca Massif of the Ronda peridotites, Málaga (Spain) is the object of this study.

Apatite and zircons were extracted from 5-6 kg of initial rock of rodingitized granitic dykes, from an outcrop (Fig. 1C) along the Malaga-Campillos road (A-357), using conventional methods including crushing and Wilfley table/heavy liquids/magnetic separation steps. Both, apatite and zircon were prepared for fission track analysis by the external detector method, using the usual procedures of the ETH laboratory (Seward, 1989). All the samples were irradiated at the ANSTO facility (Australia). Zeta values of 100.5 ± 2.7 for CN1/zircon and 293.1 ± 10.9 for CN5/apatite were used (JJE). Tracks were counted using a *ZEISS* microscope with magnifications of 1250X for the apatite and 1600X (oil) for the zircon. All the ages are presented as central ages with 2σ errors, following the method by Galbraith (1981).

Results

The studied samples yielded one apatite and two zircon fission-track ages (Table 1). The high values obtained in the chi-squared test (PX^2: Table 1) indicate that all of the crystals form a single population in each sample, as it is expected in rapidly cooled rocks.

The zircon ages are 16.8 ± 1.8 and 16.7 ± 1.8 Ma (Fig. 2B & C), both with 2σ errors. These ages are in agreement with those calculated by Andriessen and Zeck (1996) for the Torrox gneisses (17.2±2.5 Ma) and Sánchez-Rodríguez (1998) from Los Reales nappe in the Western part of the Betic Chain (17.1±1.9 Ma). The apatite fission-track age is 16.9 ± 3.0 Ma (Table 1, Fig. 2A). This apatite age also concurs with previous results from Andriessen and Zeck (1996), Sosson *et al.* (1998) and Sánchez-Rodríguez (1998).

As the fission-track ages obtained for zircon and apatite are nearly coincident, this implies that fast cooling as seen in the early stages, was also maintained during the lower temperature evolution of the Alpujarride Complex.

It is accepted that at high cooling rates the closure of the radiometric systems takes place at higher temperatures. Yamada *et al.* (1995) showed that with the fanning model the upper bounding temperature for initiation of annealing can be as high as 390°C, with a mean closure temperature of 240°C for zircons. Foster *et al.* (1996) determined zircon closure temperatures for a range of cooling rates, estimating a closure temperature of 260° ± 25°C for a cooling rate of 50°C/Ma, while for higher rates the closure temperature was

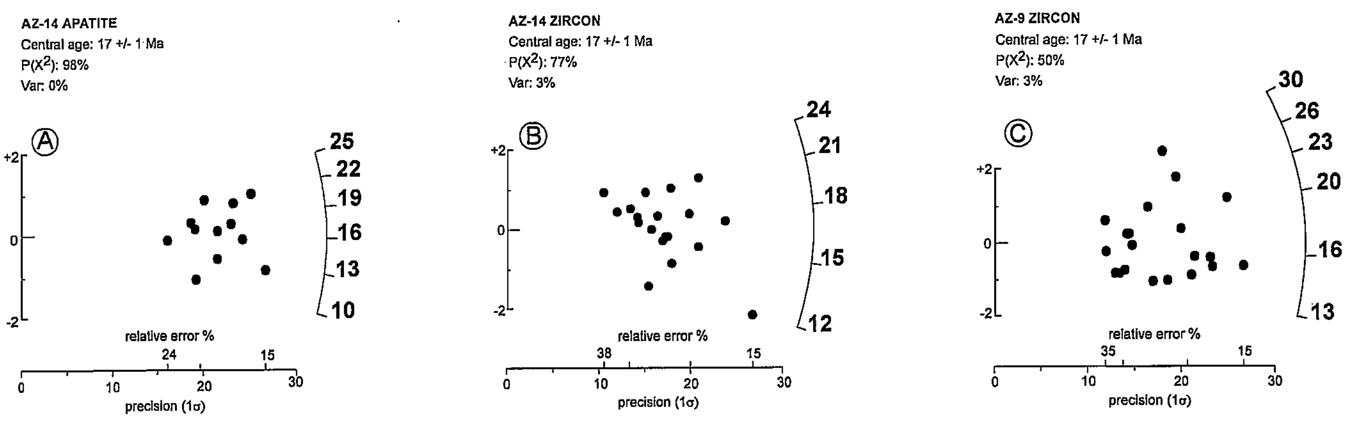

Fig. 2.- Radial plot (Galbraith, 01981) showing the differences cooling ages of apatites (A) and zircons (B & C) of the studied samples.

Fig. 2.- *Diagramas radiales (Galbraith, 1981) con las edades de enfriamiento de apatitos (A) y circones (B y C) de las muestras estudiadas.*

increased. Foster *et al.* (1996) state that for cooling rates between 200° and 500°C/Ma the effective closure temperatures are "extraordinarily high" and not resolvable because in their study the ages were concordant with other methods such as $^{40}Ar/^{39}Ar$ on hornblende, biotite and K-feldspar. Green *et al.* (1996) clearly showed that temperatures greater than 250° are required for significant annealing and from a study in the Southern Alps suggest at least 300°C. Finally, Rahn (personal communication) estimate a closure temperature of between 330 and 350°C for a cooling rate of 100-200°C/Ma in an annealing study of zero damage zircons - a state which is compatible with the zircons in the Ronda. Thus we take here an effective closure temperature for zircon at 300 ± 50°C which covers the range of those listed above but would caution to the higher side.

Estimates for the closure of apatite fall in the range 75-125°C for cooling rates between 1 and 100°C/Ma (Wagner and Reimer, 1972; Haack, 1977; Gleadow and Lovering, 1978). The upper level of 125°C was used in this study.

Thus one may conclude that the rodingitization process, beginning at 300° to 350°C (Esteban *et al.,* 2003), falls within the range of closure of zircon and apatite for extremely high cooling rates (Fig. 3) in the granitic dykes in the Ronda peridotites. Therefore, the mean zircon fission-track age obtained in this work (16.8 ± 1.8 Ma) corresponds to the timing of rodingitization, in Miocene times, during the extensional collapse of the Betic Cordilleras.

Monié *et al.* (1994) reported an age of 18.7 ± 0.2 Ma on biotites of granitic dykes at Sierra Alpujata massif with cooling rates ranging from 100-350°C/Ma. As the cooling ages for the closure temperature of the $^{40}Ar/^{39}Ar$ system (350°C or higher in the case of such rapid cooling) and the highest stability limit of the serpentine minerals (500°C) are nearly coincident considering a cooling rate of 350°C/Ma (Monié *et al.*, 1994), it is possible to estimate the age that would correspond to this upper limit of 500°C. Thus, an age of 19.1 Ma would correspond to the beginning of the serpentinization. In contrast, the apatite-fission track age obtained in this work (16.9±3.0 Ma), points to a minimum stability limit of the serpentinization similar to the closure temperature of the apatites in this case probably greater than 120°C. Therefore, these age restrictions lead us to suggest that the homogeneous serpentinization imprinted in all the ultramafic massifs, was a process lasting 2.2 Ma at least, from the upper stability limit of the serpentine to the closure temperature of the apatites.

Conclusions

The ages reported in this work in the rodingitized dykes from the Carratraca Massif, obtained through fission-track analysis, are in complete agreement with the previous cooling ages at the Betic Cordillera, suggesting a geologically quasi-instantaneous cooling, between the closure temperatures of zircons and apatites. The mean zircon and apatite

Sample	Irradiation	Mineral	Altitude (m)	Nº of grains	ρ_d (N_d) (10^6 t/cm^2)	ρ_s (N_s) (10^6 t/cm^2)	ρ_i (N_i) (10^6 t/cm^2)	U (ppm)	PX^2 (%)	Var (%)	Central age ±2σ (Ma)
AZ-14	Eth-230-5	Apatite	269.0	14	1.270 (7422)	0.362 (144)	3.969 (1581)	39.1	98.0	0.00	***16.9 ± 3.0***
AZ-9	Eth-231-16/17	Zircon	266.0	20	0.3462 (2175)	3.642 (783)	3.768 (809.9)	435.3	50.3	3.49	***16.8 ± 1.8***
AZ-14	Eth-231-23	Zircon	269.0	19	0.3130 (2175)	3.785 (760)	3.561 (715.0)	455.1	77.5	2.73	***16.7 ± 1.8***

ρ_d: Density of tracks in the glass dosimeter. (N_d): Number of tracks counted in the glass dosimeter

ρ_s: Spontaneous track density (N_s): Number of spontaneous tracks counted.

ρ_i: Induced track density. (N_i): Number of induced tracks counted.

PX^2: Is the probability of obtaining X^2-values for ζ degrees of freedom, where ζ: (number of crystals –1).

Var: Variation

All ages are central ages (Galbraith, 1981). Apatite ages are calculated using dosimeter CN5 with a ζ-factor of 293.13 ± 10.87. Zircon ages are calculated using dosimeter CN1 with a ζ-factor of 100.48 ± 2.71. Irradiations were performed at the ANSTO nuclear reactor, Lucas Heights, Australia.

Table I.- Fission track data from the granitic dykes of the Ronda peridotites.

Tabla I.- *Datos analíticos de las trazas de fisión de los diques graníticos de las peridotitas de Ronda.*

fission-track ages obtained during this work indicate that the serpentinization and rodingitization in the Carratraca massif were active at least during a time span between 19.1 to 16.8 Ma.

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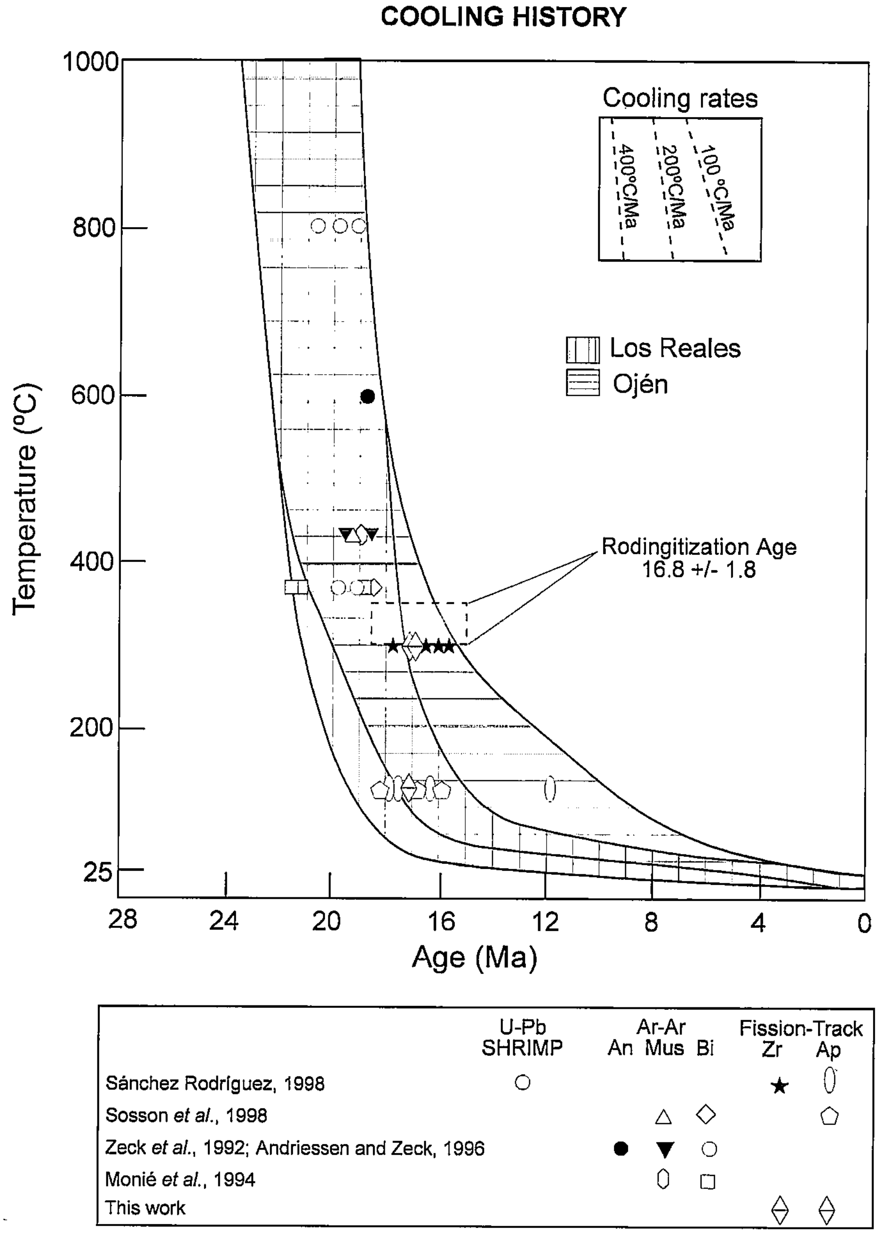

Fig. 3.- Temperature-time diagram with zircon and apatite fission tracks ages for Los Reales and Ojen nappes (Navarro-Vilá & Tubía 1983) belonging to the Alpujarride Complex (Modified from Sánchez-Rodríguez 1998). The dashed rectangle represents the temperature and age range obtained in this work for the rodingitization process.

Fig. 3.- *Diagrama que relaciona temperatura-tiempo con las edades de las trazas de fisión fisión de apatitos y circones obtenidas en los mantos de Los Reales y Ojén (Navarro-Vilá y Tubía, 1983) del complejo Alpujárride (modificado de Sánchez-Rodríguez, 1998). El rectángulo sombreado representa los rangos de temperatura y edad obtenidos en este trabajo para el proceso de rodingitización*

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