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RAPID COMMUNICATION

A revised Aquitanian age for the emplacement of the Ronda peridotites (Betic Cordilleras, southern Spain)

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Abstract

The hot emplacement of the Ronda peridotites (Betic Cordilleras) developed a dynamothermal aureole and partial melts that led to the intrusion of granite dykes in the peridotites. Previous geochronological data place rather broad limits for this event between 22 and 19 Ma. Analyses of neocrystalline zircon rims from large zircon populations yield a U–Pb SHRIMP age of 22.3 ± 0.7 Ma for the dynamothermal aureole formation, and intrusion ages of granite dykes between 22.6 ± 1.8 and 21.5 ± 3.8 support that conclusion. Therefore, these new ages provide a more robust constraint on the hot emplacement of the Ronda peridotites at middle crustal levels.

Keywords: Betic Cordilleras, Ronda peridotites, anatexis, dyke, U–Pb SHRIMP.

1. Introduction

The Ronda peridotites, the largest exposures of subcontinental lithospheric mantle of the world, are incorporated into the Internal Zone of the Betic Cordilleras, southern Spain (Fig. 1). The peridotites rest over a continental crustal sequence composed mainly of gneisses, quartzites, metapelites, marbles and minor amphibolites belonging to the Guadaiza and Ojen nappes (Navarro-Vilá & Tubía, 1983). As result of the hot emplacement of the Ronda peridotites, the underlying crustal rocks developed a dynamothermal aureole and experienced partial melting, leading to the intrusion of granite dykes in the peridotites (Tubía & Cuevas, 1986).

The structural evolution of the Ojen (Tubía, Cuevas & Gil Ibarguchi, 1997) and Guadaiza (Esteban *et al.* 2008) dynamothermal aureoles as well as the emplacement of the granite dykes (Cuevas, Esteban & Tubía, 2006) have been studied in detail, but the ages of the aureole formation and dyke intrusion are as yet poorly constrained. U–Pb SHRIMP dating of zircons from the dynamothermal aureoles of Guadaiza and Ojen nappes provided a discordant ^{206}Pb–^{238}U age of 22.5 ± 1.2 (2σ) and a concordia lower intercept age of 20.8 ± 1.2 (2σ) Ma, respectively, that were interpreted as the maximum age for zircon recrystallization during a migmatization event that led in some cases to zircon Pb-loss (Sánchez-Rodríguez, 1998). Previous results from undeformed dykes reflect mainly cooling ages and provide diverse age values: 22 ± 4 (2σ) Ma from Rb–Sr whole rock analyses (Priem *et al.* 1979) and 18.8 ± 8 (2σ) Ma (Monié, Torres-Roldán & García-Casco, 1994) or 18.9 ± 0.8 (2σ) (Sosson *et al.* 1998) from ^{40}Ar–^{39}Ar on biotite. According to Sánchez-Rodríguez & Gebauer (2000), the lower intercept age of 18.8 ± 6 (2σ) Ma obtained by U–Pb SHRIMP analyses of zircons from an undeformed dyke represents the time of recrystallization of the granite dykes.

In addition to the large errors of most of the previous results, it is worth noting an apparent low resolution implicit in the fact that the SHRIMP crystallization age was younger than the Rb–Sr and Ar–Ar cooling ages or even than some fission-track ages (Esteban *et al.* 2004). With the aim to constrain better the emplacement age of the Ronda peridotites, we present new U–Pb SHRIMP ages on zircons from three samples (Fig. 1): a mylonitic gneiss from the dynamothermal aureole of the Guadaiza nappe (Gu-35) and two granite dykes, tb-06–838 and tb-06–842, that intrude in the peridotites of Sierra Bermeja and Sierra Alpujata massifs, respectively (Fig. 1).

2. Description of samples

Gu-35 is a representative sample of the deformed migmatite layer that has been interpreted as a component of the dynamothermal aureole developed below the Ronda peridotites (M. T. Lundeen, unpub. Ph.D. thesis, Univ. Harvard, 1976; Lundeen, 1978; Tubía, 1988; Tubía, Cuevas & Gil Ibarguchi, 1997; Esteban *et al.* 2008). This lithology is a fine-grained mylonite with the mineral assemblage of quartz + K-feldspar + plagioclase + biotite + tourmaline + sillimanite. K-feldspar porphyroclasts with zircon inclusions are common (Fig. 2a). The calculated migmatization pressure–temperature conditions are approximately 725 °C and 600 MPa (Esteban *et al.* 2008). The aureole grades progressively downwards to schists and quartzites of lower-grade metamorphic conditions.

Granite dykes were crystallized from felsic magmas derived by partial melting of the continental crust related to the formation of this dynamothermal aureole. They emanate from the aureole and intrude within the overlying peridotites (Cuevas, Esteban & Tubía, 2006). Moreover, their ^{87}Sr/^{86}Sr signature (Priem *et al.* 1979) also confirms their crustal affinity. Tb-06-838 is a slightly deformed porphyritic dyke containing euhedral to subhedral crystals of plagioclase, cordierite and K-feldspar immersed in a euhedral and fine-grained cordierite–plagioclase–quartz matrix. Cordierite is slightly pinnitized and shows hourglass twinning and epitactic microstructure with inclusions of

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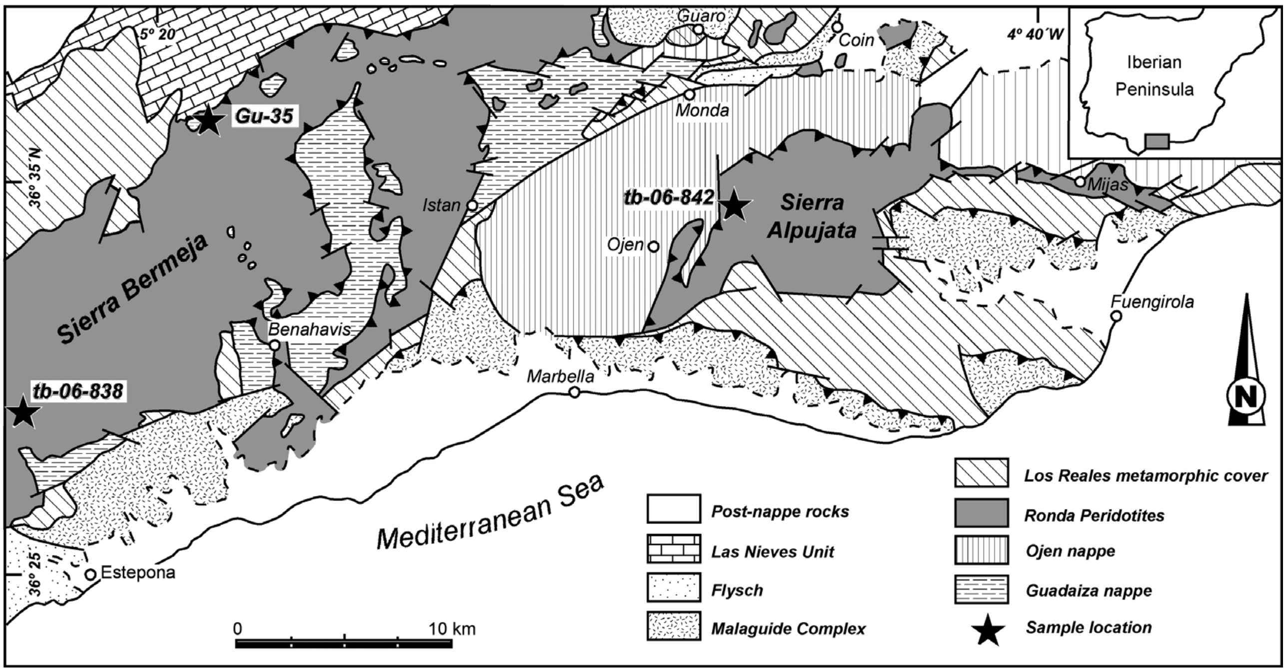

Figure 1. Tectonic map of the western Internal Zone of the Betic Cordilleras (modified from Navarro-Vilá & Tubía, 1983) with the location of analysed samples.

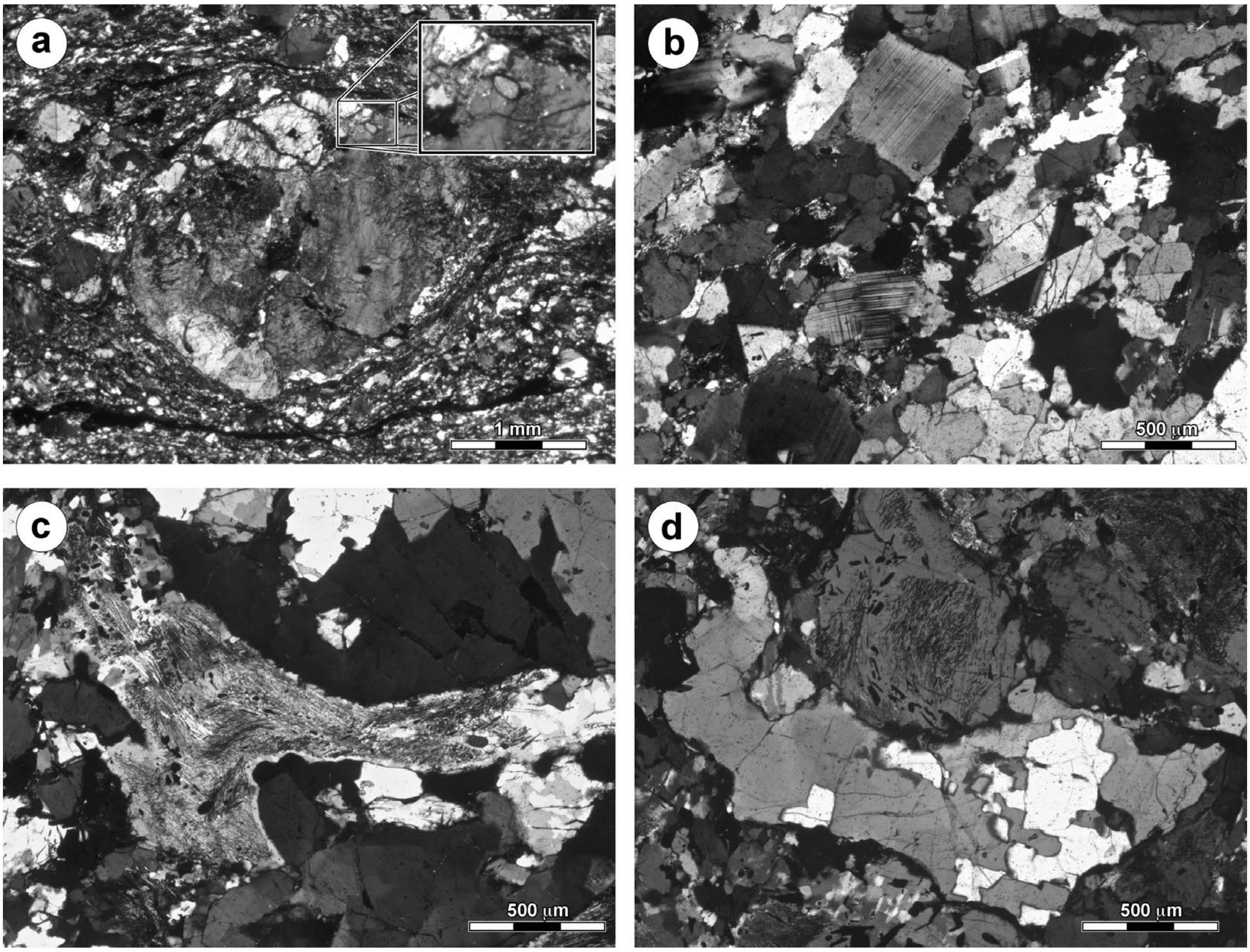

Figure 2. Photomicrographs of analysed samples. (a) K-feldspar porphyroclast surrounded by the mylonitic foliation in sample Gu-35. The insert shows a zircon grain included in the porphyroclast. (b) Porphyritic texture with euhedral cordierite and mechanical twins in a plagioclase crystal (sample tb-06–838). (c) Anhedral poikilitic cordierite with abundant inclusions of sillimanite needles and (d) high temperature, chessboard microstructure in a grain of quartz (sample tb-06–842).

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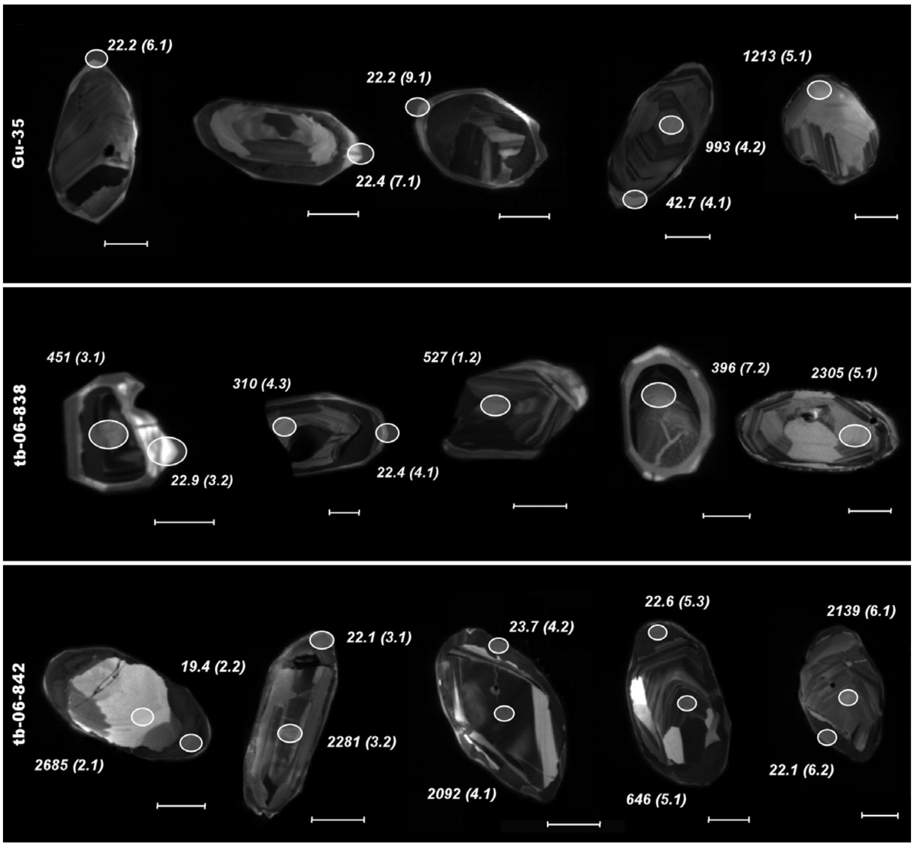

Figure 3. Cathodoluminescence images of studied zircons. Ellipses show the spot locations. The attached numbers give the obtained ^{206}Pb–^{238}U age and the spot name. All scale bars are 50 μm long.

prismatic sillimanite. Mechanical twins in plagioclase crystals are frequent (Fig. 2b). Tb-06-842 is a mylonitic dyke composed mainly of quartz, feldspar, garnet and boudinaged crystals of cordierite. Cordierite appears as lobulated and intergranular xenomorphic grains (Fig. 2c), rich in inclusions of biotite, garnet, hercynite, ilmenite and prismatic sillimanite (Fig. 2c). Two generations of garnet can be differentiated petrographically: (1) coarse-grained poikilitic crystals, with anhedral shapes and optically zoned and (2) small, subhedral and inclusion-free crystals included within feldspar and cordierite. Chessboard patterns and basal sub-grain boundaries are frequent in the quartz grains (Fig. 2d), pointing to high-temperature conditions during mylonitization.

The dark colour of these dykes in the field, together with their degree of deformation, serves to distinguish them from the white, undeformed granite dykes previously dated (Cuevas, Esteban & Tubía, 2006).

3. U–Pb SIMS SHRIMP dating

Zircons from studied samples were extracted from 10 to 20 kg blocks in order to obtain very large zircon populations with wide enough neocrystallized peripheral areas to perform precise SHRIMP analyses. Selected zircon grains were mounted in epoxy resin together with the TEMORA 1 reference zircons (Black *et al.* 2003) and analysed on a SHRIMP-II SIMS at the Centre of Isotopic Research (CIR) at VSEGEI (St Petersburg). Cathodoluminescence (Fig. 3) and electron back-scattering images were used to reveal the internal structures of the zircon grains and target areas for analysis. The results were obtained with a secondary electron multiplier in peak-jumping mode and following the procedure described by Larionov, Andreichev & Gee (2004). Seven cycles for each analysed spot were acquired. Every fourth measurement was carried out on the zircon Pb/U standard TEMORA 1.

The U–Pb ion microprobe data are presented in online Appendix Table 1 (http://journals.cambridge.org/geo). The results were processed with the SQUID 1.02 (Ludwig, 2001) and Isoplot/Ex 3.00 (Ludwig, 2003) software, using the decay constants of Steiger & Jäger (1977). The common lead correction was done on the basis of measured $^{204}Pb/^{206}Pb$ according to the model of Stacey & Kramers (1975). The data are plotted in Figure 4.

Zircon grains from all the samples have many similarities. They display rounded, corroded or truncated inherited xenomorphic cores with typical magmatic oscillatory and sector zonings (Fig. 3). The cores are surrounded by CL-bright or CL-dark unzoned rims with very low $^{232}Th/^{238}U$ ratios, typical of newly grown domains (online Appendix Table 1 at http://journals.cambridge.org/geo). However, some grains also have external areas with more than one unzoned domain (e.g. zircons tb-06–838.4 and Gu-35.7).

Zircon core morphology points to their detrital nature, while their magmatic oscillatory zoning and mean Th/U ratio (0.51) confirm an igneous origin. Nineteen spot analyses were carried out, yielding ^{206}Pb–^{238}U ages from 310 to 2685 Ma (online Appendix Table 1 at http://journals.cambridge.org/geo). Some of the Archaean grains are significantly discordant (Fig. 4), attesting to Pb-loss.

Fifteen analyses have been carried out in the widest peripheral areas of the zircons in order to date the last events recorded by new zircon growth. The peripheral newly grown domains for all three samples give similar *c.* 22 Ma concordia ages (Fig. 4) with similar Th/U ratios, except for four spots (see online Appendix Table 1 at http://journals.cambridge.org/geo), which yield mixed

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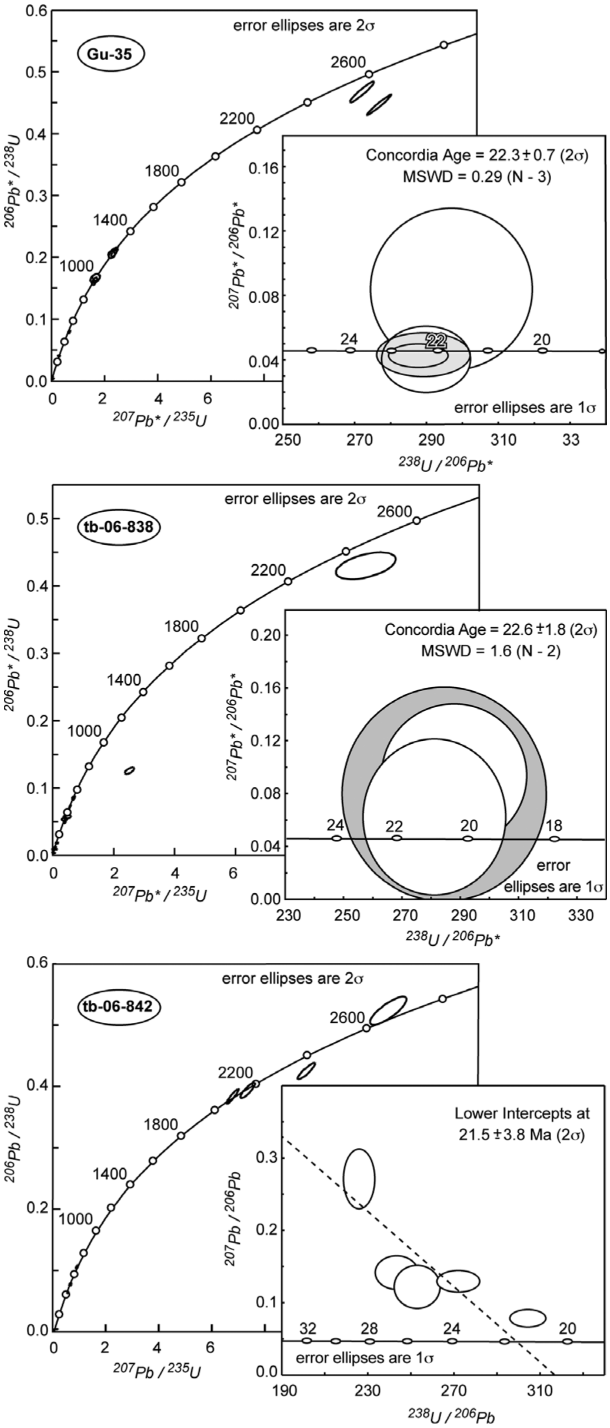

Figure 4. Concordia diagrams for each analysed sample with all the zircon age data based on the ^{207}Pb/^{238}U versus ^{207}U/^{235}U ratios. Each diagram has a Tera-Wasserburg diagram with the youngest concordant age data set based on ^{207}Pb/^{206}Pb versus ^{238}U/^{206}Pb ratios. All age errors are 2σ.

core–rim ages with no geological meaning. Samples Gu-35 and tb-06-838 have concordia ages of 22.3 ± 0.7 (2σ) (Th/U = 0.02–0.04) and 22.6 ± 1.8 (2σ) Ma (Th/U = 0.06–0.09), respectively, while sample tb-06-842 gives a lower intercept age of 21.5 ± 3.8 (2σ) Ma (Th/U = 0.01). A high probability of age coherence is indicated by the overlapping of the youngest most concordant data from all three samples. On a total ratio anchored Tera-Wasserburg plot, all the analyses define a mixing line intersecting the concordia at 21.7 ± 0.8 Ma (2σ - MSWD 3.2) and also confirm their age coherence. According to the presented data, we think that the age of 22.3 ± 0.7 (2σ) Ma can be interpreted as the time of the dynamothermal aureole formation. The ages obtained for the granite dyke crystallization, albeit imprecise, do support their formation from the aureole.

4. Discussion and conclusions

According to previous geochronological data from the dynamothermal aureole and granite dykes associated with the Ronda peridotites, only a vague span of 3 Ma, between 22 and 19 Ma, can be established for the emplacement of the ultrabasic rocks. Sánchez-Rodríguez (1998) indicated that Pb-loss related to migmatization in the dynamothermal aureoles could result in the lower-intercept ages of 22.5 to 20.8 Ma and also that some results could represent mixed ages with no geological meaning since the SHRIMP spots include portions of innermost, older zircon domains due to the narrow rims. We have been able to avoid similar analytical errors working with large zircon populations and selecting zircon grains with rims broad enough to be analysed (Fig. 3). This time-consuming approach has proved to be very successful, as a precise age of 22.3 ± 0.7 Ma has been obtained for the formation of the dynamothermal aureole of the Guadaiza nappe. This result is consistent with the ages obtained for the crystallization of the granite dykes. The diverse ages for the intrusion of granite dykes (see the Introduction) suggest that partial melting conditions in the aureole prevailed during a period of several millions of years.

Based on the previously published radiometric ages (Priem *et al.* 1979; Monié, Torres-Roldán & García-Casco, 1994; Sosson *et al.* 1998; Sánchez-Rodríguez & Gebauer, 2000), it was proposed that the intrusion (*c.* 19 Ma ago) of the granite dykes was restricted to late metamorphic stages in the dynamothermal aureole (Cuevas, Esteban & Tubía, 2006). The new data presented here attest that the generation and intrusion of granite melts occurred about 3 Ma prior to what was thought. On this point, we would remark that several generations of dykes can be recognized based on cross-cutting relationships, the mylonitic dykes being commonly older than undeformed ones (Cuevas, Esteban & Tubía, 2006). This observation provides a coherent explanation for the range of ages of the granite dykes published up to now and also for the apparent inconsistency arising from the finding of younger ages for the crystallization of some granite dykes than for the cooling ages of other, and probably older dykes.

Therefore, from the new data presented in this work we propose that: (1) the age of 22.3 ± 0.7 Ma dates the formation of the dynamothermal aureoles and hence the emplacement of the Ronda peridotites in middle crustal levels, at temperatures high enough to promote the generation of partial melts which intrude as granite dykes in the peridotites and (2) the development of the aureole and the intrusion of the granite dykes formation persisted from 22.3 to *c.* 19 Ma.

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